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Systems valuing of natural capital and investment in extensive pastoral systems: Lessons from the Patagonian case

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ABSTRACT

In Patagonian (Argentina) wool production systems, historical performance records, observed landscape changes, and long-term demographic modeling of sheep flocks, indicate that non-sustainable ecological and economic dynamics have developed during recent decades. In order to elucidate possible causes of these trends, a dynamic model of the wool production system including basic ecological and economic feedback mechanisms was applied to the analysis of alternative investment policies. The values of the various components (ewes, forage, soil) of natural capital (NC) involved in the production systems were estimated in this study through a systemic approach and their losses during wool production cycles were incorporated in their financial analysis. Our results indicate that external investment in increasing the ewe stocks (a common practice in these systems) is not sustainable in time unless a simultaneous external investment in forage NC is performed. More specifically, external investment to increase in 20% the ewe stocks would be expected to generate positive net cash flows during 6-8 years, if due account is taken from the losses of NC produced. Successive investments of the same sort would generate increasingly shorter periods of positive cash flows or even negative results after 15-25 years. Re-investment of a fraction of the net revenues obtained through wool sales in the reposition of forage resources also proves to be a non-sustainable policy. External investment on forage resources at about a 10:1 ratio with respect to investments in the ewe stock would produce positive net cash flows sustainable in time. It is concluded that sustainable investment policies in extensive range systems of Patagonia should consider the ecological-economic relations and feedbacks existing between forage consumption by ewes and ewe natality/soil erosion controls exerted by forage and market behavior. The structure of analysis of investment policies on extensive pastoral systems of the Patagonian Monte here proposed seems valuable to be extended to other regions with similar ecological-economic characteristics.

1. Introduction

1.1. *Sustainable grazing lands: a growing economic-ecological perspective*

Lands used for pasture of domestic animals cover extensive areas of the world and display conflicts of resource use that receive increasing attention (Jones and Dowling, 2005). Semiarid grazing lands pose additional conflicts because their dynamics largely depend on stochastic climate variations (Le Houérou et al., 1988). Cyclic stochasticity (however hardly predictable) requires adaptive managing policies. These however must cope with characteristic response time lags due to the slow rates of reposition of the soil and forage sustaining these systems.

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Domestic grazers and forage constitute renewable natural capital (Costanza and Daly, 1992). Typical turnover times of sheep are in the order of 5-10 years while those of forage plants vary widely between several years to decades depending on their life form (grasses, forbs, shrubs, etc.). Soils also constitute a coupled form of natural capital (NC), supplying sustain and nutrition to plants. Soils are constructed at a very low pace by the combined action of plants and other organisms and the action of climate factors, and changes in its quality typically occur with turnover times in the order of centuries (Parton et al., 1993). Soil degradation, however, may occur after a few years by the action of impacts originated in anthropogenic activities (inadequate cropping, overgrazing, etc.).

There is mounting evidence that contemporary grazing land management practices are not ecologically sustainable in extended pastoral areas of the world (NLWRA, 2001). Conventional economic approaches used to value and regulate resource uses do not seem appropriate to warrant modern community values and inter-generational transfers of NC (MacLeod and McIvor, 2005). However, most ecologically sustainable uses of pasture lands will have to be achieved in privately owned areas (Perrings and Walker, 2005) under conditions and rules set by contemporary management systems, markets and institutional arrangements. These should allocate the benefits and costs of landscape conservation between landowners and the wider community as represented by public investment (HRSCEH, 2001).

1.2. *Recent evolution of natural capital in the pastoral production systems of Patagonia*

The extensive pastoral systems in semiarid Patagonia (Argentina) constitute a case of interest since similar semi-arid lands occupy wide areas of the world terrestrial environment. These include regions such as chaparral, woodland and savannas in southern California, Chile, Mexico, Argentina, areas surrounding the Mediterranean Sea, and southwest parts of Africa and Australia (NASA, 2004). Grazers in these lands like sheep (*Ovis aries*), goats (*Capra hircus*), guanacos (*Lama guanaco*), lamas (*L. glama*), etc. constitute either free or enslaved NC (in the sense of England, 2000) providing meat, milk and fibers to local, regional or international markets.

Patagonia is an extended region in the South American continent and has a surface of almost 800,000 km2. In Argentina, it is limited to the north by the Colorado River and to the south by Tierra del Fuego, the southern extreme of America, where Cape Horn is located. Except at the Andes area the Patagonian relief is dominated by extended plains, covered with semiarid vegetation. The regional wool production systems started at the beginning of the 20th century (Defossé et al., 1992) and are presently carried at large *estancias* (10000-50000 ha or more) usually consisting in some few paddocks around a shared watering place. Flock management has been extensive, with limited human intervention and native vegetation has been almost the only source of forage for sheep, with flocks behaving as "semi-natural" populations (Golluscio et al., 1998; Paruelo et al., 1998). Ranchers usually attend the wool markets on a yearly basis, and take decisions about their business depending on the price obtained for their production. As in other regions of the world, the Patagonian wool economy has had deep economic, environmental, and social regional impacts.

However, there are several groups of evidences indicating that these systems are not ecologically and economically sustainable in time, and that gradual losses in the NC sustaining them have occurred during the last decades. Sheep stocks fell from 20 millions in 1952 to 11 millions in 1993 (Golluscio et al., 1998). This decline has been observed at different spatial scales: individual ranches, counties, provinces and the whole region. Texeira and Paruelo (2005) fitted demographic matrix models to historical records available at large ranches located along a representative regional environmental gradient at western Patagonia. They found that computed ewe survival and recruitment rates were much lower than those that would fit observed present stocks, indicating that regular flock imports occurred along recent decades in order to partly restore those lost due to natural causes.

Sheep grazing impacted on the forage stocks of Patagonia, producing structural and floristic changes that are eventually (but not always) partially reverted after releasing the grazing pressure (Soriano et al., 1980, Bertiller, 1994, 1996, Del Valle, 1998). In eastern Patagonia, partial recovery of preferred grasses occurs only after 2-3 decades of sheep exclusion (Bisigato et al., 2002). Prevailing changes in the plant cover under grazing pressure are in the direction of a diminution of preferred plants and an increase in non-forage, non-preferred species (Bertiller and Bisigato, 1998). Ecosystem modeling experiments (Parton et al., 1993) with parameters obtained from field experiments at eastern Patagonia, show that observed trends of vegetation dynamics under moderate grazing are compatible with a gradual diminution of the plant cover at a regional scale (Carrera et al., pers. comm.).

