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Sustainability and range management in the Patagonian steppes*

Rodolfo A. Golluscio, V. Alejandro Deregibus[1] and José M. Paruelo
IFEVA, Departments of Ecology and Plant Production (1), Faculty of Agronomy, University of Buenos Aires, Av. San Martin 4457, 1417 Buenos Aires, Argentina.

Abstract. *One hundred years of grazing by domestic herbivores hampered the ecological sustainability of the Patagonian steppes. We propose three management-related factors of such ecosystem degradation: (1) overestimation of carrying capacity of the rangelands, (2) inadequate distribution of animals in very large, heterogeneous paddocks, and (3) year-long continuous grazing. We suggest that these three management factors interact with the highly selective grazing habit of sheep generating a pattern of grazing heterogeneity at three scales: landscape, community, and population. Grazing differs in intensity among areas of the same paddock, among plant species, and even among individuals of the same species. As a consequence, the most palatable species within a patch are almost continuously subjected to a very high frequency of defoliation in the most preferred areas, which increases the mortality of the most preferred individuals of these forage species. We review the available ecological knowledge and range management technologies that may contribute to revert degradation. A quick assessment of both the availability and spatial heterogeneity of forage resources is now possible with the aid of remote sensing. Range assessment will allow to estimate the carrying capacity of each paddock, and separate different vegetation units. From information on the phenology of the different vegetation units it is possible to decide the timing of grazing and/or resting periods of single paddocks. Rotational grazing methods allow for a recovery of the most preferred species and for a reduction of the heterogeneity of defoliation at the three mentioned levels. Research efforts are needed to develop warning systems, improve the productivity and use efficiency of meadows, and design and evaluate grazing methods for the most arid areas of the region.*

Introduction

By the time G. Musters traveled across Patagonia horses were the only domestic herbivores (Musters 1871). Aborigine economy was almost exclusively based on gathering and on hunting wild animals (guanaco, ñandú, piche, fishes, birds, etc.). The European colonization of inland Patagonia started at the end of the 19th century, and by the beginning of the 20th century the whole region was devoted to the sheep industry. Native rangelands were, and still are, almost the exclusive source of forage for sheep (Soriano and Paruelo 1990). Grazing has been identified as one of the main causes of ecosystem degradation, a process that hamper the sustainability of the region (Borelli et al. 1984, León and Aguiar 1985, Soriano and Movia 1986, Paruelo and Sala 1992 [Appendix 2]† , Paruelo et al. 1993a [Appendix 2]). However, the mechanisms underlying the causal relationship between grazing and degradation are not yet clear.

The objectives of this article are (1) to suggest some explanations to the degradative effects of sheep grazing on the Patagonian ecosystems, (2) to analyze the ability of available technologies to offset the degradative effects of grazing, (3) to discuss some experiences of range management that

* Spanish version available on request.
† Appendix 2 is a list of supplementary references not published in formal books or journals.

