Challenges in managing forest genetic resources for livelihoods

examples from Argentina and Brazil

Barbara Vinceti, Weber Amaral and Brien Meilleur

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IPGRI
Via dei Tre Denari 472/a
00057 Maccarese
Rome, Italy

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Weber Amaral
(Global Co-ordinator of IPGRI's Programme on Forest Genetic Resources)

Foreword

Global concerns for the fate of tropical forests continue to mount despite the fact that "progress in implementing sustainable forest management around the world has been steady and encouraging" (FAO 2003)[1]. "The estimated net annual change in forest area worldwide from 1990 to 2000 was –9.4 million ha (this figure represents the difference between the estimated annual rate of deforestation of 14.6 million ha and the estimated annual rate of forest area increase of 5.2 million ha)," (FAO 2001)[2]. In coming years, population increases combined with growing per capita consumption will continue to result in agricultural expansion into new lands, mostly through deforestation. Preliminary findings of a study by the Food and Agriculture Organization (FAO) indicate that agricultural land is expanding in about 70% of countries, and in two-thirds of these countries forest area is decreasing (FAO 2003)[1].

A large number of species found in habitats that are rapidly disappearing require conservation measures. However, our limited knowledge of the impacts of deforestation, uncontrolled exploitation and other threats to genetic diversity in tropical forests is a problem that restricts the capacity of regional, national and international institutions to plan and implement appropriate actions. There are many major challenges to developing strategies for the conservation and sustainable use of forest ecosystems and their tree species. These include the difficulties of setting priorities for intervention; scaling up research findings from local dimensions to larger scales, and feeding these results into regional action plans; generating best practice for ecosystem and species management based on work limited to model species; raising awareness within national programmes in order to ensure that recommendations and guidelines for conservation and sustainable use of forests are adopted into policy and practice; and, very importantly, engaging local communities in conservation actions, making sure they can benefit directly from the sustainable management and use of forest resources.

It is important to note that past efforts at conservation, through establishing protected areas, national parks and reserves, have not given sufficient consideration to the distribution of species and their infraspecific genetic variation, both of which are central to ensuring the maintenance of adaptive capacity and production potential to meet present and future needs. Thus, research is needed at ecosystem, species and infraspecific levels in order to support the development of complementary conservation strategies and effective policies that reconcile the needs and interests of local communities and governments.

The Convention on Biological Diversity provides an overall framework for the protection of forest ecosystems and their tree species. Countries that ratified the Convention are required to assess and monitor their biological resources and to develop effective strategies for conserving them. These strategies and methods for the conservation and sustainable use of tropical forest trees should ensure that forest ecosystems make an increased contribution to the livelihoods of local communities and national economies as well as securing the genetic diversity of target species for the future.

Discussions between German partners and the International Plant Genetic Resources Institute (IPGRI) during a workshop in 1995 on '*In situ* conservation of plant genetic resources for food and agriculture in developing countries' resulted in a decision that efforts related to the conservation, genetic management and sustainable use of forest genetic resources should receive high priority. Consequently, in close collaboration with two German forestry research institutes, with identified partners in Brazil and Argentina, IPGRI initiated a consultation process that ultimately resulted in the German Federal Ministry for Economic Co-operation and Development (BMZ) funding this project, entitled 'Conservation, management and sustainable use of forest genetic resources with reference to Brazil and Argentina'.

[1] FAO, 2003. State of the world's forests, Food and Agriculture Organization of the United Nations, Rome, Italy
[2] FAO, 2001. State of the world's forests, Food and Agriculture Organization of the United Nations, Rome, Italy

This book presents the project activities that were undertaken, within a framework that integrated socioeconomic, policy, population genetic and ecological features of four different forest ecosystems spread across South America, through a participatory and multidisciplinary research approach. Project implementation was a true learning event for all the parties involved. It resulted in unexpected problems, unforeseen delays, communications difficulties, and co-ordination and implementation challenges that turned the project into a pioneering experience.

In view of the above, we all felt it was important to share the experiences of the project partners with the broader community so that others could learn from the mistakes that were made as well as from the positive outcomes. I would thus like to summarize a few of the key learning experiences, more details of which are found in subsequent chapters of this publication. First and foremost is the importance of involving key stakeholders as equal partners, from the initial stages of project planning through to the interpretation of results. It was felt that no compromises should be made and that the project proposal should adequately reflect this in the activities and budgets that correspond to this critical phase. A second, related point is the need to allow sufficient time for individual research partners to engage rural community stakeholders in the implementation of the activities that they had agreed to undertake. This required flexibility in project implementation, sometimes more than current practices allow. Thirdly, as the approaches needed to be truly ‘bottom up’ in order to allow and ensure the required commitment and true participation of all stakeholders, it was necessary to facilitate this essential participation through adequate budgetary arrangements. It is not sufficient to assume that stakeholders have the means to participate ‘at their own expense’.

On behalf of IPGRI, I would like to use this opportunity to express my whole-hearted thanks to the Brazilian and Argentinean scholars, institutions and local communities, and NGOs who contributed in so many ways to this project; to the German researchers for their partnership; to BMZ as the donor; and to the German Technical Co-operation (GTZ) as the implementing agency. Their collective patience and understanding for the delays and changes needed to bring this project to fruition are enormously appreciated. I would also like to thank my IPGRI colleagues who invested so much time and effort to co-ordinate the implementation of this project. And finally, to my friend and colleague Abdou Salam Ouédraogo, who unfortunately could not witness how significantly ‘his’ project has contributed to our common goal of conserving and utilizing the dwindling forest genetic resources of this world, I express my most sincere gratitude. I hope that this publication will further contribute to this aim.

Jan Engels
Director, Genetic Resources Science and Technology Group
IPGRI, Rome, Italy
Rome, December 2004

Contents

Introduction

Land is a valuable, but limited resource. Hence there is great pressure to change the way in which land is used, leading to steady losses and increased isolation of habitat remnants throughout the world. Recognition of the urgency and the extent of forest loss has spurred an increasing number of studies on forest conservation and sustainable use. Most natural resource planners recognize genetic diversity and its underlying processes as essential components of ecosystem and species stability, adaptability and conservation, but rarely is there explicit provision for the conservation of genetic diversity in management planning and decision-making.

Conservation of genetic diversity is essential for many reasons. Among these are the adaptation of populations to changing environments, the risks to short-term seed and population viability from inbreeding depression, and the need to maintain genetic resources for possible future use. Therefore, goals for the conservation of genetic diversity must include maintaining the variation that affects the fitness of individuals, provides for adaptation to future environmental change, and permits ongoing genetic processes such as gene flow and natural selection to occur while genetic drift is minimized (Namkoong 1993)[1].

Given the pervasiveness of the processes of deforestation, landscape fragmentation, ecosystem simplification and associated species loss, there is an urgency to the task of integrating human population needs with the preservation of essential ecosystem processes. Some communities of forest and/or forest margin dwellers (indigenous or non-indigenous) still depend largely on forest resources for subsistence and income generation. However, increasingly, these communities are becoming disconnected from forest resources, and their economic strategies have become a less important element of community forestry-based conservation. There is therefore a need to first examine the nexus between the interests of resource users and the objectives of biodiversity conservation, and second, to analyze how current patterns of use affect the long-term maintenance of forest genetic resources (FGRs).

This book presents research findings from case studies that have explored relationships between current patterns of forest use and their effects on FGRs in four forest ecosystems.

The volume is divided into three sections. Chapters in the first section address themes that permeate the project case studies: the main threats to FGRs, the relationship between forest conditions and community-based forest management, the magnitude of extraction of nonwood forest products (NWFPs) and their current economic importance, and modelling approaches that support the management of forests and particularly FGRs.

The seven chapters in the second section outline the structure of the project funded by the German Federal Ministry for Economic Co-operation and Development (BMZ) and the results that were generated from the four research sites during the four years of project activities. These include descriptions of the first meetings with local stakeholders and research partners, identification of the species investigated, discussion of the methodologies adopted, and the use of the data obtained in order to implement models that portray the relationships between social dynamics, natural resources management and forest genetic processes.

There are two chapters in the third and final section. The first of these examines the degree of success that resulted from the adoption of a participatory approach during the research phase, and the difficulties of implementing a fruitful connection between the research disciplines (socioeconomics, species ecology, reproductive biology and genetics). It also discusses the lessons learned from project experience and provides general considerations on how to achieve better stakeholder participation and true interdisciplinary research. The second chapter in this section presents examples of practical applications for FGR research in the management of forest resources.

[1] Namkoong, G. 1993. A gene conservation plan for loblolly pine. Can. J. For. Res. 27:433–437

The BMZ-funded project illustrated in this book contains core elements of the FGR research that is undertaken around the world within the International Plant Genetic Resources Institute (IPGRI) programme. This programme is oriented towards the formulation of better FGR management practices that will simultaneously maintain ecosystem health and improve local community livelihoods while focusing on species that are overexploited, threatened or play particularly important roles in local economies. The dissemination of research findings from the BMZ-funded project via this publication is also an important part of IPGRI's FGR programme of increasing awareness about the need for FGR conservation and sustainable use. This is so that stable, diverse and healthy forest ecosystems will be able to provide a wide range of products and services to local as well as global beneficiaries for many years to come.

The book's 13 chapters are briefly introduced below.