Evidences also indicate that the soil NC experienced reductions along recent decades under the impact of wool production systems. Del Valle et al. (1998) indicate that the soil thickness (an index of the integrity of the soil profile) varies from 0.9 to 0.1m over the Patagonian region depending on the severity of degradation attained. Losses of the soil layers over the plant root-inhibiting depth vary from 0.25 to 0.75 m, and about half of the Patagonian surface is slightly to severely degraded. Ares et al. (2003) identified structural changes in the vegetation cover at extended areas of eastern Patagonia indicating a progressive alignment of plant patches along the direction of predominant winds, an indication of progressive wind erosion of soils.

1.3. *Development of a conceptual model to characterize ecological and economic sustainability of Patagonian wool production systems*

The signs described in the previous section indicating non-sustainability of Patagonian wool production systems seem to be similar across Patagonian sub-regions that differ in their productive potential, climate, soil quality and market positioning. This motivates the identification and investigation of dynamic traits of those systems that would be common across regional ecological differences. In this study, this is pursued through a simulation model.

Detailed simulation models of grazed ecosystems have been available since several decades ago (see for instance Weishampel, 2005 for a detailed list of about a hundred books and references on the subject). Because of the inherent complexity of grazed ecosystems, detailed models are structurally oriented to address specific aspects of their dynamics (soil nutrients-vegetation-flock dynamics, water balances, meat-milk production, economic profitability). This type of models is strongly site-oriented, and requires the definition of many local parameters describing the characteristics of the climate, soils, forage-grazer stocks and market conditions. In practice, the availability of local ecological information limit the application of these models to long-term research sites or the areas used to tune the model behavior. These models can attain considerable success in depicting dynamic relations among the system components, but they are of limited use to identify modal functional relations across regions with differing ecological characteristics. Stochasticity of some major driving factors (typically in the behavior of climate and markets) limits the predictive ability of detailed simulation models of grazed ecosystems.

A simpler conceptual model that would be robust to local differences in its predictions seems more adequate to inspect the kind of questions related to regional sustainability and NC pursued in this paper. In a conceptual model, the number of parameters involved is kept to a minimum and restricted to those characteristics known to be modal across the region of interest. Predictions of a conceptual model are usually formulated in comparative terms among simulated alternatives.

In this study, a conceptual simulation model is used to simulate investment projects consisting in increasing the stock of ewes and/or forage by defined percentages and their middle and long-term (15-25 years) performance is evaluated. Functions to account for the monetary value of the changes in NC involved in the project are developed and integrated into the calculus of cash flows.

In Section 2.1, the theoretical frame for the systemic analysis of wool production systems is presented. Based on this frame, the system components are identified (Section 2.2) and a conceptual model is formulated. Section 2.3 describes the techniques of financial analysis to characterize the economic sustainability. Relative comparisons between investment alternatives are then formulated (Section 2.4). Results of a calibration of the model to mimic the trends of depletion of NC described in Section 1.2 and typical cash flow sequences under the various investment alternatives are presented. Their implication to intra-generational equity and ecological-economic sustainability is discussed.

In particular, we address the following questions:

1. How investment policies can be designed to achieve both ecological and economic sustainability of Patagonian wool production systems?
2. What are the trans-generational transfers of NC stocks and how generation equity principles about the Patagonian pastoral system can be formulated?

2. Methods

2.1. *Theoretical frame for the analysis of extensive pastoral ecosystems*

For the sake of this study, the case of the Patagonian sheep pastoral systems is treated in the frame of dynamic system's theory, by inspecting the values and changes in NC generated during sheep husbandry within their particular spatial-temporal context (Stahel, 2005). In particular, issues related to the sustainability of the NC (domestic grazers, native vegetation, soils) involved in the production system under various investment alternatives are addressed.

In extended pastoral systems, herbivores, forage and soils are dynamically dependent on each other (Fig. 1). Decreases in forage and soil stocks are coupled in a negative feedback loop. The vegetation stock protects the upper soil from the eroding effects of water (Foster et al., 2003) and wind (Ares et al., 1990,

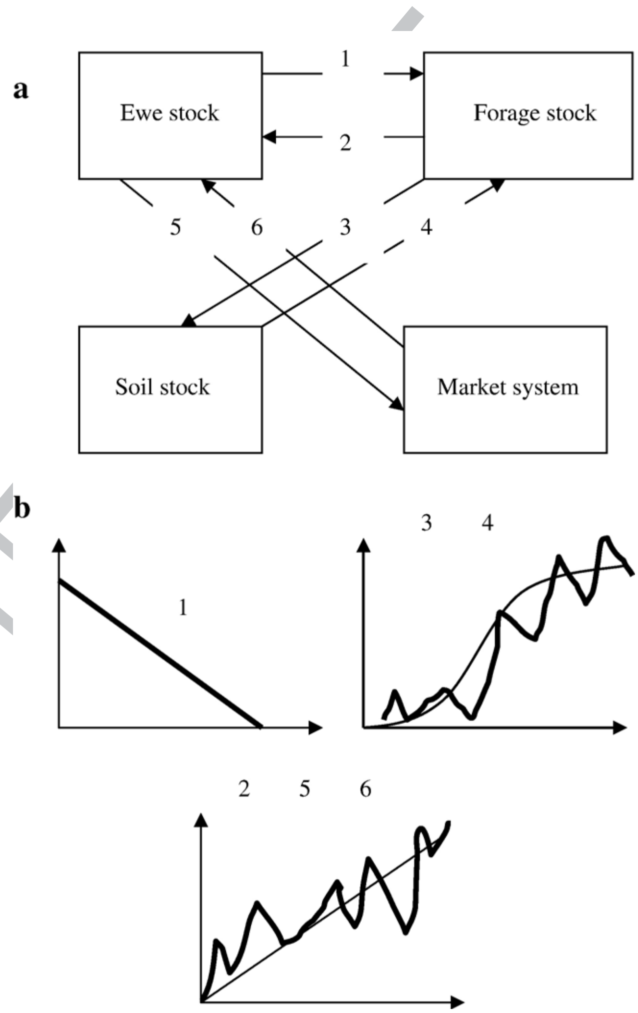


Fig. 1 – (a) Major subsystems of the Patagonian wool production system. Three stocks of natural capital (sheep, forage, soil) interact among them and with the wool market system. (b) Functional forms of main interactions (sketched, donor subsystem increases along the *x*-axis, receptor increases along the *y*-axis). 1. Sheep consume forage and reduce the standing forage stock. 2. Forage regulates sheep survival and recruitment rate. 3. Forage protects the soil from water–wind erosion. 4. Soil sustains forage plants and supply nutrients for growth. 5. The sheep stock determines the amount of wool that can be offered to the market each year. 6. The gross revenue obtained at the market conditions the amount of potential re-investment in maintaining–reducing–expanding the sheep stock. Stochastic variations occur at interactions 2–3–4 caused by climate fluctuations and 5–6 caused by market behavior.

