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Cost-effective species conservation: an application to Huemul (*Hippocamelus bisulcus*) in Chile

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ABSTRACT. In this paper we study the cost-effective allocation of the land in the Cordilleran Protection Area (CPA), Region VIII, Chile, for the conservation of a highly threatened species: the Huemul (*Hippocamelus bisulcus*). Using a production possibilities frontier (PPF) approach, a linear programming optimization model for a ten-year time period is proposed. Our model takes into account both the preferences of the species for different habitats and the opportunity cost of the land. We evaluate different possibilities of land allocation and identify cost-effective alternatives in the provision of both conservation and income.

The results confirm the hypothesis that both the population of Huemul and income from economic activities can be increased compared with current levels. Therefore the current allocation of the land in the CPA is not cost-effective.

1. Introduction

From an economic point of view, it is important to identify the value of species and genetic resources. In order to avoid the loss of these resources it is also crucial to identify the variables that put stress on ecosystems and landscapes, which produces the loss of both biodiversity and system resilience. This would allow the formulation of policies to promote a determined biodiversity level, achieving sustainable development that provides a flow of services to society.

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The management of ecosystem resilience through biodiversity conservation must include the spatial limits of the socio-ecologic system, the key services of the ecosystem, and property rights, as well as other factors (Walker *et al.*, 2002). Biodiversity analysis, however, is characterized by a high degree of complexity and uncertainty (Perrings *et al.*, 1995; Brock and Xepapadeas, 2002), due to a lack of knowledge about many of the variables that influence the dynamics of each of the biodiversity levels or hierarchies.

Biodiversity conservation should be based on landscape analysis and not limited to the establishment of reserves. Biodiversity conservation ought to focus not only on the dependence of biodiversity on a unique habitat type, but also include the impact of different vegetative covers (for example, those used in agriculture or forestry) on landscape biodiversity as well as on ecosystem stability. This type of approach considers interactions in the ecosystem which ultimately determine the level of benefits (use and non-use values) provided by each ecosystem.

The population of Huemul (*Hippocamelus bisulcus*) in Central Chile (and its habitat) has been degraded by human activities such as forest clearing, human settlement, and livestock-related diseases. In an attempt to counteract this degradation there has been a campaign for the conservation and protection of the species and its habitat (Povilitis, 1998). The Chilean Ministry of Agriculture created a zone in 1974, designated as the Cordilleran Protection Area (CPA), in the Bio-Bio Region of Chile. The main objective of the CPA is to 'protect the last resources of fauna and flora of the zone', with particular emphasis on the Huemul (*Hippocamelus bisulcus*). This species is likely to become extinct unless new actions or policies encouraging its conservation are implemented in the near future.

The aim of this paper is to measure the cost-effectiveness of management policies for Huemul conservation in Chile's Region VIII. First, some concepts applicable to the economic analysis of biodiversity conservation are reviewed. Then, the potential productive capacity of the CPA is estimated and compared with a baseline given by the actual production scheme. In this way the cost-effectiveness of area management is measured. Finally, we consider other policies that take into account the preferences of the species for certain habitat types. The new policies include changes in land use and reveal a lower opportunity cost for Huemul conservation. They also provide sustainable development allowing Huemul conservation and protection, as well as economic benefits for future and present communities in the study area.

2. Background

Many studies have included several of the considerations discussed above. Some authors have studied the trade-off between biodiversity and the objective of production of commodities. Other authors have considered the restriction of resources allocated for conservation via land or management strategy budgets. For example, Marshall *et al.* (2000) explore the cost-effectiveness of threatened species management. They consider changes in the parameters describing the population of a species like population density, adult and juvenile survival rate, and growth rate. The constraint is species viability, which is defined as a survival probability function associated with the minimal acceptable limit of a species. Spatial elements (i.e., species distribution throughout different types of sites) are not included in this analysis.

Polasky *et al*. (2001) analyze the selection of biological reserves, incorporating differences in the distribution of terrestrial vertebrates and on land values within the study site. A species is considered conserved if it is found in at least one of the sites assumed to be a reserve. This spatial,[1] non-temporal model maximizes the number of species conserved, restricted by the available conservation sites and the budget. They conclude that the inclusion of differential land costs produced more cost-effective results than those where homogenous costs were assumed throughout the different study area sites.