Chapter 1 considers various impacts of human interventions on FGRs, including the biological consequences of major threats to forest ecosystems and associated tree species. A range of examples illustrates the effects of various types of disturbance on genetic diversity and on gene flow in species with different characteristics and within different ecosystems. Criteria and indicators for monitoring the conservation of genetic diversity are examined along with several modelled approaches to FGR conservation and use. The chapter then explores challenges to the conservation and sustainable use of FGRs from the vantage of species biology, conservation priority-setting and the allocation of funds.

Chapter 2 analyzes the principal factors that have influenced the success or failure of community-managed forest resources in a range of Latin American contexts. It reviews and summarizes the findings of a growing body of literature that deals with this issue and then examines these within three Latin American case studies. A descriptive analysis of the International Forestry Resources and Institutions (IFRI) methods in documenting principal forest characteristics in Latin America is presented in order to highlight the opportunities and challenges for local forest-user groups.

Chapter 3 illustrates how NWFPs are crucial resources for livelihoods in many parts of the world. This chapter addresses issues related to the potential of NWFPs for income generation at local, national and global levels. It examines how using and trading NWFPs affects the sustainability of different extraction regimes and livelihood strategies, with a focus on South America and particularly Brazil. Challenges in defining exactly what NWFPs are and in monitoring their sustainable use are highlighted, with recommendations made for further research.

Chapter 4 demonstrates how models can help us understand biological processes and identify management options. It describes the growing use of models in the study and management of natural forest ecosystems, forest plantations and forests disturbed by humans, and presents the range of their applications (from predicting forest growth and yield to estimating the effects of natural and human-influenced disturbances on forest ecosystems). The chapter than examines in detail several models adopted in FGR studies to simulate forest genetic dynamics in order to predict the effects of human interventions on forest ecosystems.

Chapter 5 introduces FGR and associated conservation issues in Latin America. It presents the structure and objectives of the BMZ-funded project in conservation, management and sustainable use of FGRs in Brazil and Argentina, undertaken under the auspices of IPGRI.

Chapter 6 presents the first BMZ-funded project case study that investigated threats to the genetic resources of *Araucaria araucana* in Argentina. Genetic processes were examined in *A. araucana* forests that were differently affected by human activities and along an environmental gradient, and then analyzed in relation to biological dynamics and socioeconomic conditions. Suggestions are made on how to incorporate research results into guidelines for sound management of *A. araucana* FGRs.

Chapter 7 assesses the conservation status of another araucaria species, *A. angustifolia,* in the State of Paraná, Brazil. This BMZ-funded study investigated the repercussions of FGR access and use policy on the conservation status of mixed *A. angustifolia* forests.

This species dominates one of the most important naturally occurring biomes in south and southeastern Brazil that has been subjected to dramatic overexploitation.

Chapter 8 provides a brief overview of the evolution of land use and land tenure regimes in the Brazilian Amazon, illustrated by examples from Acre State. The genetic and ecological characteristics of four NWFP species are assessed in two types of rural settlements: Settlement Projects (Projetos de Assentamento or PAs) and Extractive Settlement Projects (Projetos de Assentamento Extrativista or PAEs). These two types of settlement were chosen because they were characterized by different tenure and land use regimes that it was believed would differentially affect natural resources. The chapter reviews the settlement types and how they were created, and then makes recommendations for improved forest management practices based on the research findings.

Chapter 9 describes the current situation of the FGRs of selected species, chosen in consultation with local stakeholders and found within heavily degraded fragments of the Atlantic forest in the eastern corner of the State of São Paulo (Pontal), Brazil. Key findings and their interpretation are preceded by a description of the events that led to the reduction of the forest in the Pontal region, and to the degradation of what was once a highly diverse semideciduous forest biome.

Chapter 10 provides the results of a modelling exercise undertaken at one of the *A. araucana* (pehuén or araucaria) forest research sites in Argentina. The objective was to compare the dynamic behaviours of araucaria forests subjected to different use regimes and ultimately to identify the factors that influence forest ecosystem genetic processes. The goal in applying the model was to simulate, determine and then to monitor sustainable levels of FGR use for both management and conservation purposes.

Chapter 11 presents the results of further modelling of FGRs in the vulnerable *A. araucana* forest ecosystems of Argentina. Modelling was carried out to determine how genetic diversity was spatially distributed throughout the species' range in that country. Cline theory was applied in a two-dimensional landscape analysis of selection pressures, gene flow and species distribution patterns to predict areas of high genetic diversity within the *A. araucana* range. The study provides a promising first step towards developing predictive tools for genetic conservation, both in *A. araucana* and in other species, as well as a novel means of assessing spatial evolutionary processes.

Chapter 12 assessed the performance of the participatory methods used in the BMZ-funded project and across a range of social and environmental contexts in Brazil and Argentina. An analytical framework was employed to evaluate the degree to which partnerships were developed between researchers and local people in forest resource management and policy development. Lessons learned from the BMZ-funded project are outlined in the latter part of the chapter, emphasizing both the need for capacity-building among researchers and for longer time frames to implement participatory research based on effective partnerships.

Chapter 13 illustrates the practical implications of FGR research in addressing forest management issues. A portfolio of case studies is drawn from the recently concluded BMZ-funded South American research project and from other studies carried out by IPGRI in collaboration with research institutes and national research centres in developing countries elsewhere. The cases highlight the difficulties encountered when trying to scale-up research findings, extrapolate best practices from investigations limited to model species, or find fertile sociopolitical environments likely to adopt proposed solutions.

Part 2

Case Studies from IPGRI's Research Project

Chapter 10

A modelling case study: options for FGR management in *Araucaria araucana* ecosystems

L. Gallo[1], F. Letourneau[1] and B.Vinceti[2]

[1] *Instituto Nacional de Tecnología Agropecuaria (INTA), San Carlos de Bariloche, Argentina*

[2] *International Plant Genetic Resources Institute (IPGRI), Rome, Italy*

1. Introduction

One of the major outputs of this project into forest genetic resources (FGRs), funded by the Germany Federal Ministry for Economic Co-operation and Development (BMZ), was to develop and apply a general model that could improve our understanding of the dynamics of FGRs in forests used by local communities. Our ultimate goal was to use this model to compare the behaviour of different forest ecosystems, and ultimately to identify the factors that influence their genetic processes. We believed that this approach would help us to determine and then to monitor sustainable levels of FGRs for both management use and conservation purposes. In this chapter, we present the results of our modelling activities for the *Araucaria araucana* (pehuén or araucaria) forests of Argentina.

2. The Pehuén Model

In the last 30 years or so, the field of forest conservation genetics has mostly focused on identifying centres of tree species' genetic diversity, and investigating altered genetic processes that somehow jeopardized FGR conservation (Young *et al*. 2000). But in terms of real world applicability, this work has largely missed a major component of FGR conservation and use by not taking into account the most important actors in conservation: human beings.

Combined with such natural disturbances as fire, volcanism and windstorm, human actions have also shaped the characteristics of *Araucaria araucana* forests over time. As seen in Chapter 6, deforestation has significantly reduced the extension of Argentine araucaria forests (Veblen *et al.* 1999; Rechene 2000). Such major disturbances have affected the stability of araucaria ecosystems and the survival of their species. They have modified forest habitats and changed their floristic composition and genetic characteristics, but with an intensity that varies across the natural range of the species. Araucaria forests continue to change under the influence of human use. Selective logging and seed (piñones) collecting are now strongly affecting araucaria ecosystems and genetic processes, and this is especially true in the fragmented eastern populations of the species that now regenerate mostly by vegetative means. Therefore, when studying pehuén genetics and forest dynamics, the addition of the human element and its various socioeconomic contexts is essential, even though it increases the investigative and analytical challenge.

The complexity of such human-modified systems is not easily disentangled through linear thinking or strictly deterministic analytical tools. The dynamic interdependencies among the many parameters and variables to be considered when modelling such systems mean that a holistic approach needs to be used (Haraldsson 2000). Systems thinking and one of its components, system dynamics, enhances our ability to understand dynamic inter-relationships (Richmond 1993), and these are therefore appropriate tools for conceptualizing and analyzing entities like forests that we hope to conserve while still exploiting their resources (= 'conservation through use' systems).

Through a model that applies systems research approaches, we try to describe the pehuén or araucaria forests of Argentina, that are dominated by *Araucaria araucana* and inhabited by indigenous Mapuche Indians. The most important elements integrated into our model are:

- The extent of the forest ecosystem to be modelled and changes to it that result from human actions (= boundaries of the system)
- Seed productivity in different forests
- Seed consumption by domesticated and wild animals
- Seed collecting by Mapuche
- Forest genetic diversity
- Condition of pasturelands (productivity and carrying capacity)
- Amount and distribution of wealth within Mapuche communities, and
- Per capita Mapuche income from off-farm sources.

Throughout this chapter we call our modelled araucaria forest the Pehuén Model. We created it with two objectives in mind:

- to represent the structure and dynamics of araucaria forests through a descriptive, conceptual model that identifies links and feedbacks among genetic, ecological and socioeconomic processes and variables, and
- to predict the future behaviour of the system by factoring into the model both current management practices and more sustainable alternatives, thereby allowing us to evaluate the outcomes of different management regimes over time.

2.1 Materials and methods

The key species in the forest ecosystem we have modelled is *Araucaria araucana*. This large tree is native to Argentina and Chile, growing mostly at heights of between 900 and 1800 metres above sea level (m asl), with sporadic occurrences at altitudes as low as 600 m asl (Armesto *et al*. 1997). Araucaria grows mostly on soils derived from recent volcanic ash deposits, though it can also be found on deeper soils derived from metamorphic and sedimentary rocks (Armesto *et al*. 1997). The natural distribution of araucaria covers a rainfall gradient ranging from 900 to 2500 mm of rainfall per year in Argentina, with some Chilean sites receiving up to 4000 mm per year.