Visser et al., 2005). In turn, as the plant stock diminishes and soil erosion increases, the ability of the remaining soil to sustain and supply nutrients to plants feeds back into increased vegetation loss which in turn triggers more soil erosion (Toy and Foster, 1998). Grazing accelerates this feedback loop by removing a part of the plant stock, reducing the amounts of standing vegetation and of dead plant material that flows back to soil reconstruction and maintenance (Schnabel et al., 2001; Rice and Owensky, 2001). In semiarid areas like Patagonia, the seasonal renewal of forage stocks is strongly dependent on the extremely variable precipitation regime characteristic of semi-arid lands (Le Houérou et al., 1988).

A second interacting feedback loop occurs between the sheep and forage stocks, which can be depicted through a usual consumer-resource cycle. In such a system a population of organisms exploits a flow of energy, a detritus stock or another population (Getz, 1999). This latter case corresponds to the interaction of sheep and forage, where the consumer acts upon the rate of forage disappearance and the available forage stock acts upon the rates of consumer re-population and/or survival.

A further element to be considered in the analysis of the Patagonian pastoral system is the mechanism through which the exchange value (Stahel, 2005) of wool is established. Depending on the quality and amount of their wool production, ranchers can attend local, regional or international (La Torraca and Aguirre, 2002) markets. Local and regional prices are significantly tied to the dynamics of the wool international market, which shows short and long memory features and fractional orders of integration (Witherell, 1968; Barkoulas et al., 1999). The international supply-demand balance depends on the behavior of large international buyers acting within a periphery of smaller, relatively high-cost buyers (Simmons and Hansen, 1998). The realized price obtained by ranchers at each production cycle back-feeds into decisions about maintaining, increasing, or reducing the sheep stock to be kept in the wool production system for the next year. Reinvestment in the forage capital stock (i.e. using a fraction of the obtained yearly net revenues to buy forage or enhance forage production) is not usually considered under extensive conditions.

The time scale at which perturbations of these processes are propagated into the wool production system is comparable to human generation times (20-30 years). The relevance of this time scale is further supported by observations of the slow recovery of land areas where sheep husbandry has been eventually abandoned during long periods in eastern Patagonia (Bisigato et al., 2002), or in areas intentionally excluded from sheep access during several decades in central-west areas (Soriano et al., 1980). The context underlying such time scale poses questions of intergenerational transfer of NC losses and eventual responsibilities in investment aiming to their restoration.

2.2. *Identification and system formulation*

The Patagonian pastoral system is modeled in terms of four composing subsystems:

1. The sheep stock
2. The forage stock.
3. The soil stock.
4. The market system (Fig. 2)

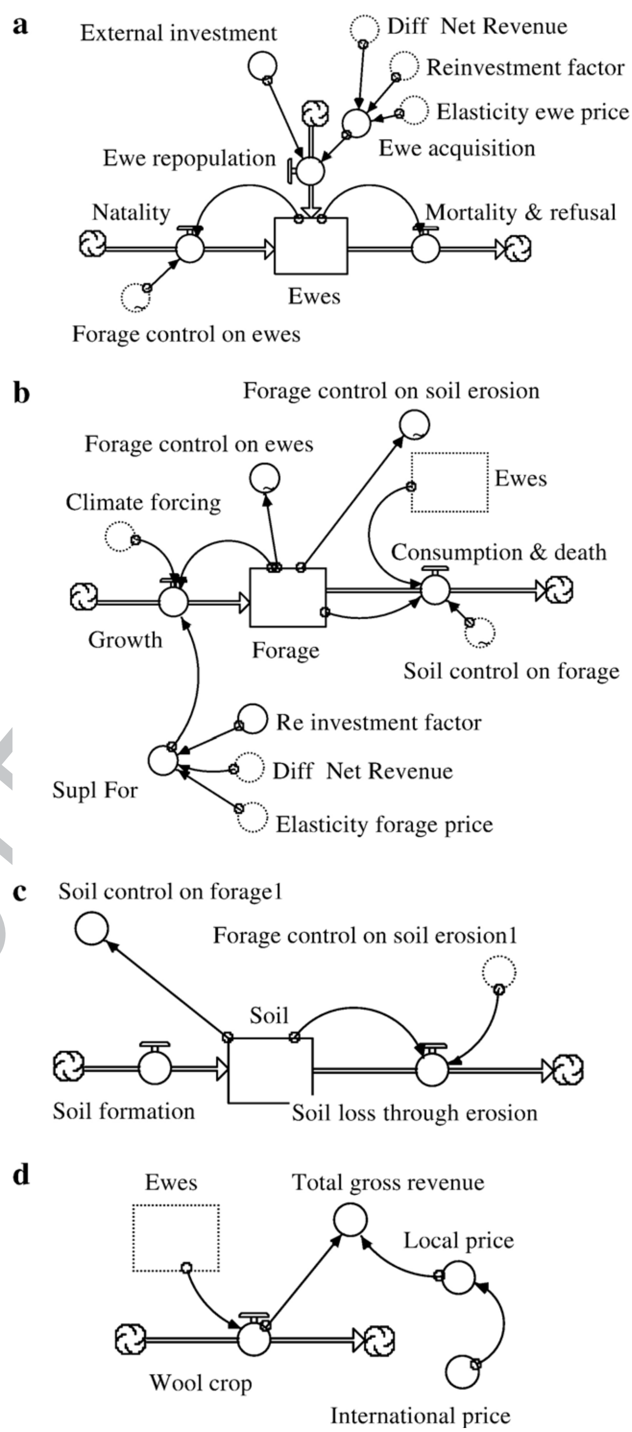


Fig. 2 – The subsystems of the Patagonian pastoral system as depicted in the object-oriented simulation language Stella. Boxes represent stocks, thick arrows are annual flows. Thin arrows represent controls and clouds represent the boundary conditions. (a) The ewe stock. (b) The forage stock. (c) The soil stock. (d) The market system. Symbols printed in dotted lines are shared by two or more subsystems. See text for details on components and parameters and Box 1 for the homologous system of differential equations.