On the other hand, Lichtenstein and Montgomery (2003) and Nalle *et al*. (2004) incorporate in their work the economic and biological consequences of land use alternatives. They analyze ecosystems characterized by different vegetative covers according to the type of land use. They measure the cost-effectiveness of management policies considering marketable products (wood) and those without monetary value, for example species of fauna that society values simply for its existence. With these use and non-use values, a production possibilities frontier (PPF) between a market product (timber) and a non-market product (biodiversity) was calculated. The model sought to maximize the income received from productive activity (lumber extraction) restricted by a biodiversity index depending on the number of individuals of each species. The indices were defined as a combined probability function (in Lichtenstein and Montgomery, 2003) or as a geometric mean (in Nalle *et al*., 2004). The conclusion in both papers is that a new type of management would improve the efficiency in one of the following two ways: increasing the income from forest product extraction while maintaining the biodiversity level, or increasing the biodiversity level while guaranteeing a stable income from timber products.

3. Case study

One of the most employed *in-situ* biodiversity conservation measures is the protection of areas with specific conservation goals. The protected areas go farther than the simple conservation of a species or habitat and consider the ecosystem as a whole. To conserve a species, it is necessary to consider also the habitat in which the species lives. There are certain advantages of using a habitat, rather than a species perspective (Perrings, 1995): first, the opportunity cost of protecting an additional species is low (economies of scale); second, uncertainty regarding which species are more valuable is less significant; third, interdependence between species is considered in the analysis. In spite of these considerations, the entire ecosystem is more than just species and habitat conservation. It includes also the recognition of the ecosystem's worthiness in the provision of other services.

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[1] As pointed out by an anonymous referee, the Polasky *et al.* study is spatial only in the sense that the potential sites are located somewhere. But their spatial location does not affect species protection.

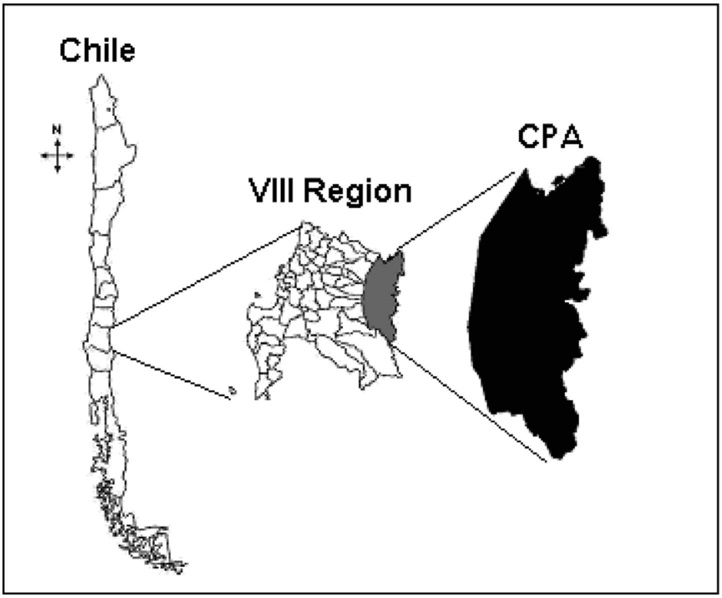

Figure 1. *Map of study area: Cordilleran Protection Area (CPA) in the Bio-Bio Region, Chile.*

Chile's Region VIII includes presently a Cordilleran Protection Area: Los Nevados de Chillán-Laguna del Laja (CPA). The Chilean Agricultural Ministry created this protection area in 1974 (see figure 1). It has an area of 560,376 hectares in cordillera and pre-cordillera zones.[2] The CPA is very important from the ecological and biological viewpoint since it hosts the last and most threatened Huemul population in Central Chile. It is also an ecological transition zone with great heterogeneity of available environments that make the existence of rich, diverse fauna and flora and a high level of endemic species easier (CONAMA, 2002). Furthermore, the CPA is located within the Valdivian Eco-region, which is one of the 233 most biodiverse eco-regions in the world (Olson and Dinerstein, 1998). Last but not least, it is one of 24 hotspots with the greatest biodiversity conservation value at the international level (Da Fonseca and Olivieri, 1998).[3] The Huemul (*Hippocamelus bisulcus*) of the CPA (see figure 2) is a deer that is highly threatened by activities such as livestock management, human settlement, forest clearing, and hunting. It is perhaps the most documented species in the area. Due to its geographical separation from other regions, the population in the CPA is very important from a genetic

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[2] *Cordillera* is defined as a system of mountain ranges, often consisting of a number of more or less parallel chains (Merriam-Webster Online Dictionary, 2005).