Araucaria araucana mixes with other tree species along rainfall and latitudinal gradients, but it is most commonly associated with *Nothofagus* spp. and *Austrocedrus chilensis*. The three most common forest associations are:

- *Araucaria araucana* and *Nothofagus pumilio* (called 'lenga' in the Mapuche language). This association generally occurs in the western, wetter part of the araucaria range at higher elevations (1100–1800 m asl) on south-facing slopes. This forest type has been commercially exploited
- *Araucaria araucana* and *Nothofagus antarctica* in shrub form (called 'ñire' in the Mapuche language). This association is found in east–west running valleys and near the upper forest limit. The araucaria canopy emerges from a prostrate and shrubby layer of ñire. Currently this forest type is an important source of fuelwood for Mapuche communities and is affected by grazing and by natural and/or man-made fires
- *Araucaria araucana* in pure stands is found near the upper forest limit on poorer soils, and also at lower altitudes interspersed in a steppe environment. Forest fragments on the steppe occur in isolated woodlots that are heavily disturbed by human activities (such as seed collecting, livestock grazing, etc).

2.2 Model design

The Pehuén Model was designed to answer a specific question: is it possible to simultaneously increase the regeneration capacity of the forest while also improving the livelihoods of the local people that depend upon it?

Model design followed four steps, as outlined by Randers (1980): *conceptualization, formulation, testing and implementation*. During step 1, conceptualization, the purpose of the model is defined and its boundaries and key variables are identified. The behaviour of a modelled system is dependent upon its structure and the elements included. Thus establishing the system's boundaries precedes the identification of key variables and processes that are also included in the model (Haraldsson 2000). The model should include all the elements that interact to make it dynamic (Cover 1996). If the causes of a system phenomenon or process lie outside the system as it is currently described in the model, then it is necessary to expand the original boundaries to encompass it. It is also necessary to describe comprehensible units of the key variables, and to define the causal relationships within the system that are represented through feedback loops.

In step 2, formulation, the diagrams that visually describe feedbacks are drawn and converted into level and rate equations. In step 3, testing, parameter values are estimated and the model is tested using simulations based on the system's present conditions, but projected over a defined future period of time. Finally, in step 4, the model is implemented to simulate system responses to management alternatives.

Feedbacks within the system are described using causal loop diagrams (CLDs). Each component of a system acts as a cause or an effect in related processes (Haraldsson 2000). CLDs are maps that represent this behaviour, and illustrate the relationships between and among components of a system. A feedback represents a cascading process where an initial event ripples through a causation chain ultimately to affect itself (Martin 1997). There are two kinds of feedbacks: positive and negative. A positive feedback occurs when compounding, reinforcing or amplifying processes produce an exponential behaviour. A negative feedback drives balanced or stabilized systems to produce either asymptotic or oscillatory behaviour (Haraldsson 2000). Figure 1 presents an example of a causal loop diagram with positive and negative feedbacks.

System levels, flows and rates are determined so that computer simulations can be run. Levels are quantities that accumulate over time, flows are movements in and out of levels, and rates control the change in levels per unit of time. For example livestock population is a level, and recruitment and mortality of livestock are flows regulated by rates that modify the number of livestock in the system. The feedback mechanisms for the Pehuén Model, as exemplified in Figure 1, were imported into the STELLA (Structural Thinking, Experiential Learning Laboratory with Animation; Richmond 1994) modelling environment in order to run a computer simulation. In STELLA, levels and changes in levels are expressed through stock (rectangular boxes) and flow (arrows) symbols (Figure 2). A rate of change might be thought of as a faucet that controls the flow of water into a bathtub (Roberts 2001).

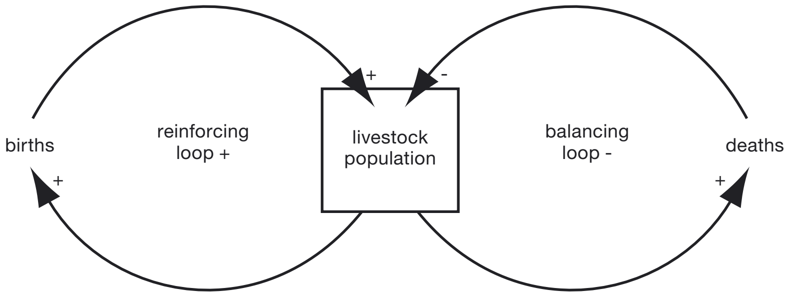


Figure 1. Example of a causal loop diagram (CLD) showing the positive (births) and negative (deaths) feedbacks to a livestock population.

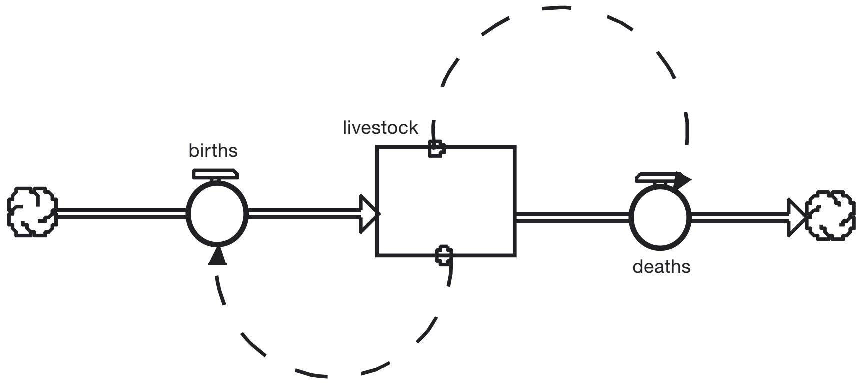


Figure 2. Relationships from the Figure 1 CLD displayed in STELLA stock and flow notations. Solid arrows (recruitment and mortality at their respective rates) flow in and out of the rectangular box, which represents the size of the livestock population. Dotted arrows indicate feedbacks from livestock population on flows.

2.3 Conceptualization of the model

The first step in designing a model is *conceptualization* (Albin 1997). It includes the following steps: a) definition of the objectives of the model and its boundaries, b) identification of key variables, c) description of the behaviour of the variables, and d) description of the principal mechanisms or feedback loops of the system. The purpose of the Pehuén Model was to identify and analyze the relationships among the different elements, processes and players interacting within the araucaria forest ecosystem and, more specifically, to incorporate the impact of the indigenous communities on the forest and especially on the FGRs. Therefore, key ecological and socioeconomic variables were included in the system to help deepen our understanding of current araucaria FGR dynamics and to predict the evolution of the forest under future conditions.

Boundaries

The boundaries of the system corresponded to the boundaries of the Mapuche community of Chiuquilihuin (for more details on this study site, see Chapter 6). The area inhabited by the Chiuquilihuin Mapuche was identified as the most suitable for the study because its socioeconomic, ecological and forest genetic dynamics were representative of those found in other Mapuche communities. The size of the community territory is approximately 5000 hectares, located in the southern Andes in the Province of Neuquén in Argentina: between approximately 39º35’30”S and 39º39’30”S and 71º13’30”W and 71º0’0”W. To the north and west it borders Lanín National Park, and to the south and east it borders other Mapuche communities and private ranches. The landscape is hilly and mountainous, ranging from 750 m asl to 2000 m asl. Precipitation decreases from 1800 mm to 1200 mm per year along a west–east gradient. *Nothofagus* spp. and *Araucaria araucana* are commonly found in association at higher elevations, and in the more humid western areas they form dense forests. In the eastern part of the modelled area several fragmented but pure stands of *A. araucana* are found scattered in a steppe environment (800–1000 m asl) that is degraded by overgrazing (Figure 3). Little or no sexual regeneration was found within the araucaria woodlots in the steppe.

Subsystems

Three subsystems were identified as principally influencing the araucaria system within Chiuquilihuin territory: 1) community livelihood, 2) seed availability for sexual regeneration of the forest, and 3) livestock. The seed availability subsystem was divided into two

Figure 3. An isolated individual of *Araucaria araucana* in the steppe near the community of Chiuquilihuin (photo: A. Jarvis).

components as detailed data existed to describe them separately (see Chapter 6): seed production, which is based on the reproductive capacity of the mature trees; and seed consumption, which includes seed predation by animals, and human collecting of seeds for a variety of purposes. The CLD diagram in Figure 4 describes the main variables and feedback mechanisms identified.

We characterized the genetics of the forest stands used for the modelling exercise and studied their gene flow. Gene flow appeared to move from the west towards the eastern fragments in the study area, with genetic information arriving via pollen from the continuous western forest stands of *A. araucana* and *Nothofagus* spp. However, there were indications that differentiation through genetic erosion would begin in the not-too-distant future in the eastern araucaria stands, which are pure but fragmented old-growth trees that are now degraded by overgrazing. This will most likely result from a lack of natural sexual regeneration, and will dampen the relatively high genetic diversity still found in the seed pools of these fragments. The likely effects of low or no sexual regeneration, restricted seed dispersal by rodents owing to the disturbance caused by continued fuelwood exploitation, and the eventual removal of some mature individuals, are described in the Figure 4 CLD in relation to the genetic processes of (assumed) endogamy and migration.