For convenience, the sheep stock dynamics is traced in this study through the number of ewes, since male lambs are mostly excluded from the wool production system except for a reduced number of them kept for reproductive use (Fig. 2a). Increases in this stock through ewe natality are regulated by the availability of forage ("Forage Control on Ewes"), and stock decreases occur according to characteristic mortality and/or discard rates decided by the rancher ("Mortality and Refusal"). Ewes can also be imported and added to the stock ("Ewe repopulation") through re-investment of a fraction of locally obtained revenues ("Diff.(erential) Net Revenue") or acquisition with external funding ("External Investment").

The forage stock (Fig. 2b) represents the amount of native plant biomass foraged by sheep. Forage stocks increase through growth conditioned by climate forcing and decreases through consumption by ewes and death of plant material. About 55% of the forage stock renewal is estimated to be consumed by sheep at stationary ewe/forage stock ratios (Lauenroth, 1998), the consumption term increasing/decreasing proportional to the size of the ewe stock. The size of the forage stock exerts controls on the natality flow of ewes (Dunn and Kaltenbach, 1980) and on the amount of soil loss through erosion. The function describing this latter effect reproduces basic concepts in rangeland soil conservation as advanced by the Task Group on Unity in Concepts and Terminology (Smith et al., 1995). In this context, the effect of a protective plant cover on the magnitude of soil erosion losses is described as a sigmoidal functional relation, such that its maximum derivative occurs at a point defined as a Site Conservation Threshold (SCT). Forage death is also controlled by the stock of soil ("Soil control on forage", see also Fig. 1b). Controls exerted by the forage stock on the ewes and on the erosion of the soil stock reflect the stochastic nature of forage growth as controlled by climate forcing. Supplementary forage ("Supl.For.)" can also be imported and added to the stock through re-investment of a fraction of locally obtained revenues ("Diff.(erential) Net Revenue") or the acquisition of forage from external sources ("ExtInvestForage").

The soil stock (Fig. 2c) represents the relative depth of the top soil horizon capable of sustaining plant growth. Erosion ("Soil loss through erosion"), produces soil losses depending on the amount of protective cover supplied by the forage stock ("Forage control on soil erosion"). The soil stock exerts control on forage death (see above). Annual increases in the soil stock through the process of soil formation are assumed constant during the simulation time, at an annual rate that compensates soil erosion losses at maximum forage stock level.

The market system sets prices to the annual flow of wool crop (Fig. 2d) and generates Total Gross Revenues (*TGR*). The wool crop flow depends on the size of the ewe stock. After deduction of production costs, a variable fraction of the total net revenue can be re-invested in retaining a fraction of the ewe stock, a circumstance which amounts to an internal ewe acquisition (Fig. 2a). Also, re-investment in additions to the Forage stock is possible, as explained above (Fig. 2b).

Valuing of forage and soil NC is a central concept in this study and was attained through an extended ecological pricing method (Patterson et al., 2005) where the annual *TGR* during a production cycle were related to the simultaneously occurring forage and soil depth losses by means of elasticity functions:

$$e_{forage} = \mathrm{TRG}/\sum F_{losses} \tag{1}$$

$$e_{soil} = \mathrm{TRG}/\sum S_{losses} \tag{2}$$

where *TGR* is expressed in monetary units and $\sum F_{losses}$, $\sum S_{losses}$ are the annual losses of forage stock due to consumption by ewes and plant senescence, and the soil erosion losses.

Stochasticity is introduced in the model in order to simulate the effect of climate (Fig. 2b) on forage growth and the fluctuations of international prices of wool (Fig. 3d) on the *TGRs*. A Probability Distribution Function (PDF) of annual average forage growth flows was based on estimates obtained with the Century v.5 model (Parton et al., 1993) with parameters corresponding to the Patagonian Monte and centennial climate series compiled by Mitchell et al. (2003). Annual average wool prices were assumed to be normally distributed with mean and standard deviation as on records for the 20μ-Merino wool class at the Northern and Southern Australian wool market (Landmark Operations Limited Inc., ABN, Australia). Box 1 shows the model equation system homologous to the diagrams in Fig. 2 as well as the model parameters and controlling functions.

2.3. *Financial analysis of investment alternatives*

This was attained by computing the Net Cash Flows (Π) obtained after investment on replenishment of some or several components of the NC. In order to evaluate investment policies, differences between Total Gross Revenues (*TGR*) were estimated by comparing the behavior of the system with and without a principal investment on the ewe stock. Natural capital costs considered were those corresponding to ewes,

Box 1
Model equation system

$$\mathrm{d}E/\mathrm{d}t = f_1(F)E + Ei + Er - a_1E$$

$$\mathrm{d}F/\mathrm{d}t = a_2F + Fr + Fe - a_3E - a_4F - f(S)F$$

$$\mathrm{d}S/\mathrm{d}t = a_5 - f_2(F)S$$

1. **Stocks**
   E: ewes; *F*: Forage; *S*: soil
2. **Investment flows**
   Ei: Ewe repopulation through external investment
   Er: Ewe repopulation through internal re-investment
   Fr: Forage reposition through internal re-investment
   Fe: Forage reposition through external investment
3. **Parameters, control functions**
   a_1: mortality and refusal rate of ewes
   a_2: growth rate of forage plants, stochastic
   a_3: rate of forage consumption by ewes
   a_4: rate of death of forage plants
   a_5: rate of soil reconstruction
   a_6: rate of wool production per ewe
   $f_1(F)$: function of *F* controlling ewes' natality rate
   $f_2(F)$: function of *F* controlling soil erosion rate
   $f(S)$: Function of *S* controlling *F* death rate

forage and soil stocks and their values were estimated at each annual period by multiplying their *TGR* elasticity (as in eqs. 1-2) by the change in their stocks caused by the propagation of the investment effects. Variable costs considered were those due to sanitary care of the flock, shearing and administrative costs as obtained from recent local sources. Investment alternatives were compared through the Present Values (*PV*) (Park, 1993) of Π during *i* years while $\Pi>0$, at δ discount rate:

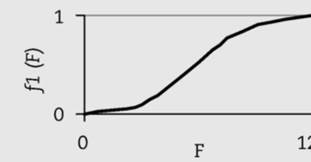
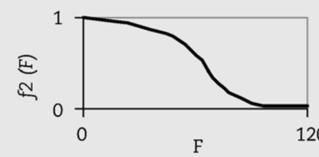
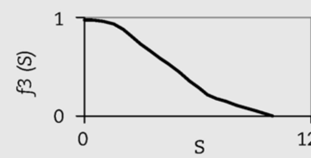
$$PV = \int_{t=0}^{t=i} e^{-\delta t} \Pi(E,F,S,t)dt \qquad (3)$$

Confidence intervals of *PV* estimates were obtained from 50 realizations of the stochastic model corresponding to each investment alternative. Box 2 presents a summary of the variables used for the financial analysis of investment alternatives, elasticity pricing of NC, capital and variable production costs and Net Cash Flow equations used in this study.

2.4. *Model calibration. System behavior without investment*

The model stocks were initialized at a value=100 to ease comparisons of percentile changes. Parameters and control functions (Table 1) were tuned through inverse modeling to produce a behavior under non-investment corresponding to the conditions prevailing during the last decades at the Patagonian pastoral systems, as described in the introductory section. These implied the stock of ewes to decrease at a rate of 1-1.5% /year, the forage stock at 0.1-0.2% year and the soil stock at 0.4-0.8% / year. Higher rates (1-5%/year) of reduction in the forage stock occur during periods of unfavorable climate but recover during favorable periods. During periods of forage depletion, losses of the soil stock can also increase. Replacement of the soil stock occurs at a slow rate, thus resulting in progressive slow, net losses of soil (Fig. 3).

Table 1 – Parameter and functional values used to calibrate the model of the Patagonian pastoral system to observed trends in regional natural capitals (see also Section 1.2, Boxes 1–2)

Parameter, function	Value (s)	Units
a_1	20	%E / year
a_2	rdm[1] (0.01, 0.01)	% F/ year
a_3	0.0055	% F/ year
a_4	0.0045	% F/ year
a_5	2.7	% S/ year
a_6	2.5	kg/E
f_1 (F)	 $y = 1/(1+76.4\,e^{0.08\,x})$	
f_2 (F)	 $y = 1-(1/(1+240.6\,e^{0.09\,x}))$	
f_3 (S)	 $y = 1-(1/(1+26.2\,e^{0.08\,x}))$	
LP[2]	rdm (0.6, 0.1) x rdm (6.18, 1.0)	u$/kg

[1] rdm (a, b): random distribution, with mean a and standard deviation b.
[2] Local prices assumed as a random fraction of random international prices.

Box 2
Financial analysis

1. **Gross revenues**
   $TGR_{w,\,wo}$: Annual total gross revenue (u$), with ($_w$) or without ($_{wo}$) investment
   LP: local price of wool, stochastic (u$/kg)
   $TGR_{w,\,wo} = a_6 E_{w,\,wo} LP$
2. **Elasticity price of natural capitals**
   $e_{ewes} = TGR_w / a_1 E_w$
   $e_{forage} = TGR_w / (a_3 E_w - a_4 F_w - f(S) F_w)$
   $e_{soil} = TGR_w / f_2(F_w) S$
3. **Capital and variable production costs**
   $CC_E = e_{ewes}(E_w - E_{wo})$
   $CC_F = e_{forage}(F_w - F_{wo})$
   $CC_S = e_{soil}(S_w - S_{wo})$
   C_{ss} = sanitary care and shearing costs
   C_t = technical assistance and personal costs
   $PC_{w,\,wo} = C_{ss} E_{w,\,wo} + C_t$
4. **Cash flow attributable to investment**
   $\Pi = (TGR_w - PC_w) - (TGR_{wo} - PC_{wo}) - (CC_E + CC_F + CC_S)$

3. Results

3.1. *Answering questions on sustainability of investment in the Patagonian pastoral systems*

Consider a Patagonian rancher behaving as a monopolist agent (Millner-Gulland, 1999) seeking to maximize the present value (*PV*) of investments on a wool production system, over the shortest possible time period, such that

$$O = \{\max PV(i)\}, \text{subject to } PV>0 \qquad (4)$$

Let the principal investment be in acquiring ewes to increase the current stock by 20%, at δ=5%. For a current stock of 100 ewes, let us assume that such an investment would amount to u$ 60. After the investment, the system would experience related decreases in the forage and soil stocks, subject to climate fluctuations (Fig. 4a). These changes would be reflected in TGR_w changes with respect to the baseline condition (without investment) during a number of years.