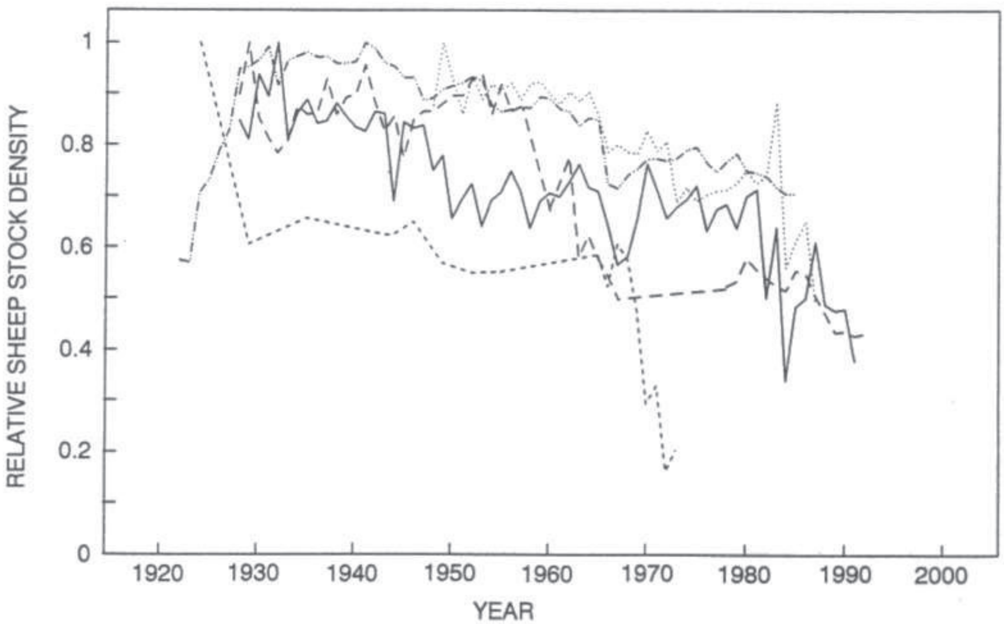

Figure 1. Sheep stock density variation in different ranches of Patagonia: Estancia Pilcañeu (____), Estancia San Ramón (__ __ __), Estancia Montoso (........), Estancia Alicura (_ _ _ _), and Estancia Leleque (_.._.._.._). For each ranch, the relative stock density was calculated as the ratio between the stocking density of each year and the maximum stocking density of the historical record. Data correspond to the sheep stock at shearing. Historical data of cow density were not available, but ranch managers consider it very low as to modify the trends.

incorporate these technologies, and (4) to analyze the constraints that prevent the diffusion of these practices.

The problem

We propose that the central problem for animal husbandry in Patagonia is that it is becoming a non-sustainable activity in wide areas. Patagonian sheep population has declined over the last decades from 20 million in 1952 to 11 million in 1993 (Soriano and Movia 1986, Paruelo and Sala 1992, Sancholuz and Chaia 1993, Encuesta Nacional Agropecuaria 1993). This regional pattern of stock reduction closely followed the trend at the individual ranch scale (Paruelo et al. 1992, Golluscio et al. 1998) (Figure 1). Such reduction in sheep density is generally associated to low lamb marking indexes and/or high mortality rates (Golluscio et al. 1998). Therefore, the reduction in livestock numbers is not a voluntary decision of ranchers, but a consequence of the population dynamics of flocks. Degradation of forage resources appears as the main cause of the low or negative growth rate of Patagonian sheep populations (Soriano and Movia 1986, Golluscio and Mercau 1995, Golluscio et al. 1998).

The degradation of forage resources reduces the ecological sustainability of sheep husbandry in Patagonia by reducing ecosystem carrying capacity. However, sustainability also has economic and social dimensions (Barbier 1987, Lowrance 1990). During the last three decades, wool prices declined at a rate not matched by a similar decrease in production costs (Román 1993 [Appendix 2]). The combination of biological degradation and unfavorable economic context makes animal husbandry a non sustainable activity in most Patagonian ranches. In this paper, we will focus on the biological aspect of the problem by reviewing the available techniques that could allow to control the negative impact of sheep grazing on vegetation.

Hypothetical causes of the problem

We propose that the main biological cause of rangeland degradation is that sheep foraging behavior is highly selective at different scales. This assumption is based on our experience and scarce experimental evidence. At the landscape scale, sheep clearly prefer meadows, locally named "mallines" or "vegas". Somlo et al. (1986 [Appendix 2]) reported that the frequency of meadow species (*Juncus balticus* and *Cyperus sp.*) in sheep diet was higher (from 9% in winter to 61% in spring) than the area covered by these meadows on the entire paddock (3 %). At the community scale, sheep prefer grass species currently considered as highly productive, palatable, and mesophytic (*Poa* spp., *Bromus* spp., *Hordeum* spp., etc.). These are a minor component of the arid and semiarid steppes (Woolfolk 1955, Soriano 1956a, Boelcke 1957, Amigo 1965, Huss 1973 [Appendix 2]). Sheep preference for these grasses is associated to their relatively high protein content and digestibility (Somlo et al. 1985). A reanalysis of aboveground net primary productivity (ANPP) and diet data for grazed and ungrazed areas shows that "mesophytic" grasses accounted for 23% of total biomass in pastures grazed by domestic herbivores and for 42% after three years of exclosure (calculated from Soriano et al. 1976). They accounted for 66% and 29% of the diet, but for only 12% and 1.7% of the vegetation cover in good and poor condition pastures, respectively (calculated from Bonvisutto et al. 1980 [Appendix 2], 1984 [Appendix 2]). In steppes of Tierra del Fuego, "mesophytic" grasses (*Poa* spp. and *Deschampsia* spp.) are also more frequent in the diet of sheep and llama than in the plant communities (Posse et al. 1996, Posse and Livraghi 1997). At a population scale, the intensity of grazing differs among individuals of the same species growing within the same patch. This heterogeneity is associated to the structure of the tussocks, because the amount of standing dead material or flowering culms reduce sheep preference for a given tussock (Westoby 1979/80, Briske 1991, Stuth 1991). As a consequence, a positive feedback exists: grazed tussocks have a more attractive structure than ungrazed ones (Paruelo et al. 1992).