[3] An eco-region is an ecosystem with an ensemble of habitats and communities that geographically distinguish and define it in biological rather than political terms, and in which the majority of the species share common environmental and dynamic conditions (Fundación Vida Silvestre – WWF, 2003)

Figure 2. *Huemul (Povilitis 2002).*

and evolutionary point of view. The Huemul prefers 'steep, broken terrain with forest and shrub cover, and also requires access to lower elevations where snow accumulation is light' (Povilitis, 1998). Since it requires great extensions of habitat (Povilitis, 2002), the conservation of the Huemul offers the possibility of preserving a wide range of species, such as the avifauna in Central Chile (Estades, 1997; Figueroa *et al.*, 2000). Huemul habitat also protects biodiversity in this area (with mammal and bird species being the most representative). An analysis of Huemul protection turns out to be also an analysis of biodiversity conservation, although the results obtained here are not completely applicable to other species.

The CPA includes several different sites, including two reserve areas (*Los Huemules de Niblinto Reserve* and the *Ñuble National Reserve*) and the *Laguna del Laja National Park*. There are several types of land use within the sites, including agriculture, livestock, forest plantations, tourism, hydroelectric production, and a large extension of natural forests from which firewood, charcoal and lumber are extracted.[4] In the CPA, the Huemul conservation strategy is not limited to land acquisition in order to create protected areas. The strategy also includes the participation of different landowners in protecting Huemul on their property and the establishment of corridors to connect groups of Huemul (López *et al.*, 2001). Property ownership is currently distributed as follows: 18 per cent under official protection (the two reserve zones and the national park), 4 per cent unprotected government property, and the remaining 78 per cent private property (CODEFF, 2003).[5]

4. Methods and data

The present work adapts the principal criteria of Lichtenstein and Montgomery (2003) to the proposed case study. First we calculate a potential

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[4] The Bio-Bio Region presents the greatest diversity of firewood species in Chile (CONAMA, 2002).

[5] Private property is distributed among small landowners, lumber companies, agricultural and tourism companies, and the energy sector.

productive capacity in the area. The results of this simulation process are then compared with a baseline for the proposed time horizon. For the calculation of the baseline, we assume that the current production scheme remains the same over the whole time horizon; i.e., productive investment projects are not incorporated. This assumption in some way limits the results obtained in this work. We analyzed the problem for a ten-year period. It has been estimated that the population would become extinct in this period unless protection and conservation actions were taken (Povilitis, 1998, 2002).

In the process of simulating the potential productive capacity, the decision variables were taken as the proportions (**Y**) of area of each management unit (MU) assigned to each activity.[6] We want to find the proportion (Y_{ij}) of each activity i in MU j of size A_j that maximizes the value of the designated production. The index of Huemul population level depends on the total quantity of land used in activities compatible with Huemul existence. This is then a function of **Y,** and the topographic characteristics of the land. The management prescription is defined by the set of activity proportions applied. The benefits will also depend on the proportion of each activity that is designated in each MU. Let us suppose that there are n activities (uses) and m management units. In order to find the PPF, the following model is evaluated for different values of the parameter $\overline{X}$

$$\underset{Y}{\text{Max}}\ W(Y) = \sum_j \sum_i ((P_i Q_i - C_i) A_j Y_{ij}) \tag{1}$$

$$\begin{aligned} \text{s.t.}\quad & X(Y) \geq \bar{X} \\ & \sum_i Y_{ij} = 1 \quad \forall j \\ & Y_{ij} \geq 0 \\ & R_j \cdot \mathbf{Y} = r_j \quad \forall j \end{aligned} \tag{2}$$

for $j = 1, \ldots, m$ management units, and $i = 1, \ldots, n$ economic activities, where:

P_i: is the constant price in Chilean pesos (CL$) of a unit (ton or cubic meter) of the good from activity i;
Q_i: is the production of activity i in the ten-year period, in units[7] per hectare;
C_i: is the total cost per hectare of the activity i in the whole period;
A_j: is the total area of the management unit j;
Y_{ij}: is the proportion of the area of MU j designated to the activity i;

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[6] Each management unit corresponds to one of the different polygons into which the Geographic Information System (GIS) divides the zone. This division is performed according to common characteristics in each one: slope, altitude, covering, and exposure degree. The information in GIS format was obtained from the Census and Evaluation of Native Vegetative Resources of Chile – Native Forest Census – (CONAF-CONAMA-BIRF, 1998).