Research results generated for the seed availability subsystem allowed us to produce CLDs of seed production in relation to precipitation for the various araucaria forest stands included in the study. We found precipitation to be the principal factor controlling seed production in all the forest ecosystems investigated (see the simulation of seed production patterns over 50 years in Figure 9). In fact, the number of seeds produced in any given year was determined by the annual average precipitation that occurred two years before. This could be related to the effect of precipitation during the pollination time (Sanguinetti *et al.* 2001).

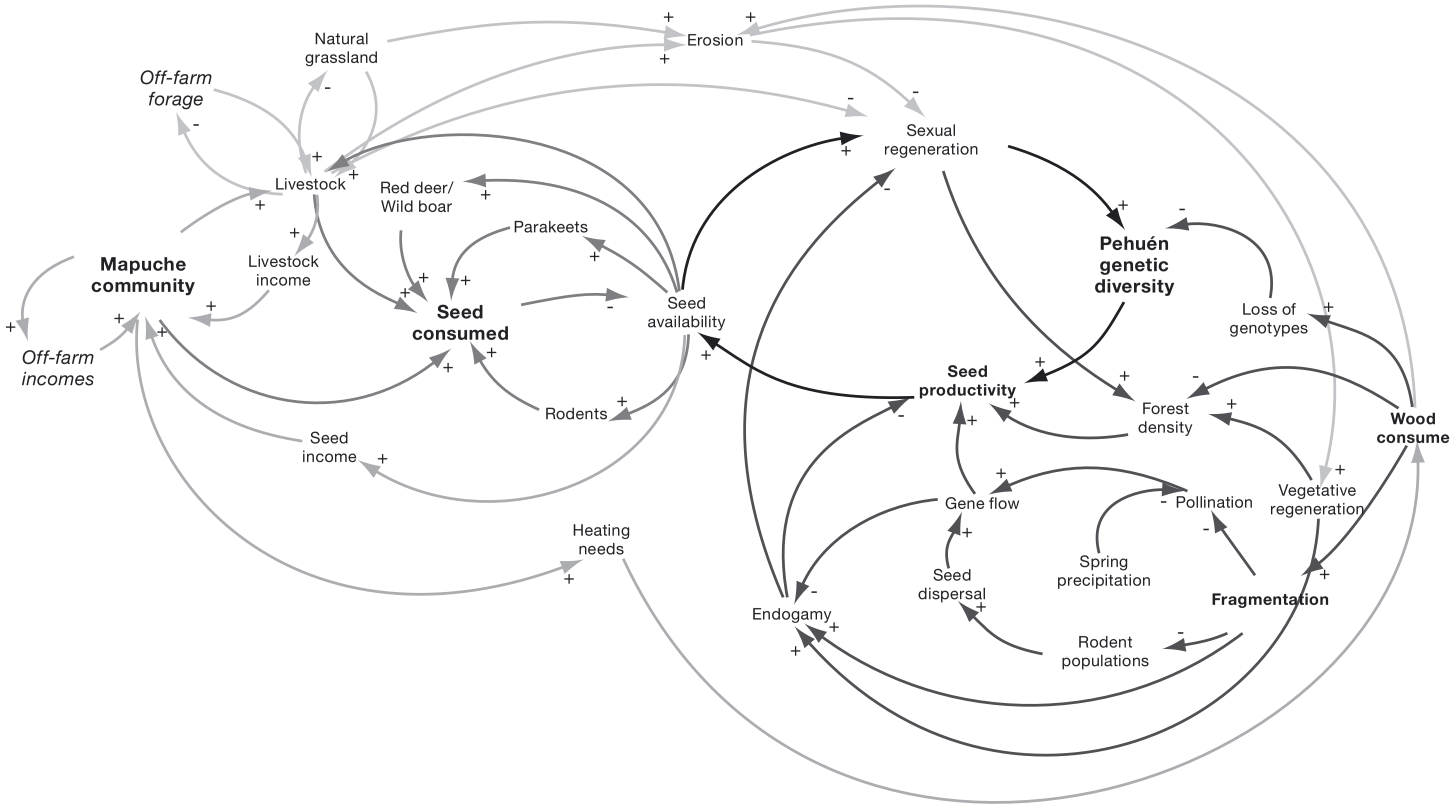


Figure 4. Causal loop diagram (CLD) showing the variables identified for each of the three principal subsystems.

In researching the seed consumption component of the seed availability subsystem, we found that seeds were being removed from the system by domesticated animals such as sheep, goats, cows and horses, by wild exotic animals like red deer and wild boar, by native rodents and parakeets, and by the collecting activities of the Chiuquilihuin Indians. Some seed predators were also involved in gene migration as they contribute to the dispersal of seeds, and this is also reflected in our model. Because araucaria seeds were used as livestock feed by the Chiuquilihuin community, livestock management decisions also affected seed availability and we attempted to incorporate these into the seed availability subsystem of our model.

The mechanisms by which the variables of the three main model subsystems affect genetic diversity were identified through existing theoretical and experimental population genetic knowledge adapted to the characteristics of the pehuén system. For example, we assumed that araucaria forest fragmentation would have an indirect influence on genetic diversity by affecting gene migration. In the eastern araucaria forest, fragmentation increases the distance pollen must travel and/or decreases the available habitat for dispersers. At least at the time of our research, the genetic diversity of the fragmented araucaria populations was still comparable to that found in the denser forest stands to the west, with no evidence of increased endogamy and/or fixation or loss of alleles. Very likely, this was due to the sustained gene flow that was occurring along the west–east araucaria forest axis.

Soil erosion is another important system variable that has serious ecological, genetic and socioeconomic repercussions. Habitat loss resulting from soil erosion was occurring with varying degrees of intensity within the study area, and this was factored into our model. The most dramatic erosion occurs in the fragmented and isolated eastern araucaria stands that were surrounded by grasslands. The model reflects our conclusion that erosion affected regeneration, and particularly induced vegetative regeneration. We flagged this as a subject for future ecological research.

The community livelihood (or socioeconomic) subsystem was represented in our model with the following process components: livestock management, seed consumption, wood harvesting, income derived from seed, income from livestock, and income from off-farm activities. These components were analyzed and their variables quantified. In order to assess the sustainability of current livestock management practices, analyses of the carrying capacity of the different grasslands scattered around the araucaria forests, and of their role in the pehuén system, were undertaken in collaboration with pastureland experts using geographic information system (GIS) tools from the Instituto Nacional de Tecnología Agropecuaria (INTA) in Bariloche, Argentina.

2.4 Indicators of sustainability

The amount of seed available for natural sexual regeneration of araucaria trees was identified as the key variable in the long-term stability of the pehuén system since it was strongly correlated with the maintenance of genetic diversity and, consequently, with the long-term evolutionary potential of araucaria forests. Minimum production of 18 000 seeds per hectare was determined to be the threshold for genetic sustainability. This value was obtained by combining estimates of the average germination capacity (70%) of seeds produced by several *A. araucana* populations in the study area, along with observation of the natural regeneration density of stands not affected by human seed collecting or by seed consumption by livestock or wild exotic animals. Under ideal conditions, a 70% annual araucaria seed germination rate would provide 12 600 seedlings/ha, and this amount would be expected to secure araucaria regeneration with enough natural seedling selection and therefore genetic sustainability in araucaria forest evolutionary processes.

The indicator of the sustainability of araucaria ecosystems was identified to be the forage productivity of wet meadows, one of several pastureland types found in the study area (see Table 6, Chapter 6). Wet meadows are the most productive (see Section 3 below), and are also the most resilient of the pastureland types to grazing pressure. Wet meadows were determined to be seriously degraded, and their carrying capacity consequently reduced, when forage productivity in relation to maximum productivity declined by 20% or more. This value represents the threshold for ecological sustainability.

Annual average per capita income of US$ 500 (equivalent to 1500 Argentinean pesos/year) was identified as the principal indicator for sustainability of the socioeconomic subsystem. Any downwards change in average income is considered unsustainable.

3. Structure of the STELLA model

The three subsystems identified above were adapted into the STELLA modelling environment to allow a prediction of future conditions through simulation (Figure 5). Forage availability for livestock was modelled separately as data were available to represent the dynamics of pasturelands. The subsystems modelled are described below.

Livestock

This subsystem simulates the behaviour of livestock (sheep, goats, cows and horses; see Figure 6) in the Pehuén Model. With regard to this subsystem, the modelling exercise could be refined by better describing pastureland degradation and regeneration processes, but this is a first attempt to describe livestock dynamics, and further research should be undertaken to gather more detailed data. In order to standardize representation of grazing densities and the food requirements of these animals, a conversion into Sheep Livestock Units (SLUs) was adopted (one SLU is a standard measure used to homogenize livestock numbers per surface area) in order to make comparisons possible. One SLU is equivalent to 1 sheep weighing 40 kg consuming 365 kg of dry forage per year (Siffredi *et al.* 2002). The conversion used was 1 sheep or goat = 1 SLU, 1 cow = 7.5 sheep or goats (or 7.5 SLUs), and 1 horse = 10 sheep or goats (10 SLUs).

The number of SLUs grazing in the study area was made dependent on annual variation in birth and mortality rates, and on the number of SLUs slaughtered annually. Livestock mortality was described in the model as partly controlled by the carrying capacity of the system, which corresponds to the ratio between the amount of food available on average every year and the amount of food consumed by one SLU. The amount of food available is calculated by converting the annual total production of all pasturelands into annual availability of dry forage, combined with pehuén seed availability. This latter value is calculated as the ratio between seed production any given year and the amount of seed removed from the system by predators for consumption other than as livestock feed. Based on their nutritional values, Sanguinetti *et al*. (2001) converted araucaria seeds into equivalent dry forage units at a rate of 1 kg of seeds equalling 2.5 kg of dry forage.