In areas where the dominant species are preferred by sheep (mesic grass steppes or meadows), grazing induces major changes in community structure and functioning. In the *Festuca pallescens* steppes of Western Patagonia, long term grazing was associated to a shrub encroachment process (León and Aguiar 1985). This increase in the relative abundance of shrubs would reduce ANPP and have a major impact on the carrying capacity of the steppe (Aguiar et al. 1996). Meadows also experience structural changes under overgrazing conditions (Del Valle 1993 [Appendix 2]). These changes are similar to those described for many other humid grasslands: grazing increases the abundance of planophyle dicotyledonous species and concentrates the biomass in the lower strata of the canopy (Sala 1988). As the adaptation to drought would act as an exaptation to grazing (Coughenour 1985, Milchunas et al. 1988), the susceptibility of plant communities to grazing would decrease towards the most xeric steppes of Central and Eastern Patagonia. Supporting these ideas, the impact of grazing on the structure of grass-shrub steppes of the Occidental District, where palatable grasses are a minor component of the community, is lower than in the more humid grass steppes of the Subandean District (Golluscio and Mercau 1995, Perelman et al. 1997).

We propose three management factors related to the impact of grazing on the Patagonian rangelands, which interact sinergically with the high sheep selectivity, accelerating ecosystem degradation. This catalogue of factors is based on our experience and knowledge of Patagonian rangelands, but not in experimental results, because rigorous experimentation on range management is almost absent in Patagonia. The first factor is *the overestimation of the carrying capacity of rangelands.* Stocking density was usually decided through "trial and error" procedures (Soriano and Paruelo 1990). The most common strategy was to assign a certain number of sheep and continuously graze a given paddock throughout the year. Stock numbers were adjusted according to lamb marking rates, wool production and/or sheep body condition at shearing. The available records of stocking densities at the ranch level suggest that initial settlers estimated the carrying capacity of Patagonian rangelands as very higher than the actual ones.

In spite of the structural and functional changes generated on the ecosystems by the original decisions on stocking density, rangeland carrying capacity is still closely related to the cover of preferred grass species or plant communities in the paddock. Cingolani et al. (1998) reported that the stocking density at the paddock level in sub-humid areas of Tierra del Fuego, was correlated to *Poa* spp. cover. Similarly, in semiarid steppes, the stocking density was associated with the proportion of meadows in the paddock (Figure 2) (Golluscio and Paruelo pers. com.).

The second management factor is *the inadequate animal distribution in very large and heterogeneous paddocks.* Paddocks have around 2,000 to 5,000 ha (Aguiar et al. 1988 [Appendix 2], Cingolani et al. 1998). They usually include many plant communities, differing in their productivity, seasonal dynamics, and risk of degradation. Continuous grazing of these large paddocks avoid for a differential use of their forage resources and lead to the coexistence of over-and undergrazed areas in the same paddock (Ares et al. 1990). Because drinking water points and refuges against predators or climatic harshness are not homogeneously distributed, often sheep need to travel daily very long distances to graze the extreme of a paddock. For that reason animals tend to stay close to the refuges, or the meadows and other water points, at a density ten to twenty times higher than the average stocking density of the paddock. The distribution of animals become more heterogeneous as paddock size increases. Simulation analysis showed that the spatial heterogeneity of grazing increases drastically the rate of degradation in systems co-dominated by grasses and shrubs (Weber et al. 1998).

The third management-related factor is associated with the seasonal pattern of grazing: *almost all plant communities are continuously grazed all the year-round.* The only exceptions are the extremely cold or dry paddocks, that are used as summer ("veranadas") and winter ("invernadas") paddocks respectively. Under continuous grazing paddock internal heterogeneity would have advantages because animals may graze the different communities along the year, searching for more constant forage availability. However, such management strategy reinforces the overgrazing of some preferred areas and the undergrazing of other.