[7] Production from agriculture and cattle is measured in tons, and wood in cubic meters.

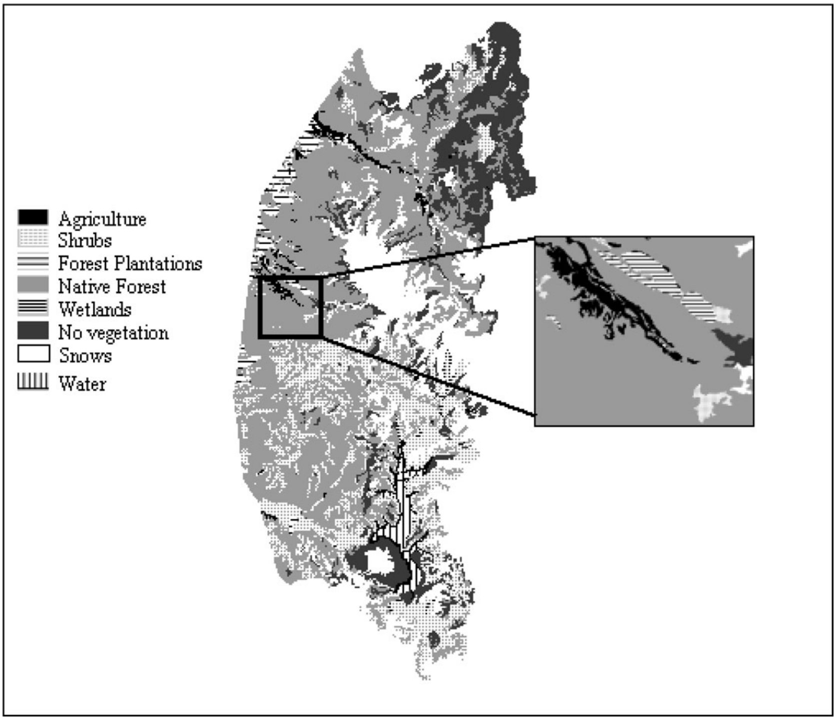

Figure 3. *Vegetative covers associated with CPA's current land uses.*

X(**Y**): is an index of the Huemul's population level that depends on the set of prescriptions (**Y**);

R_j, r_j: are a matrix and a vector of linear constraints giving the feasible uses for each MU.

In the study area, there are 5,862 MUs (m=5,862) corresponding to the division provided by the geographic information system of the Native Forest Census. Eight types of land use were identified (see figure 3). They can be divided into the six following categories:[8]

1. Reserve status
2. Old-growth forest management
3. Recreation
4. Timber production
5. Agriculture (wheat cultivation)
6. Cattle range (bovine)

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[8] The types of land use were agriculture, wetlands, shrubs and prairies, forest plantations, mixed (plantation/natural) forests, old-growth forests, snow and glacier, and barren areas.

Table 1. *Appropriate area for Huemul conservation according to habitat quality for each type of use*

USE	*Total area*	*Apt*	*Not apt**	*% Apt*	*% Not apt*
Agriculture	4,575.06	143.12	4,431.94	3.13	96.8
Plantation	11,059.15	853.57	10,330.90	7.63	92.37
Old-growth forest	252,819.97	92,092.55	160,727.42	36.43	63.57
Shrubs and wetlands	83,729.55	19,844.20	90,499.96	17.98	82.02
Total	398,536.46	92,836.26	305,700.2	23.29	76.71

Note: *Includes some areas of the SNASPE (National System of Wildlife Protected Areas)

The last five are productive activities. Part of the total study area (560,376.16 ha) was excluded in the analysis, namely snow covered areas (80,964.71 ha), barren areas (69,065.38 ha), and water bodies (11,809.61 ha). They were left out because it is unlikely that human activity in these areas has a negative effect over species protection. Since recreation is carried out only in a few of the excluded MUs of the study area, we ruled out this economic activity from the optimization model. It was also considered that there are currently no new projects to expand this activity to new areas in the time horizon analyzed (A. Contreras, personal communication, 2003).