The size of herds found in the pehuén system at any point in time depends on such variables as livestock management practices, the amount of meat consumed locally, trading opportunities for meat, the proportion of reproductive females in relation to the herds, and the amount of livestock food available; this last variable being the limiting factor. We observed that livestock in the pehuén system consumed per year on average 82% dry forage (from pasturelands) and 18% araucaria seeds (from araucaria forests). When dry forage was limited, the quantities of seed consumed increased, and this had negative effects on natural regeneration of araucaria forest stands and ultimately on the genetic diversity of those forests. This relationship demonstrates how araucaria genetic diversity is indirectly dependent upon livestock management practices of the Mapuche community.

Forage availability

We determined the forage productivity in the five pastureland types and the number of seeds that could be sustainably harvested from araucaria forests (see Chapter 6). This enabled us to establish livestock carrying capacity for the pehuén system, and to set a livestock density threshold above which overgrazing would occur. We also calculated a new variable that we called ‘enhanced carrying capacity’ that included livestock foods from sources external to the pehuén system, namely forage from summer fields in neighbouring areas outside our model boundaries, and hay supplied periodically.

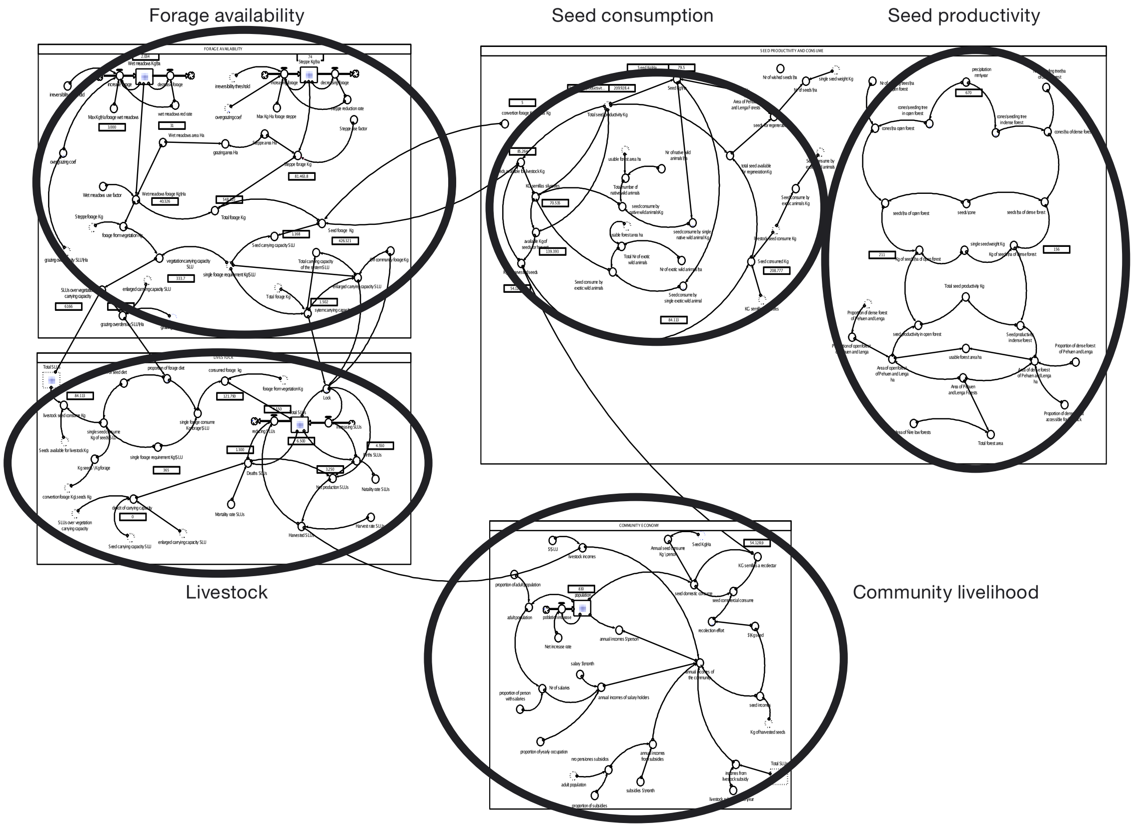


Figure 5. Overview of the STELLA stock and flow representation of the Pehuén Model, indicating the complexity of the system.

Figure 6. Mapuche people managing their livestock (photo: G. Siffredi).

Figure 7. The Patagonian steppe ecoregion with its typical xerophytic vegetation, highly adapted to resist drought, wind and herbivores (photo: B. Vinceti).

The most productive pasturelands for forage are wet meadows. These are areas where water covers the soil, or is present either at or near the surface of the soil all year round, or for variable periods of time during the year. Maximum forage production was determined to range from 3000–5000 kg/ha of dry forage for wet meadows, to 20–50 kg/ha of dry forage for the driest steppe pastureland type grazed in the pehuén system (Figure 7). A yearly proportion of production consumed by livestock (= use factor) was determined for these two pastureland extremes to be 65% and 40% respectively (see Annex 1; Siffredi *et al*. 2002).

The number of domesticated animals (= carrying capacity) that could be supported by the pehuén system was defined as the number of SLUs that could be fed sustainably by the combined supply of forage from the five pastureland types and from araucaria seeds. In our model, the availability of forage is linked to carrying capacity by a feedback mechanism. When overgrazing occurs, forage availability (pastureland forage and forest seed forage) declines along with carrying capacity. The equations that describe the relationship between the degree of overgrazing and the decline in forage productivity were formulated with the advice of experts from INTA.

Mapuche livelihood

Annual per capita income in Chiuquilihuin was chosen as the variable to be monitored to assess socioeconomic sustainability of the pehuén system. The size of the Chiuquilihuin community (306 people) and its net growth rate of 2% (including births, deaths, emigration and immigration; Pinna 2002) were used to initialize STELLA simulations (Annex 1).

Four sources of income were included in the model: livestock sales, araucaria seed sales, government subsidies and salaries. Subsidies and salaries were defined as off-farm sources. Annual per capita income from livestock was determined by calculating the volume of livestock sold by community members in a year (at current prices of 70 pesos or US$ 25/SLU) divided by the number of community members. Annual per capita income from seeds was determined by calculating the amount of araucaria seed sold at 1.5 pesos or US$ 0.50/kg divided by the number of community members. The amount of seed collected any given year was set as a function both of seed availability and of motivation to collect, this latter variable assumed to be related to traditional domestic consumption rates and fluctuations in market prices. The amount of seed sold was calculated as a variable fraction of total seeds collected by the local community.

Off-farm income from subsidies was set as a function of the proportion of adult community members entitled to receive government subsidies: 30% of the population are adults, 75% of whom receive subsidies (Pinna 2002). Income from salaries was set as a function of the number of adults with temporary jobs (25% of adult community members, working for 7.2 months/year on average) and of the average monthly salary of 350 pesos or US$ 120 (Pinna 2002). We determined average annual per capita income to be roughly US$ 500, around 1500 Argentinean pesos/year.

Seed production and consumption

A subsystem was designed to describe fluctuations in the number of seeds available for araucaria regeneration. This value was defined as the difference between the average annual number of seeds produced by the araucaria forest stands and the average annual amount of seeds consumed, which varied in relation to animal predation (Figure 8) and quantities collected by the Chiuquilihuin Mapuche.

The average annual number of seeds produced was determined by the number of mature trees/ha and the annual precipitation in the preceding two years, reflecting the time it takes for the seeds to reach maturity. Rainfall amounts measured during four years of field research were used to extrapolate precipitation trends over a longer period. The number of cones/tree was inversely correlated with annual rainfall because, we believe, that high precipitation has a negative effect on pollination (Sanguinetti *et al*. 2002). Estimates of the number of seed trees/ha varied in our model in accordance with open versus dense pehuén forest settings. We also assumed that the negative effects of heavy rainfall on pollination would not be felt so much in open and drier forests as in denser, wetter forests

Figure 8. Pre-dispersal seed predation of *Araucaria araucana* seeds by birds (photo: B. Vinceti).

(our model used 17 trees/ha to represent open, dry sites and 55 trees/ha denser, wet sites; Sanguinetti *et al.* 2002).

The proportion of modelled forest area exposed to the actions of livestock, which include seed consumption, grazing and trampling of seedlings and resulting erosion, was estimated to be 30% of the total forest area, derived from field observations. Different seed consumption rates were also attributed to consumers such as red deer and wild boar ('wild exotic animals') found within Chiuquilihuin territory, and to native wild animals (rodents and parakeets). Seed consumers were assigned different behavioural and timing values. For instance, wild animals were assumed to be the first to feed on available seeds, and then humans gathering seeds for food would further reduce seed availability, and finally livestock would consume the amount left, either by direct grazing or consuming seed fed to them by the Mapuche.

The amount of seed consumed by wild animals (both native and exotic) depended on their population sizes, on individual animal consumption rates, and on whether this was an area of forest where livestock grazing also occurred. The amount of seed collected by local people or consumed by livestock and wild animals was also dependent on fluctuations in seed production.