The three management factors increase the intensity and frequency of the defoliation of palatable grasses of the preferred areas, leading to a loss of vigor and, finally, to the death of individual plants. Defoliated plants have higher leaf photosynthetic capacity and ability to increase the carbon allocation to aboveground parts than undefoliated plants (Detling et al. 1979, Caldwell et al. 1981, Caldwell 1984, Nowak and Caldwell 1984, reviewed in Briske 1991). However, frequent and very intense defoliation events will allow no remnant leaf tissue and cause a severe depletion of "carbohydrate reserves" of palatable tussocks. These reserves are needed to regrowth after the dormant season and for root maintenance (Deregibus et al. 1982, Briske 1991). The continuous allocation of carbon to aboveground parts would reduce the vigor of belowground parts and, eventually, increase water stress, reduce nutrient uptake, and decrease the competitive ability of overgrazed plants. This process would lead to a reduction of vigor of the entire plant and finally to its death. In humid ranges of the Flooding Pampas (Argentina) continuous grazing reduced the average size of tussocks (Sala 1988), the presence of cool season annual forage species, and total plant cover (Deregibus et al. 1995). The mortality induced by grazing is very difficult to revert because regeneration of perennial grasses by seeds is not common in Patagonia (Aguiar et al. 1992, Aguiar and Sala 1994, Bertiller 1992 and 1996, Bertiller et al. 1996).

Summarizing, the traditional management of these ecosystems determines a very intense use of few palatable species and wet sites ("mallines"). The reduction of the cover of palatable species, and the degradation of meadows determine a reduction of the carrying capacity of the steppe that clearly