There are sites under each of the current land uses that are also appropriate for Huemul conservation – according to Huemul preference for certain habitat types (with slope and altitude criteria). This suggests a potential for conservation that can be realized by switching the land use. Based on the classification of habitats by Povilitis (1998), table 1 indicates the proportion of the total area for each type of current use that could be employed for Huemul conservation. This classification includes predominantly north-facing sites, with typical slopes of 30–40 per cent, and with at least 1,750 meters above sea level.

The objective function (1) of the optimization problem shows the production-discounted value in the ten-year period (i.e., the discounted value of the net benefit acquired in the time horizon). The model requires the index of population level to be equal to or greater than the minimum level, $\overline{X}$. The index population level is a function of the amount of area with appropriate habitats for the species, which depends directly on the type of activity performed in each management unit. Consequently, the index depends on the management prescriptions as follows

$$X(Y) = \delta \sum_{i=1}^{5} \sum_{j=1}^{m} h_i A_j Y_{ij} \omega_j, \tag{3}$$

where h_i is a subjective range of habitat preference between 1 and 5. This range of values is fixed according to the type of vegetative cover produced by a determined activity: cattle (1), agriculture (2), forest plantation (3), old-growth forest (4), and reserve site (5). This range was built taking into account opinion from biologists. They have observed, for instance, that Huemul individuals are severely threatened by agricultural activity due to the habitat fragmentation introduced. Cattle ranching turns out to be the most threatening activity for the Huemul, since the dogs used in herding occasionally hunt Huemul. Forest plantations and native forest might be more preferred by the Huemul because they provide a hospitable environment and some necessary elements of the Huemul's diet. Finally, a reserve site would obviously be the most preferred habitat. The parameter ω_j takes the values 1 or 0, depending on whether or not the management unit is appropriated as Huemul habitat. This depends basically on slope and altitude.[9]

The parameter δ is calculated as follows

$$\delta = 1 \Bigg/ \sum_{i=1}^{5} \sum_{j=1}^{m} h_i A_j \overline{Y}_{ij} \omega_j \tag{4}$$

where $\overline{Y}_{ij}$ takes the value of 1 if the *i*th activity is currently used in the *j*th management unit and 0 otherwise. This procedure adjusts the area sizes and the preference ranges to the index of population in such a way that the index value is regarded as unity for the current land use. The index quantifies the impact caused by each type of activity on the habitat of the Huemul, and thereby on the number of individuals.[10]

Additionally, three restrictions are incorporated into the model. First, the existing legal standards for forest exploitation were considered. They include a prohibition against cutting trees located less than 40m from a body of water and on slopes greater than 45 per cent.

Second, productivity of each MU under each use was adjusted to the slope and altitude. This adjustment (see table 2) is based on experts' opinions. With this adjustment we want to take into account the dependence of the benefits that can be obtained on the accessibility to the MU. For instance, if the normal benefit of a wheat crop were \$100, the profit of this activity would decrease to \$80 if the crop is 1,500 masl, and if it were also located on a 20 per cent slope site, the benefit would be reduced to \$76.

Third, the conversion of some types of actual use to other uses was restricted. Indeed, the MUs currently being used as reserves or covered with old-growth forests must be maintained in their current state, although an old-growth forest could become a reserve site. Additionally, sites used for agriculture, cattle-raising, and forest plantations could be designated as reserves. Land use for agriculture and cattle grazing could continue to be used for the same type of activity or could be changed to short rotation plantations or into reserve units (see table 3).

To measure the cost-effectiveness of the CPA, a base scenario was considered for the time horizon that reflects the evolution of this area under the actual management prescription. This baseline was then compared

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[9] Povilitis (1998) points out that the Huemul's primary habitat sites are 'generally 30–40 degrees in slope, and attaining at least 1,750 m elevation'.

[10] For example, if there were only two activities in the area and two MUs appropriated for habitat of Huemul, one with a reserve (109 ha) and another with agriculture (65 ha), the value of δ would be: $1/(109*5+65*2)= 0.00148$.