Densities of wild animals were determined to be 50/ha for natives and 2/ha for exotics (Sanguinetti *et al*. 2001). Seed consumption rates by humans are described in the 'community livelihood' subsystem that focused on economic activities.

4. Pehuén Model behaviour under current conditions

4.1 Initial settings

Initialization values were attributed to 27 parameters incorporated into the Pehuén Model (Annex 1). Parameters are also defined as 'variable constants' or coefficients, that is they are quantities that are known, and which the modeller may wish to change, but which must be given a value to start a modelling simulation. The equations that define the relationships between the 120+ variables (Figure 5) were formulated. The behaviour of the Pehuén Model was then tested under current management conditions. Simulations were run over a 50-year period, which seemed a reasonable time for long-term forest management planning. This period also corresponded to the estimated time required for araucaria trees to reach reproductive maturity.

4.2 Results

The simulations revealed that current natural resource management practices in the pehuén system were not sustainable, whether viewed from genetic, ecological or socioeconomic points of view.

Annual system carrying capacity for livestock was found to vary strongly in relation to annual seed production, which in turn showed a significant negative correlation with the precipitation level two years prior to the year of simulation. Forage production from pasturelands within Chiuquilihuin territory was less important than seed availability in contributing to livestock food needs.

Under current management practices, the simulation predicted that in 50 years, wet meadow forage productivity would steadily decrease to 60% of its initial value, showing that present conditions are ecologically unsustainable.

Under current conditions the simulation also showed that approximately 19 000 seedlings/ha would be found in dense araucaria forests unaffected by humans, while in open forests subject to anthropogenic pressures and grazing, there would be only about 500 seedlings/ha. In Figure 9, the cyclical peaks in araucaria seed availability, what we called 'potential natural regeneration events', are simulated over the 50-year projection period. Peaks in seed production occur at intervals of 3–5 years, reflecting low annual precipitation values two years before, but it never reaches the minimum annual production of about 18 000 seeds needed to secure proper regeneration densities. We interpret this to

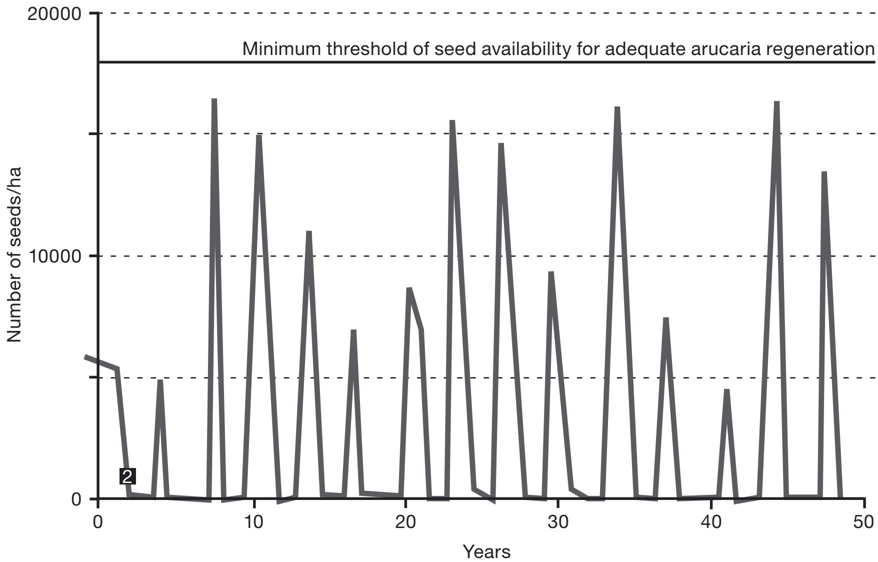


Figure 9. Number of seeds available for regeneration over the 50-year simulation. The upper horizontal line indicates the minimum threshold of seed availability sufficient to enable adequate regeneration events to occur. The simulated fluctuation in seed production is strong correlated with variation in annual precipitation two years earlier.

mean that seed will not be available to ensure adequate natural araucaria regeneration in the pehuén system over the next 50 years if management practices remain unchanged.

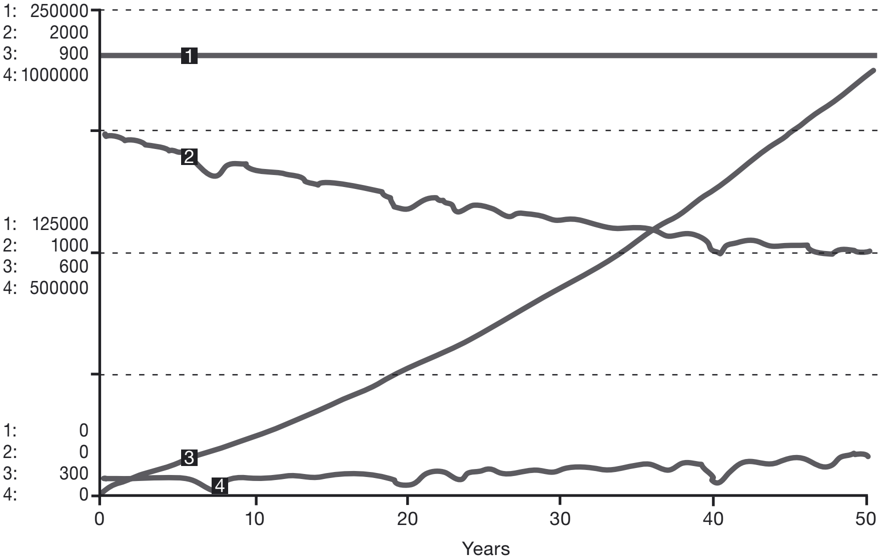
A final simulation was run to estimate variation in annual per capita income over the 50-year future period. During this time, according to the current population growth rate, the Chiuquilihuin community is expected to increase to three times its current size (Fig. 10). This growth should consequently increase araucaria seed consumption and, assuming a constant amount of SLUs in the community, reduce the annual per capita income by about 30% from US$ 500 to US$ 330 (Fig 11). Over the same period, degradation of pastureland from overgrazing would lead to a reduction in available forage (mostly due to a reduction of the wet meadows forage production; Fig 12), negatively affecting livelihoods by increasing livestock mortality and decreasing income from livestock.

Thus, without some sort of significant change, such as government interventions leading towards sustainable management and/or adoption of conservation principles, the living conditions of local communities will deteriorate and the environment will become heavily degraded, with very serious loss of araucaria genetic diversity.

5. Sensitivity analysis

A sensitivity analysis was carried out to test how responsive the model was to changes in values of certain parameters. Sensitivity analyses help to identify variables that disproportionately affect the behaviour of systems and, for modelling purposes, the values of these variables should not be estimated but rather derived whenever possible from empirical observations (Breierova and Choudhari 1996). Nevertheless, in the present

Figure 10. Mapuche children (photo: A. Pinna)



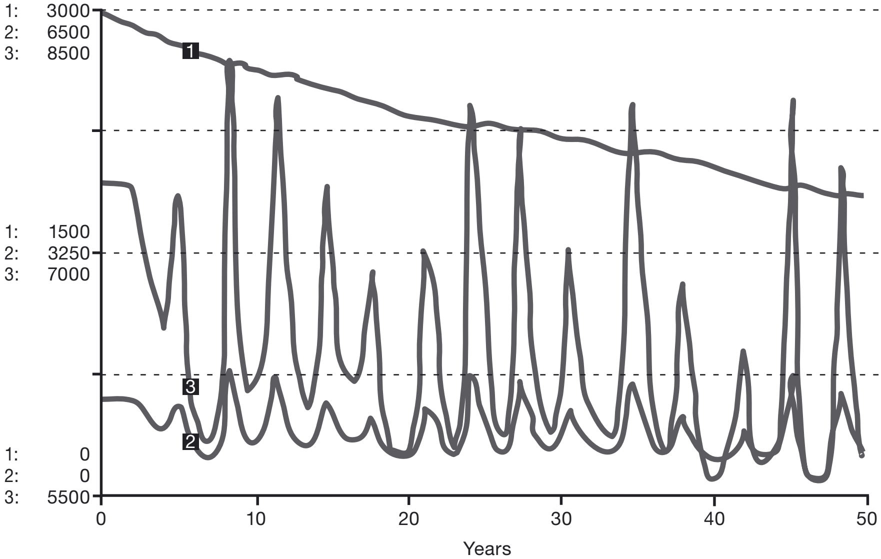
1. Annual income from livestock (US$)
2. Annual income per person (US$)
3. Increase in population (total number of inhabitants in the Chiuquilihuin community)
4. Annual income from sale of araucaria seeds (US)

Figure 11. Simulation of population increase over 50 years, based on the current population growth rate, and the consequent behaviour of annual per capita income. The number of sheep livestock units (SLUs) does not increase as it is constrained by forage availability (the maximum number of SLUs supported by the system has already been reached), therefore income associated with livestock will not increase over time either. Income from araucaria seed rises slightly owing to increased seed harvesting. Overall, annual per capita income (combining all sources) declines over the period of simulation.

dynamic model, some variables were difficult to measure in the field and some relationships were difficult to predict, for instance, responses in araucaria seed collecting in relation to changes in seed price. Hence, the value of some parameters and some conversion coefficients were based on best estimates.