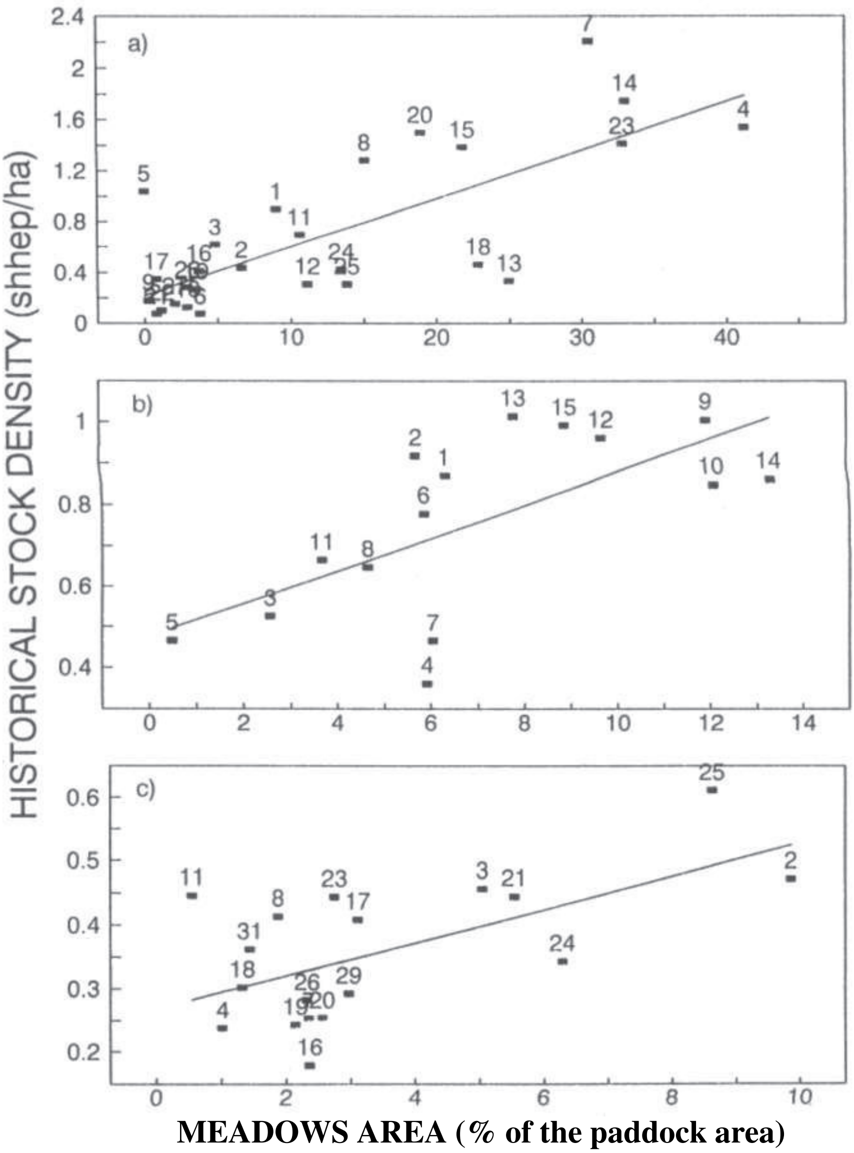

Figure 2. Average historical stocking density of different paddocks as a function of the proportion of the area occupied by meadows. Data from a) Estancia San Ramón (mean annual precipitation= MAP= 638 mm), b) Estancia Pilcañeu (MAP=305 mm), and c) Estancia Alicura (MAP=265 mm). All the linear regressions between historical stock density and proportion of meadows in different paddocks (showed as straight lines) were statistically significant ($p<0.01$). Along the precipitation gradient from c) to a), the maximum meadow proportion found in each ranch and its long term stock density increase.

jeopardize the sustainability of these ecosystems. While the palatable species of the steppe loss vigor and cover, or even disappeared, the meadows show severe deterioration, such as loss of cover, gullies, salinization and dune formation (Del Valle 1993 [Appendix 2]). Fortunately, the populations of shrubs and drought-resistant unpalatable grasses, prevented the complete denudation of these semiarid environments (Lean and Aguiar 1985, Lauenroth 1998). In addition, the existence of undergrazed areas, species and individuals within them allows for the design of management strategies based on a higher efficiency of use of forage resources than the present ones.

Proposed solutions to the problem

Following the general successional model of Dyksterhuis (1958), the reduction of stocking density was seen for many years as the most important tool to recover the degraded rangelands. The assumption was that a reduction of the stocking density would determine a reduction in the frequency of defoliation of palatable plants and in the overgrazing of meadows. The trend of sheep production indexes (lamb marking rate, mortality, etc.) during the last 10-20 years already determined a reduction in stock density (Paruelo and Sala 1992 [Appendix 2]). However, often this reduction did not improve rangeland condition. The lack of recovery of rangelands as a response to a reduction in stocking density may be explained because the reduction in sheep numbers did not cause a similar reduction in the grazing pressure on highly preferred plant individuals, species and/or sites. In addition, the reduction in stocking density did not trigger a recruitment pulse in the most preferred populations.

In this section we outline some technical tools that would need to be incorporated into management strategies to stop, or even to revert, the degradation of rangelands in Patagonia at the population, community, and landscape levels. We will focus on the ecological basis and shortcomings of these tools. The four tools we propose are (1) the identification and mapping of different plant communities, (2) the knowledge of their phenology, (3) the development of objective techniques for carrying capacity estimation, and (4) the implementation of grazing methods confering resting periods to each paddock. The use of those tools would be useful in stopping some of the above outlined problems, as the overestimation of carrying capacity (tool 3), the erroneous utilization of the temporal (tool 2) and spatial heterogeneity (tool 1), and the deletereous effect of continuous grazing on the preferred individuals of the preferred species in the preferred areas (tool 4).

1. Identification and mapping of different plant communities

An adequate description of the heterogeneity of forage resources is required for the design of a grazing system (Anchorena 1985). Mapping plant communities with the aid of aerial photographs required considerable field and laboratory effort (Lores et al. 1983, 1987, Borelli et al. 1984, 1988). The use of remote sensing and digital image processing techniques allows for a quick assessment of rangelands' heterogeneity and offers the possibility of integrating forage resources with ancillary data such as roads, paddock's layout, drinking water points, etc., into Geographical Information Systems (GIS) (Tueller 1989, Paruelo and Golluscio 1994). GIS provided a basic tool for planning range management.

LANDSAT MSS and TM data were extensively used in Patagonia for assessing rangelands resources (Paruelo and Golluscio 1994, Borelli et al. 1997). The Normalized Difference Vegetation Index (NDVI), which is calculated from the red and infrared reflectance of each pixel, shows a strong correlation with vegetation cover and primary production (Tucker and Sellers 1986, Box et al. 1989, Kennedy 1989, Paruelo et al. 1997). NDVI can be used to map plant communities by calibrating the relationship between NDVI and field data on plant functional types and species composition (Paruelo and Golluscio 1994). A map of plant communities provides the basis to characterize the internal heterogeneity of the forage resources of individual paddocks. This information is critical for optimizing the use forage resources in time and space.