Table 2. *Performance percentage per hectare according to management unit characteristics*

Characteristic	*Cattle raising*	*Agriculture*	*Forest plantation*	*Old-growth forest*
Altitude (masl)				
400–600	100	100	100	100
600–800	100	100	100	100
800–1,000	100	100	100	100
1,000–1,200	95	100	100	100
1,200–1,400	90	100	100	100
1,400–1,600	80	80	100	100
1,600–1,800	70	60	100	100
1,800–2,000	60	40	100	100
2,000–2,200	0	0	50	85
2,200–2,400	0	0	50	85
2,400–2,600	0	0	50	85
Not classified	0	0	0	0
Slope (%)				
0–15	100	100	100	100
15–30	75	95	70	100
30–45	40	75	40	100
45–60	0	15	0	100
60–100	0	10	0	70
>100	0	0	0	0
Not classified	0	0	0	0

Table 3. *Feasibility of land use conversion from actual use to different types of use*

	Actual use					
Feasible use	*Livestock*	*Agriculture*	*Plantation*	*Old-growth Forest*	*Reserve*	*Recreation*
Livestock	1	1	1	0	0	0
Agriculture	1	1	1	0	0	0
Plantation	1	1	1	0	0	0
Native forest	0	0	0	1	0	0
Reserve	1	1	0	1	1	0
Recreation	0	0	0	0	0	1

Notes: 0: Infeasible to convert to the other type of use.
1: Feasible to convert from 'Actual use' to 'Feasible use'.

with the calculated PPF. To find the PPF, the 5,862 MUs of the CPA were designated along with five possibilities of land use. The model was then solved repeatedly for a range of values for $\overline{X}$. The bottom limit of $\overline{X}$ was fixed at a level lower than the index value corresponding to the current population level. Taking a base level X=1 for the index (corresponding to around 45 individuals), the bottom limit was fixed at 0.8 (36 individuals, approximately). The upper limit resulted from a scenario in which all the species-appropriated habitats were used as reserve. In all cases, each MU could be designated to one or several of the distinct possible uses and thus its contribution to the species population level varied according to each selected use. The problem was solved with the *linprog* optimization function in MATLAB 6.1 (The MathWorks, 2001).

The management units of the present study are based on the information obtained from the Native Forest Census (CONAF-CONAMA-BIRF, 1998). This information system provides a series of units that correspond to the geographic divisions according to characteristics of slope, vegetative cover, and altitude. In the studies of Lichtenstein and Montgomery (2003) and Nalle *et al.* (2003), an average resolution of 4.65 and 0.1 hectares, respectively, for each MU were used. The Native Forest Census, however, has a much lower resolution at 79 ha.

The information for the agricultural parameters came from different sources, namely the production data of the National Agriculture and Livestock Census (INE, 1997), the Agricultural and Livestock Statistics Yearbooks (INE, 2003), and prices reports for the activities found in the study area (INDAP, 2003). Some information from studies on more profitable alternative agricultural and livestock systems was also used (Klee, 2002a, 2002b; Velasco *et al.*, 2000; Velasco, personal communication, 2003).

Finally, we took into account different existing studies to estimate the extraction of wood products from natural forests (firewood, charcoal and lumber). The studies were the National Forest Inventory (Lara *et al.*, 1998) and some others (Sandoval, 1999; Bustos and Soto, 1997; Reyes, 1998) on firewood consumption by small landowners. The sustainable management scheme for natural forests developed by Rothermel (2002) was a reference to estimate management alternatives in the old-growth forests for the most exploited species: roble (*Nothofagus glauca*), raulí (*Nothofagus alpine*) and coihue (*Nothofagus dombery*).

Using this information, we obtained the vector of net economic returns per hectare (CL$/ha) shown in table 4, for each of the activities.

Table 4. *Benefits per hectare for each activity (Chilean pesos)*

Activity	*CL$/ha.*
Livestock	11,538,000
Wheat	1,248,953
Plantation	30,602
Native forest	382,000
Reserve	0

5. Results

The characterization of sites preferred by Huemul for habitat was based on Povilitis (1998, 2002). This characterization of habitat uses, essentially, slope and altitude to classify sites either in primary or secondary habitats.