The sensitivity of the three primary indicators of genetic, ecological and socioeconomic sustainability (seeds available for regeneration, forage productivity of wet meadows, and annual per capita income) was tested. Analyses were also carried out to assess the sensitivity of the model to variations in forage productivity on the steppe, the fraction of dense forest accessible to livestock, the conversion coefficient of seeds into forage units, the total number of SLUs introduced into the modelled system, the birth and death rates of livestock, the proportion of dry forage in the livestock diet, the human population growth rate, the proportion of adults to total population, the percentage of adults that receive subsidies and salaries from government, and the amount of those salaries.

The default values for 15 of the parameters (shown in Annex 1) used for the simulation of Chiuquilihuin community dynamics were modified by ±20% to test the repercussions of these changes on the system, considering that a ±20% variation in the values was a realistic possibility that could occur for many reasons. The sensitivity analysis was undertaken without considering forage inputs from sources outside the system. Using the new values, for the 50 year projected future period, we recalculated the three primary indicators of genetic, ecological and socioeconomic sustainability and compared the quantities obtained



1. Annual forage production from wet meadows (kg/ha)
2. Annual contribution of seed to feed livestock (SLUs/ha)
3. Total number of SLUs supported by overall food availability within the system (forage and seeds)

Figure 12. Simulation of the progressive decline in forage availability from wet meadows owing to protracting overgrazing (i.e., maintaining current exploitation rates of pasturelands) over the 50-year simulation period. Wet meadows represent a very small fraction of the overall pastureland used by the Chiuquilihuin community, but they are extremely productive and contribute to most of the forage availability (their forage productivity is 30 times higher than that of the steppe). The total number of sheep livestock units (SLUs) supported by the food available within the modelled system fluctuates in strong correlation with the pulses of seed production.

to the corresponding results of the original simulations. The repercussions of these changes on the three selected indicators of sustainability were monitored, and changes of more than 5% from the original value were considered significant. Results are presented in Table 1.

The analysis provided both predictable and unpredictable results. For example, the genetic sustainability (seed available for regeneration) of the pehuén system was strongly correlated with seed production and consumption, as highlighted previously in the model diagram (Figure 4).

5.1 Discussion

If livestock grazing could, in part, be shifted to denser araucaria forests further from the Chiuquilihuin villages, the amount of seed available for regeneration in the forests near the villages would increase because grazing would be distributed more equitably throughout the pehuén system. Even though this change would result in a more extensive grazing regime, the fact that the new forests now being exploited have higher seed productivity and are further from the villages means that the forests closer to the villages would be subjected to lower grazing pressure, reduced seed consumption, and thus exhibit more regeneration.

However, the same response could result from any variation in the system that would reduce seed consumption, such as an increase in the proportion of grass in the livestock

Table 1. Results of the sensitivity analysis of 15 variables in the Pehuén Model. The initial values of the variables were changed by ±20%, producing changes in values of the three indicators of sustainability. The initial values of the principal Pehuén Model variables are presented in Annex I.

Variables modified to test the sensitivity of the three indicators of sustainability	Change in default values	Change in values of the three indicators of sustainability, expressed as percentages of the default values		
		Genetic Seed in (kg) available for regeneration	**Ecological** Productivity of wet meadows	**Socio-economic** Annual income per capita
Forage productivity of steppe	-20%	-0.4%	0.0%	0.2%
	+20%	0.3%	0.0%	-0.1%
Dense forest accessible to livestock	-20%	**-84.1%**	0.3%	-2.2%
	+20%	**196.7%**	2.7%	1.7%
Fraction of forage in livestock diet	-20%	**-27.2%**	0.0%	0.0%
	+20%	**+38.9%**	0.0%	0.0%
Total number of SLUs	-20%	**24.0%**	4.5%	0.4%
	+20%	**-7.3%**	**-7.3%**	-0.04%
Human population net increase rate	-20%	**+10.2%**	0.0%	0.5%
	+20%	**-10.7%**	0.0%	-0.5%
Livestock mortality rate	-20%	**-9.2%**	-0.6%	0.2%
	+20%	**9.2%**	0.3%	-0.2%
Conversion factor (seed to forage)	-20%	**-9.3%**	-0.3%	-0.1%
	+20%	**+8.5%**	0.0%	0.1%
Pehuén seed price	-20%	4.7%	0.0%	-1.0%
	+20%	**-8.8%**	0.0%	1.2%
Seed collection effort	-20%	**5.5%**	0.0%	-0.2%
	+20%	**-5.4%**	0.0%	0.2%
Monthly salary (pesos)	-20%	0.0%	0.0%	**-5.6%**
	+20%	0.0%	0.0%	**+5.6%**
Fraction of people with salaries	-20%	0.0%	0.0%	**-5.6%**
	+20%	0.0%	0.0%	**+5.6%**
Fraction of adults in local population	-20%	0.0%	0.0%	**-18.4%**
	+20%	0.0%	0.0%	**+18.4%**
Fraction of adult population receiving subsidies	-20%	0.0%	0.0%	**-12.8%**
	+20%	0.0%	0.0%	**+12.8%**
Livestock birth rate	-20%	0.0%	0.0%	-0.8%
	+20%	0.0%	0.0%	0.8%
SLU price	+20%	0.0%	0.0%	-0.6%
	+20%	0.0%	0.0%	0.6%

diet or an increase in the nutritional efficiency of seeds, or both. In contrast, a rise in seed collecting efforts driven, for example, by an increase in seed prices or an increase in the number of SLUs in the system, would have a strong negative effect on the availability of seed for natural regeneration (genetic sustainability indicator).

Interestingly, the sensitivity analysis showed that the system would be unaffected by an increase in the price of livestock. This might be explained, in part at least, by management constraints. The majority of the families in Chiuquilihuin own on average about 40 SLUs, and this number seems to represent an upper limit of animals that average families can manage for their own needs under their specific land ownership situations.

Finally, increasing the number of animals in the community negatively affected natural araucaria regeneration by reducing seed availability. It also led to a depression in forage productivity in wet meadows owing to overgrazing. In contrast, if just 20% of the current 6500 SLUs were removed, substantial benefits would be achieved in genetic sustainability.

6. Alternative management scenarios for the pehuén system

Based on the results of the sensitivity analysis and on the knowledge we obtained through our field research, we simulated several hypothetical management alternatives and monitored their outcomes over a 50-year period in terms of genetic, ecological, and socioeconomic sustainability. The evaluated alternatives were:

1a. Adjust livestock numbers to pastureland carrying capacity, or increase forage inputs
1b. Reduce grazing pressure (total SLUs)
2. Increase araucaria seed prices
3. Increase off-farm incomes

1a – Adjust livestock numbers to pastureland carrying capacity, or increase forage inputs.

The ability of pasturelands to recover from grazing pressure was assessed by simulating regulatory regimes that maintained livestock numbers within the limits of pastureland carrying capacity. We began the simulation by using current rates of use and current conditions of pastureland degradation, but with no additional sources of off-farm forage. We found that over a simulated period of 8 years, the pastureland productivity declined to a point where the number of SLUs that could be sustained dropped from 6500 to approximately 940. This reduction in SLUs progressively relieved pastureland grazing pressure and, when maintained at this level, a slow but steady recovery in forage productivity occurred after another 8 years, especially in the wet meadows – our ecological sustainability indicator. Under these conditions, maximum pastureland productivity was restored near the end of the 50-year simulation period. The positive repercussions of reduced grazing pressure at this rate and magnitude could also be seen in more frequent regeneration pulses, because seed availability for natural regeneration now more often passed the minimum threshold for sustainability. While this scenario seems to achieve genetic and ecological sustainability in the pehuén system, it is economically unrealistic over the simulation period, both because of current population growth and because income reductions from lower livestock numbers would presumably be unacceptable to the Chiuquilihuin community.

Nevertheless, other options exist that could maintain the current number of SLUs without causing lowered pastureland productivity, such as: (a) extending grazing areas to additional pasturelands located outside the community land that are not currently being used, (b) increasing hay supplied by the provincial government during difficult times, (c) implementing more intensive pastureland management practices, particularly in the wet meadows, by employing fences to regulate grazing, or d) by trying to restructure use of the wet meadows that are owned by a few families, by somehow making them more accessible to other community members (Siffredi *et al*. 2002). For example, with all other variables remaining unchanged, the simulations showed that by doubling off-farm forage inputs to 3 million kg of dry forage per year, the productivity of wet meadows recovered over a span of 12 years. However, this scenario did not result in natural araucaria regeneration nor increases in per capita income over time. Moreover, some of the management alternatives simulated have practical limitations in that they conflict with traditional practices, which is the case with using fences, as well as with current property ownership patterns. We concluded that improvements in pastureland management should not be considered in isolation but rather in conjunction with other solutions.

1b. Reduce grazing pressure (total SLUs).