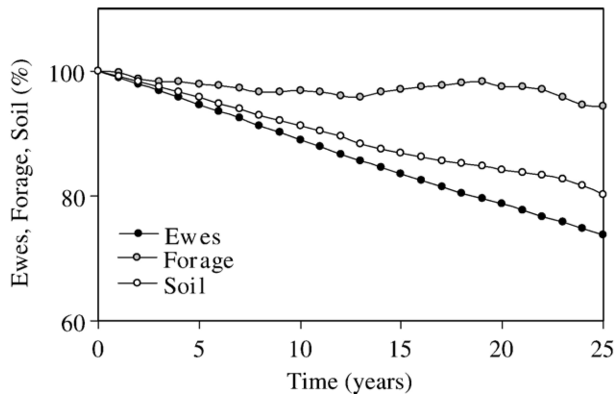


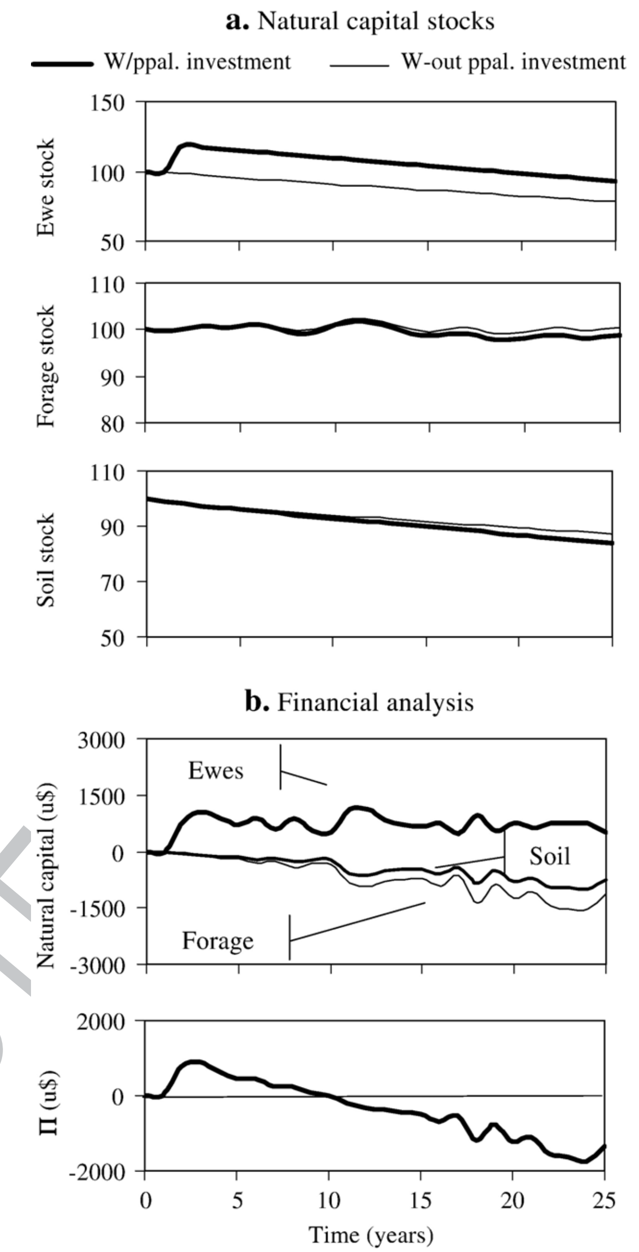
Fig. 3 – Baseline behavior of the model of the Patagonian pastoral system without investment (also see Table 1). A continuous decline in the stock of ewes occurs (about 25% in 25 years). Soil erosion losses occur and the soil stock declines during periods of low forage growth due to adverse climate variation, and slowly recovers during periods of increased forage growth. Baseline behavior would represent average presently prevailing regional conditions.

Given the trends described in Section 1.2, at about year 25 after the principal investment, the decay experienced by the ewe stock would reach again the value at pre-investment time, although the stock level would still be higher than what would be expected without investment.

A typical Π sequence that would consider the values of gains and losses in the NC would show positive values at the beginning of the investment cycle, when revenues obtained through wool sales would exceed the losses experienced by NC. Negative values would however occur at the end of the cycle as this balance is reversed (Fig. 4b). Let the result of the investment be inspected at year 8, before Π becomes negative, and consider the average PV over 50 realizations of the model in order to account for stochastic market and climate variation. The average PV would be expected to be u$ 16.41 (maximum = u$ 31.81; minimum: u$ 2.54).

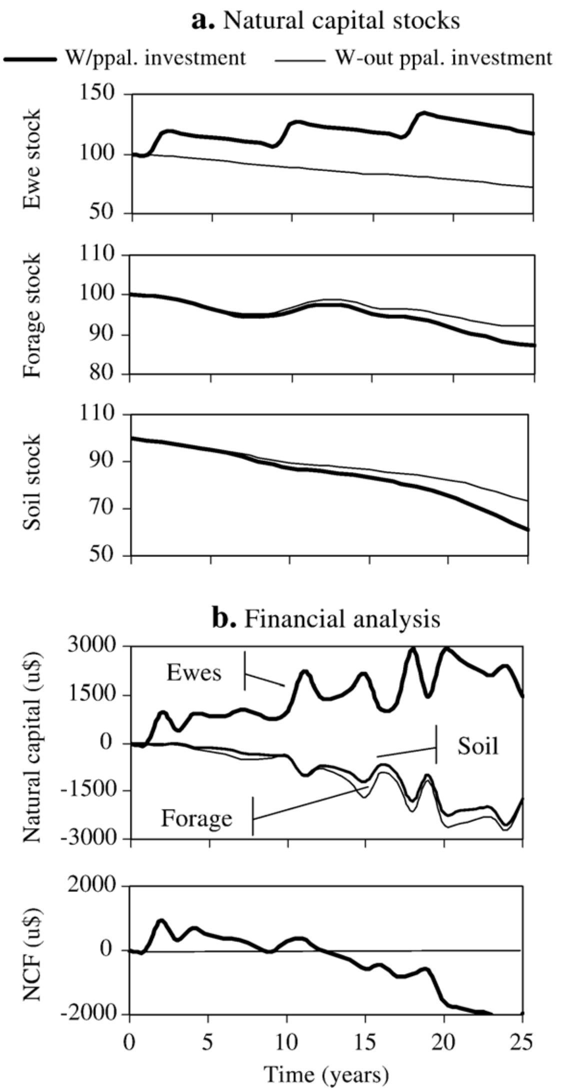
In order to satisfy the rancher's objective function, it would seem reasonable to repeat the principal investment every 8 years, in order to generate similar cycles of positive Π sequences. This proves however impossible, since the decreased levels of the NC Forage and Soil are not sufficient to supply the required inputs to the production system. As a consequence of this, the next investment cycle produces lower positive Π during only 4 years, and a third cycle yields all negative Π values (Fig. 5).

It is important to note that even in this latter case a rancher that would not incorporate NC losses into the computation of Π, would keep experiencing net revenue gains with respect to a non-investment situation, due to increased wool sales respect to the non-investment condition (Fig. 6). The resulting scenario would thus correspond to the paradigm of a "dumb farmer's" assumption (Berndt et al., 1981), where adaptive actions are assumed away while NC losses occur during a productive process (Kelly et al., 2005). Since this situation would develop at a comparatively low pace in relation to the rancher's generation time, it is likely that the depletion of NC would remain unnoticed and adaptive actions would tend to be delayed or transferred to the following generation.