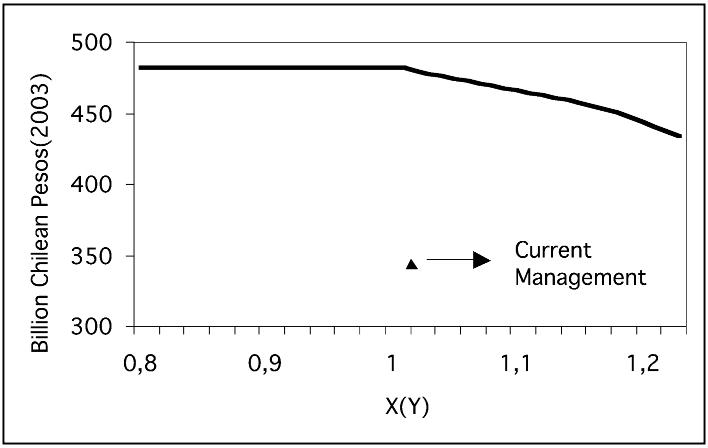

Figure 4. *Production possibilities frontier that combines forestry, agriculture, and livestock production with Huemul conservation in the CPA*

According to the database employed, the primary habitats correspond to 266 MUs and the secondary habitats to 1,141 MUs, with total areas of 25,737.32 ha and 68,098.94 ha, respectively. The rest of the MUs are assumed to be not suitable for species survival. In fact, at those sites without the topographic characteristics mentioned by Povilitis, the Huemul population would be unable to find the elements of its basic diet.

The results obtained indicate that for the analyzed period, the population index could be increased by approximately 23 per cent (X=1.23) using primary and secondary habitats as reserve sites and the rest of the MUs for production.

Using index values between 0.8 and 1.23, a PPF was obtained that shows the maximum possible benefits associated with the corresponding index value. For the bottom level the value of the objective function found was CL\$$4.818*10^{11}$. This is 42.2 per cent greater than the value obtained for the activities currently performed on the land (CL\$$3.388*10^{11}$). The value remains constant between the bottom level and the base level. This is due to the fact that the primary habitats currently used as reserve sites, which remain as reserves according to table 3, hold population levels lower than the current level. In addition, in those sites land use changes are prohibited under the current legal framework. Beyond the base level, new sites of secondary habitat need to be included in order to increase the Huemul population 23 per cent. The value of the objective function decreases as the index increases. For instance, for an index value of X=1.01 or X=1.05, the values of the objective function drop to CL\$$4.815*10^{11}$ and CL\$$4.746*10^{11}$, respectively, and so on. Finally, at the greatest index value that might be reached (X=1.23), the value of monetary income would be CL\$$4.335*10^{11}$ (see figure 4).

Two points should be taken into account when considering these results. First, the increment in the index value is given mainly by changes in land use. Additionally more appropriate habitats are designated for species protection. Second, this type of cost-effective management means a lower opportunity cost in the maintenance of protection reserves and species conservation.

As can be seen in figure 4, when the population index is increased the variation in the value of the objective function is not large. This is largely due to the restrictions placed on the model with respect to feasible changes in land use. The results indicate that increasing the population by 1 per cent results in a reduction of the earned income to about CL\$$3.1*10^8$. Nevertheless, there appear to be different slopes, since for increments between X=1.02 and X=1.15 the decrease in benefits is constant (CL\$$1.73*10^9$), and between X=1.16 and X=1.23 the average opportunity cost is CL\$$2.98*10^9$. This means that as we increase the population index the opportunity cost increases. The increment of the population index would be achieved with a type of management that: on the one hand protects the species by falling back on the application of a sustainable natural forest exploitation scheme as described by Rothermel (2002), and on the other hand obtains income level values that are superior to the values from the baseline (CL\$$3.388*10^{11}$). These results, however, do not consider the future possible variations in price or potential changes in the market for products from this activity. For this reason the application of these results will depend to a certain extent on market expectations and conditions.

It should be noted that the population level of this species depends on other issues not considered here, and not only on the sites it inhabits. In fact, the population level (basis) for the current use prescription is surely not exactly observable due to its dependence on many different factors. This introduces some uncertainty into the calculation (4) that can be efficiently captured by using the index of population.[11]

Due to the linearity of the model the variation in the value of the objective function depending on the minimal population level $\overline{X}$ required, behaves as a piecewise linear function. This behavior is actually independent of the actual population level due to the use of the index.

The most significant changes in land use were in the MUs designated as reserve sites. These sites increased over 100 per cent. This increase is due to, in addition to the MUs actually designated for species protection, other sites with primary and secondary habitats for Huemul being added (see table 5). Table 5 shows that the MUs currently used for livestock were reduced, indicating that there are currently some MUs with livestock and topographic characteristics that make them appropriate sites for Huemul habitat. Land use in MUs with old-growth forest decreased 27.44 per cent. There is a change in these sites, since some of the MUs with native forest are now used as reserve areas for the protection of species.