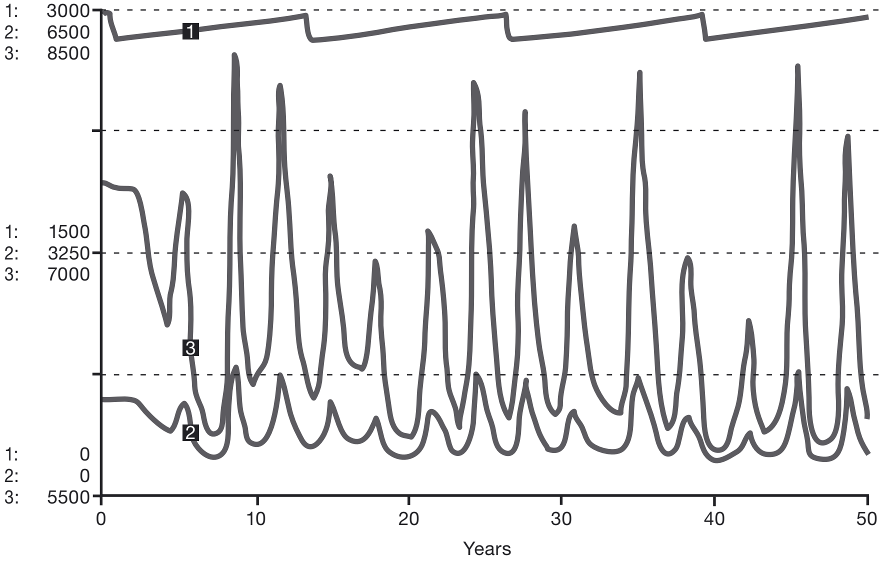
The Mapuche of northern Patagonia have practised livestock transhumance for more than 400 years, adapting themselves to a pastoral way of life (Lanari *et al*. 2003). During the BMZ-funded project, we found livestock to be unequally distributed among Mapuche families (Pinna 2002), but most families owned on average about 40 SLUs. We called this value 'cultural stock' because it corresponded to the optimal number of animals most families chose to raise. Only two farmers owned more than 200 animals, while nine farmers owned between 51 and 150 animals (Pinna 2002). In the scenario simulated, the average cultural stock figure was multiplied by the number of families in Chiuquilihuin, thereby reducing the total community livestock holdings to 2520 SLUs, which represented about one-third of the 6500 SLUs now held by the community. This calculation reflects a hypothetical condition in which all farmers own an equal number of animals. When the number of SLUs is so reduced, grazing pressure diminishes and this triggers a fast recovery of wet meadow productivity. At the same time the frequency of araucaria regeneration events (seeds available above the regeneration threshold) increased. However, reducing the number of SLUs induced an immediate 30% decrease in annual per capita income and halved annual per capita income after 50 years. This alternative was thus not sustainable from a socioeconomic point of view.

2. Increase araucaria seed prices

The management options thus far proposed have shown that by changing pastureland management and reducing grazing pressure, ecological and genetic sustainability can be achieved. However socioeconomic sustainability could not be achieved because of income losses from fewer SLUs combined with projected population growth. Therefore, we simulated alternatives that increased income using other products and income sources. We ran a simulation that maintained SLUs at 2520 while doubling income from araucaria seeds and keeping off-farm incomes unchanged. The simulation showed that this change was initially sustainable in genetic, ecological and socioeconomic terms, but in the long run higher seed prices combined with local population growth led to rates of seed harvesting that rapidly depressed araucaria regeneration. After 10 years and thereafter, seed available for natural regeneration never reached the minimum threshold for genetic sustainability. Moreover, the temporary increase in income generated by higher seed prices did not balance the income losses from the reduction in SLUs. Therefore, an increase in seed prices was seen as unlikely to produce sustainable outcomes in the long run.

3. Increase off-farm incomes

A simulation was run with community livestock holdings again set at 2520 SLUs but now with average annual off-farm income increased from 350 pesos (US$ 120) to 500 pesos (US$ 160). And we assumed that each family would benefit from at least one salary all year round. Thus, our original 'fraction of inhabitants with salaries' per family (see Annex 1) grew from the original value of 0.25 to 0.68, and the 'period during the year with employment', expressed as a fraction of a year, increased from 0.6 to 1. These relatively small and reasonable changes generated an immediate increase of 30% in annual per capita income. Combined with genetic and ecological sustainability achieved through reduced grazing pressure (Figure 13), this socioeconomic change could secure long-term stability in the



1. Annual forage production from wet meadows (kg/ha)
2. Annual contribution of seed to livestock feed (SLUs/ha)
3. Total number of SLUs supported by overall food availability within the system (forage and seeds)

Figure 13. Simulation of forage productivity of wet meadows under one of the suggested alternative management scenarios for the pehuén system, which entails an increase in off-farm incomes. Forage productivity of wet meadows displays small fluctuations and does not decline dramatically over time as projected under current livestock management conditions. The total number of sheep livestock units (SLUs) supported by overall food availability within the system is tightly linked to the pulses of seed availability over time, but periodically reaches higher values than under current conditions (i.e., without an increase in off-farm incomes).

pehuén system. But because of projected population growth, off-farm incomes would need to rise over time in order to maintain the long-term socioeconomic, genetic and ecological benefits.

7. Conclusions

Linear thinking or strictly deterministic analytical tools do not permit us to understand the complexity of human-modified ecosystems like those found in the araucaria forests of northern Patagonia. For this study, a systems approach was very helpful in representing the dynamic interdependencies among the many parameters and variables that were needed to model the functioning of araucaria forests in the area investigated.

Our simulation revealed expected and unexpected dynamic behaviour, and it highlighted the need to undertake more detailed studies of links between genetic, ecological and socioeconomic aspects of the pehuén system. In future, we will particularly need to fill data gaps and to improve our understanding of several feedback mechanisms within the system. Nevertheless, using current data and trends to extrapolate conditions over the next 50 years, our simulation showed that the pehuén system would become less-and-less sustainable in forest genetic, ecologic and socioeconomic terms. Indeed, over our 50-year simulation period, using current natural resource use patterns, further degradation of pasturelands and less-and-less forest regeneration will occur. This projected future scenario, when coupled with the projected growth in the Mapuche population, causes us to be seriously concerned about the future prospects of the pehuén system.

The sensitivity analysis and the simulated management alternatives led to the identification of four variables as most important in moving the pehuén system towards sustainability:

- Number of SLUs
- Seed production in araucaria forests
- Rate of population growth in the Chiuquilihuin community
- Off-farm incomes.

The factor exerting most pressure on the sexual regeneration of araucaria forests, and therefore, indirectly, on araucaria forest genetic diversity, proved to be livestock grazing, and most of the scenarios we modelled showed that reducing the number of SLUs solved this problem. But while reduced grazing pressure lead to genetic and ecological sustainability, projected population growth and loss of income from fewer SLUs meant that there was no socioeconomic sustainability. Moreover, without some sort of significant compensation for income losses, reducing herd sizes would be unacceptable to the Chiuquilihuin community. Livestock is not only a key resource but is a traditional part of the Mapuche economy.

Thus, our simulations showed that annual per capita income must be maintained and progressively increased at the same time that genetic and ecological sustainability solutions are being implemented. The most likely way to achieve this is through increasing off-farm incomes in the system.

However, even if more efficient livestock management could be achieved and complemented with alternative economic opportunities without a reduction in the amount of SLUs it would not guarantee genetic, ecological and economic sustainability over the long run. Such a situation indicates that political decisions are needed to achieve the two interlinked objectives of improving Mapuche socioeconomic conditions while conserving the evolutionary potential of pehuén forests. Measures implemented should be applied within a framework that respects local Mapuche culture and community traditions. We recommend that the government provide salaries for environmental monitoring and protection, in compensation for the role historically and presently played by local families in conserving the araucaria ecosystems as well as compensating local communities for the loss of income that would result from the recommended reduction in the number of SLUs.

At least one member from each Chiuquilihuin family would be officially recruited to work on community-based environmental protection and restoration projects. This would also contribute to raising awareness of conservation issues. Such government investments in environmental protection and indigenous community development might draw resources from wealthy economic sectors such as tourism, petrol and gas extraction, fruit orchards or mining. Investments in technology and institutional development should also be planned for this region.

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Annex 1. Initial values of the Pehuén Model parameters

Table 2. Initialization values of the main parameters of the Pehuén Model.

Livestock management		
Number of SLUs	(1)	6 500
Livestock natality rate	(1)	0.70
Livestock mortality rate	(1)	0.20
Number of SLU slaughtered annually	(1)	1.00
Forage availability		
Maximum dry forage production of wet meadows (kg/ha)	(2)	3 000
Maximum dry forage production of steppe (kg/ha)	(2)	90
Area of wet meadows (ha)	(2)	30
Area of steppe pastures (ha)		2 750
Dry forage from sources outside the community (kg)		1 450 000
Use coefficient of wet meadows	(2)	0.65
Use coefficient of steppe pastures	(2)	0.40
Chiuquilihuin community data		
Number of inhabitants	(3)	306
Population growth rate	(3)	0.02
Fraction of adults in total population	(3)	0.30
Fraction of inhabitants with salaries, per family	(3)	0.25
Part of the year with employment (expressed as a decimal)		0.60
Monthly salary (pesos)		350
Fraction of adult inhabitants with subsidies	(3)	0.75
Monthly subsidies (pesos)		160
Annual subsidy for livestock raising (pesos/SLU)		1.00
Price of pehuén seeds (pesos/kg)		1.50
Price of livestock (pesos/SLU)		70
Seed production and consumption		
Area of *Araucaria araucana–Nothofagus pumilio* forest (ha)	(2)	2 642
Fraction (%) of dense *Araucaria araucana–Nothofagus pumilio* forest		0.80
Fraction (%) of *Araucaria araucana–Nothofagus pumilio* forest accessible to livestock		0.30
Exotic wild animals per hectare	(4)	2.00
Annual average precipitation (mm)	(5)	–

(1) Estimated from field observation
(2) Siffredi *et al.* 2002.
(3) Pinna et al. 2002 and the pehuén project report
(4) Sanguinetti *et al*. 2001.
(5) Not shown here. The 50-year series used in the model was extrapolated from precipitation trends starting from rainfall amounts measured during four years of field research.