	PV
	Years 1-8
Average (50)	16.41
Standard deviation	6.39
Minimum	2.54
Maximum	31.81

Fig. 4 – Investment on the stock of ewes at the Patagonian pastoral systems. (a) An initial investment aimed to produce a 20% increase in the stock of ewes is simulated and compared with the baseline condition (without investment). The stock increases due to the investment, then declines gradually and reaches the initial level after about 25 years. Incremental declines in the stocks of forage and soils also occur. (b) The balance between the stock of the ewes, Forage and Soil natural capitals render Net Cash Flows (Π) increasingly negative. The Net Present Value of the investment is moderately favorable during the first 8 years after the investment.



	PV		
	Years 1-8	*Years 9-16*	*Years 17-21*
Average (50)	17.40	14.28	-23.22
Standard deviation	5.60	5.96	7.91
Minimum	3.28	3.21	-42.67
Maximum	28.57	27.63	-9.70

Fig. 5 – Investment on stocks of ewes at the Patagonian pastoral system. (a) An initial investment aimed to produce a 20% increase in the stock is repeated at 8 year intervals in an attempt to generate sustained positive net cash flows along time. The stock of ewes is maintained and even increases after a 25 year period, but the loss of the natural capitals Forage and Soil becomes steeper than in the case shown in Fig. 4. As a consequence of higher capital losses, the PV of successive investments is gradually lower and investing is no longer profitable after year 14.

3.2. *Seeking sustainability: alternative investment policies*

Since the decay in the forage and soil stocks limit the length of periods during which $\Pi>0$, it seems reasonable to explore investment policies that would result in replenishing/recovering the losses. Recovery of the soil stock is an inherently slow process, and therefore practical considerations would emphasize considering investments in supplementary forage stocks instead. We consider two alternative policies. a: Annual re-investment of a fraction (0.20) of TGR_w to acquire additional forage stock; b: Periodic (4-year intervals) external investments on the acquisition of supplementary forage stocks.

Alternative a. produces a slight lengthening of the period of prevailing positive Π with *PV* (non-significantly) higher than in the case with no re-investment in forage stocks (Fig. 7, compare with Fig. 5b). Alternative b. works considerably better than those, provided the ratio (External investment in *F*):(Investment in *E*)≈16:1, yielding sustained positive Π during 25 years, and higher *PV* than in the former alternatives. *F* and *S* stocks are conserved during the whole investment period, satisfying both economic and ecological sustainability.

3.3. *Other investment alternatives*

The model could reproduce the effect of other types of alternatives among those common of range science. Since the outcomes of those can to a considerable extent be inferred from the analysis of the model structure and the performance of the cases described above, only a short mention to them will be here made.

A reduction of ewe stocking rates releases the consumption of forage (see term a_3E, Box 1) but also reduces *TGR*. Since the value of NC is formulated in terms of *TGR* elasticities, the net outcome is a temporary reduction in the profitability of the wool business. This is a rather trivial case because a reduction in the number of ewes reduces the amount of wool production (however not in a linear fashion) and hence the length of the period of positive net cash flows, very much in the same way as it happens in real situations.

In humid and sub-humid climates, forage production is usually incremented through fertilization and/or irrigation.

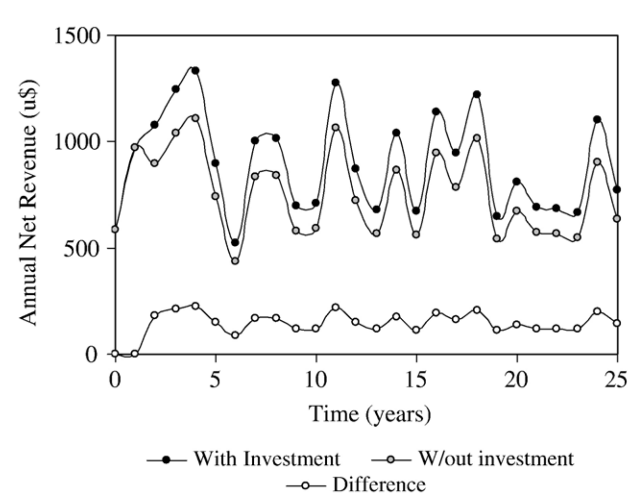
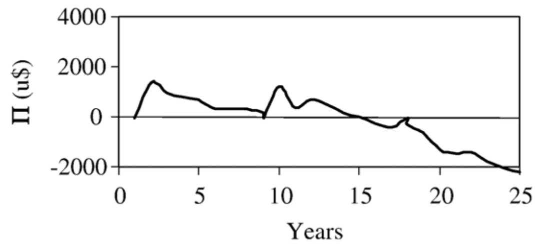


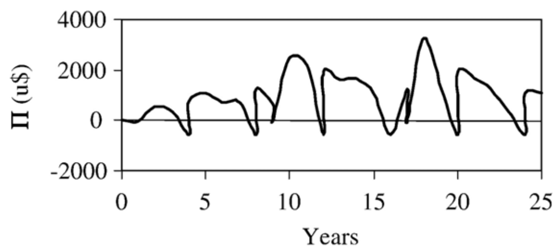
Fig. 6 – Annual revenues in the wool production system as in Fig. 5. The rancher keeps experiencing positive net revenues even in a scenario of gradual depletion of natural capitals and finds no incentive to seek alternative investment policies during periods as long as human's generation time.

a



	PV		
	Years 1-8	Years 9-13	Years 14-18
Average (50)	19.09	17.62	-17.52
Standard deviation	6.42	5.92	8.39
Minimum	6.19	6.62	-54.47
Maximum	36.54	37.83	-2.88

b



	PV		
	Years 1-8	Years 9-17	Years 18-25
Average (50)	16.67	44.41	49.06
Standard deviation	6.38	13.75	21.63
Minimum	4.68	14.78	10.51
Maximum	34.43	67.97	111.15

Fig. 7 – Statistics of PV of cash flows (modal graphs shown) of 50 stochastic realizations with the Patagonian wool production model, assuming additions investments to a main external investment to increase the stock of ewes by 20% every 8 years, a: 20% of the obtained TGR is annually re-invested in the acquisition of additional forage stocks; b: external investments are made every 4 years in a proportion 16:1 with respect to those in the stock of ewes, to acquire external forage stocks. PVs correspond to periods with positive cash flows.