These results indicate that it is possible to outline area management policies that would generate greater social benefit while also increasing species viability. This could be the beginning of long-term sustainable development that includes species protection and generates economic

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[11] An anonymous referee highlighted this remark.

Table 5. *Changes in land use that tend to achieve cost-effective management in the CPA, comparing actual use to some of the population index levels employed in the optimization method*

	Actual		*X=1*		*X=1.23*	
Activity	*Number of MUs*	*%*	*Number of MUs*	*%*	*Number of MUs*	*%*
Livestock	753	12.85	627	10.7	561	9.6
Wheat	63	1.07	294	5	262	4.5
Plantation	124	2.12	14	0.2	15	0.3
Native forest	3,787	64.60	3,764	64.2	2,731	46.6
Reserve	1,135	19.36	1,163	19.8	2,293	39.1
Total number of management units: 5,862						
Value of objective function	$\$3.388*10^{11}$		$\$4.818*10^{11}$		$\$4.335*10^{11}$	

benefits for the involved communities. In this way, under the assumptions of our work, the main conclusion is that the actual CPA management scheme is not cost-effective mainly because the actual scheme does not consider the species' habitat characteristics.

6. Conclusions

This research evaluated cost-effectiveness in the Cordilleran Protection Area of Region VIII (Chile). We used a production possibilities frontier approach with an optimization model restricted by a minimum level of the Huemul population index. The hypothesis of the investigation was that the actual management is not cost-effective in comparison with alternative management schemes, and that a greater level of economic and ecological benefits could be achieved.

Given the assumptions of our study, the principal conclusion is that the actual management scheme in the CPA is not cost-effective, largely because it does not consider the species' habitat characteristics. In fact, our model indicates that the Huemul population level can be greater than it is presently, while maintaining or increasing the level of benefits.

The current distribution of property rights shows a high proportion of land owned by private agents. In spite of this, the results suggest that the current management is not cost-effective. This is a consequence of the fact that the private owners usually do not exploit their land with the most profitable activity. Usually different aspects, like accessibility to roads, are taken into account for land acquisition. Such criteria, however, like land productivity, do not come into consideration. Some studies have also shown (Klee, 2002a, 2002b) that in the region under consideration more profitable agricultural production can be achieved if changes in some processes are applied. In the model it is assumed that land productivity is optimal for the activity carried out in the MU. Different results could emerge with the inclusion of a new variable that accounts for soil quality and its impact on agricultural output.

This work differs methodologically from other studies in the literature by using continuous variables (area percentages) in the optimization model. Previous studies include binary variables for each MU whether or not a prescription is implemented. This allows us to simplify the optimization problem and use standard tools at a level available to policy makers. MUs can be defined at as small a scale as desired, and then binary variables can be implemented. This division is something that should be made *a priori*; and this *a priori* criterion could be unknown for the policy maker. Regarding the numeric resolution of the model, the problem is of medium size requiring standard resolution tools.

Future extensions of this work could consider the following research line. A temporal restriction needs to be introduced into the model in order to capture the relationship between habitat type and species growth. With the inclusion of more species – principally avifauna, not included in this study due to lack of information – the configuration of the final results as well as the calculated PPF could change. Other important restrictions such as the existence of institutions that implement these alternative management policies are not considered in this work. For instance, the inclusion of property rights is crucial when considering the implementation feasibility of the management prescriptions generated by the model. Cooperation incentives, especially for private landowners, could be necessary for policy implementation; e.g., incentives would likely be necessary if a site needs to be changed from agricultural or livestock activity to a reserve. Species dynamics, which consider how the population level varies with the number of individuals in the long run, should also be incorporated into the model. Bearing in mind the uncertainty in the measurement of ecological variables (e.g., species population), the inclusion of viability functions in the model would make it a more relevant but complex (non-linear) problem. Additionally, it is important to take into account the connectivity of the area containing the species habitat. The objective function could also include additional benefits of natural forests such as scenic beauty, recreation, and the development of water resources through different hydrographic basins. Finally, more information (still not available) could be used in order to analyze the effects of parcel placement and of surrounding land-uses. One might expect that the inclusion of these restrictions could change the final configuration of land use.

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