The model could simulate such type of investments, by adequate re-definition of the parameter a_2, provided field experimentation were available to relate amounts of fertilizer–water to increments in forage growth rate. Such information does not exist in the case of most Patagonian steppes, and expert knowledge based on local experience and results obtained in other semiarid lands indicates that this is not a feasible alternative.

The amount of wool production and–or its quality could be increased by investing on improving the genetic quality of ewes, hence increasing their forage/wool conversion, development rate, etc. In the model, such type of investment can be simulated through adequate calibration of the function f_1E (the forage/ewe conversion function) and–or the linear function relating the number of ewes and the amount of wool produced (see Fig. 2e). Combinations of this type of investment with that in Fig. 7b would yield high levels of profitability.

4. Conclusions

4.1. *Lessons from the Patagonian case: directing investment to ecologically meaningful components of the productive system*

The conceptual model presented in this study addresses the modal traits of interactions prevailing in Patagonian wool production systems. Conclusions that can be drawn from it are of a semi-quantitative nature, embodying the major recognized factors influencing the performance of those systems. In its present form, it has been tuned to reproduce the regional trends of NC depletion estimated to have occurred during the last 4–6 decades. By changing the adequate parameters (see Box 1), the model can be tuned to simulate varying conditions of land quality, forage availability, soil fertility, ewe mortality and–or wool quality.

The major findings of this research are as follows. First, we identified the relative magnitudes of forage and soil NC losses in extensive wool production systems of Patagonia. The results indicate that these have a major effect on the economic sustainability of wool production. The effects can counteract those of traditional investment policies on to increasing the ewe stock to compensate flock losses due to decreasing carrying capacity of the pastoral lands. Elasticities of the TGR_w with respect to forage and soil capital components are about one order of magnitude greater than that respect to ewe capital. Consequently, equilibrated investment in maintaining the NC needed in the production system requires nearly 10/20-fold greater investment amounts in forage-soil with respect to those in ewes. Direct investment in soil capital seems impractical because of the long turnover time of this type of NC. Opportune investment (in time and quantity) in the forage stock would produce sustained periods with positive net revenue returns.

Second, re-investing a fraction of the TGR_w obtained through increasing the ewe stock in replenishing the forage stock does not seem a feasible alternative. The high ratio of forage to ewes investment needed to compensate their relative capital losses cannot be attained without severely limiting the Π of the productive system. Although minor improvements (like a moderate lengthening of the time during which positive Π can be realized) in the business cycle can occur at relative high (20% of TGR_W) re-investment rates, increasing this amount simultaneously reduces the positive Π values and reduces PV values below the acceptance threshold ($PV>0$). Alternatively, external investment on forage stocks at sufficiently high rates produces sustained PVs along extended (>25 year) business cycles. These results contradict common knowledge prevailing about Patagonian pastoral systems, which assumes direct investment on ewe capital as a feasible alternative to improve their economic performance.

4.2. *Further lessons from the Patagonian case: systems modeling of productive processes involving natural capital and feed-back controls*

Some of the basic mechanisms of the development of Patagonian wool production into non-sustainable systems have also been identified in other pastoral areas of the world, and their analysis allows some generalizations. Gardener et al.

(1990) reports that cattle stock numbers in Queensland (Australia) were during several decades largely restricted by environmental limits, particularly low herbage quality. As in Patagonia, the paradigm to improve economic productivity of grazing systems in Australia after 1980 relied on increasing the stock numbers, with the consequent deterioration of the forage and soil resources (MacLeod and McIvor, in press).

The reasons why ranchers in Patagonia and elsewhere might prefer investing in increasing the flock stocks instead of doing so in the forage capital seem complex, and probably tied to socio-cultural traits. Studies on other extensive pastoral systems give some cues about those. Results of a wide survey involving several provinces in Mongolia (Lise et al., in press) indicated that some herders ranked the perception of the quality of the environment second after a security factor, while some others would rank it first. Other herders adopted a reverse assurance game in choosing the growth of the flock size as a means to improve their enterprises. Choices vary from region to region and depended on the size of the production systems. Alternatively, in grazing systems with access to broad markets, the sophistication of market demands and mechanisms, requiring managers to devote increasing attention to quality specifications and quality control systems might also result in less managerial attention been paid to monitoring environmental trends (MacLeod and McIvor, in press). Since pastoral systems are extended over vast surfaces of the world, it might be technically or economically impossible to repair NC degradation once it has occurred, and their effect on future generations raises complex issues of intergenerational equity (Common and Stagl, 2005).

The experience on inducing the adoption of ecologically-oriented management of pastoral systems shows that economic reasons, inconsistency with adopted commercial practice and equity arguments are usually raised as barriers (Green and MacLeod, 2002), although these are not the only reasons invoked. In Argentina, the promotion of the wool production industry is of national interest, and public resources are assigned under previsions of National Law #25422 (Ovine Law) to help finance the recovery of physical and NC losses in the pastoral systems, including those in the Patagonian region. Orienting financial support to the restoration of the NC involved in the production of wool with due attention to the ecological mechanisms operating in the pastoral systems, can be a powerful means to overcome adoption barriers to sustainable management.

4.3. *Issues related to intergenerational transfer of losses in natural capital*

In a previous section, an explanation was advanced to account for the occurrence of eventual intergenerational transfers of NC losses when assuming away their occurrence. The foregoing analyses raises two further issues:

1. Present Patagonian ranchers operate productive systems that experienced significant losses of NC during past decades. External investment on forage stocks might be needed to solve a production scenario where the PV of investment could not be sustained while NC are progressively recovered during the next few decades. On grounds of pursuing intergenerational equity, society as a whole should undertake the task of starting the recovery of past losses of NC and reducing further transfers of them to coming generations.
2. Investment policies centered on maintaining/enlarging the sheep stock, preventing the action of predators on sheep flocks, etc., without simultaneously increasing the sustaining forage stock are deemed to failure and further transfer of losses ahead in time. It is important to note that investment on the forage capital must be external to the present production systems, since internal re-investment might not suffice to attain the needed recovery while maintaining an acceptable value of the rancher's objective function.

Acknowledgments

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