2. Characterization of the phenology of plant communities

Satellite data also allows to characterize the seasonal dynamics of carbon gains (phenology) at the ecosystem level. NDVI data derived from the AVHRR sensor of the NOAH satellite showed the seasonal dynamics of the vegetation at 1x1 km (Aguiar et al. 1988, Paruelo et al. 1991) or 8x8 km pixels (Paruelo et al. 1998a, Jobbágy et al. in press). Based on the NDVI dynamics, Soriano and Paruelo (1992), and Paruelo et al. (1998a) identified "biozones" differing in their functioning. These biozones were characterized by their mean annual production, the difference between minimum and maximum production, and the day of peak production (Paruelo et al. 1998a).

Recent studies showed that climatic variables are good predictors of some critical phenological variables at the ecosystem level (Paruelo et al. 1993, Paruelo and Lauenroth 1995, 1998, Tieszen et al. 1997, Jobbágy et al. in press). Models based on mean annual precipitation, mean annual temperature, thermal amplitude and precipitation seasonality accounted for a high proportion of the spatial variability of the date of the start of the growing season, the date of peak production, and the length of the growing season (Paruelo and Lauenroth 1998). Jobbágy et al. (in press) showed that the temperature in July was a good predictor of interannual differences in the start of the growing season in NW Patagonia rangelands. The knowledge about the influence of climatic factors on the production dynamics of different biozones, provides the basis for decisions on the timing and duration of grazing at the paddock level.

3. Carrying capacity assessment

Several methods to assess the carrying capacity of individual paddocks are currently used by different institutions involved in natural resources' management in Patagonia (INTA Santa Cruz, INTA Río Negro and Chubut, and FAUBA; see detailed description in Appendix 1). Some of these methods estimate the carrying capacity at the paddock level as the average carrying capacity of the different vegetation units of the paddock, weighed by the area covered by each unit. Others, based on satellite data, obtain integrated estimates for the whole paddock (top-down approach). Within the first methods, carrying capacity of each vegetation unit may be derived from field estimates of forage production (bottom-up approach). Some agencies use the biomass growing between large tussocks (the "intercoironal" biomass of INTA Santa Cruz; Borelli et al. 1990 [Appendix 2], Cibils 1993 [Appendix 2]). Others base the estimate of carrying capacity on the relative frequency of palatable species (the Pastoral Value of INTA-Río Negro and Chubut; Ayesa and Becker 1991 [Appendix 2], Elissalde et al. 1991 [Appendix 2], Somlo et al. 1995 [Appendix 2]). An alternative approach, intermediate the between bottom-up and top-down approaches, is the estimation of Annual Net Primary Production (ANPP) of each vegetation unit within a paddock from empirical models of the relationship of ANPP with NDVI (FAUBA; Paruelo et al. 1997, and 1998a) or with mean precipitation (FAUBA; Sala et al. 1988, Paruelo et al. 1998b)

Stocking density estimates based on field estimates of forage production are useful when there are well established empirical relationships between particular fractions of total biomass and stocking density. However, the use of such methods is spatially constrained to those ecosystem for which these empirical relationships were validated. In addition, as any bottom-up approach, problems arise when point data need to be extrapolated to larger areas (see Appendix 1).

Estimates of carrying capacity from mean NDVI or mean annual precipitation (MAP) data, in contrast to the field-based estimates, are easy to extrapolate in space and are less dependent on local information. However, they may have lower local validity than field-based estimates because are based on regional relationships between ANPP and NDVI (Paruelo et al. 1997), or MAP (Sala et al. 1988), and between ANPP and herbivore biomass (Oesterheld et al. 1992, Mc Naughton et al. 1993). In addition, these models ignore the differences in ANPP and Harvest Index (annual animal intake as a proportion of ANPP, Figure 3) among sites with the same NDVI or precipitation, but different vegetation structure (see Appendix 1).

The methods outlined have different sources of uncertainty in the estimation of the carrying capacity. One of these causes of uncertainty is the difficulty to evaluate how much of the available biomass is actually grazed. For example the INTA Santa Cruz method assumes that the short grasses and forbs interspersed among tussocks of *Festuca gracillima* ("intercoironal") is the main source of forage, and define a coefficient (allowance coefficient) to account for differences among plant communities. In the Appendix 1 we show that this coefficient is directly related to the importance of the "intercoironal" biomass in the overall diet. The FAUBA methods assume that the Harvest Index is only dependent on ANPP, but not on the floristic composition of the communities.

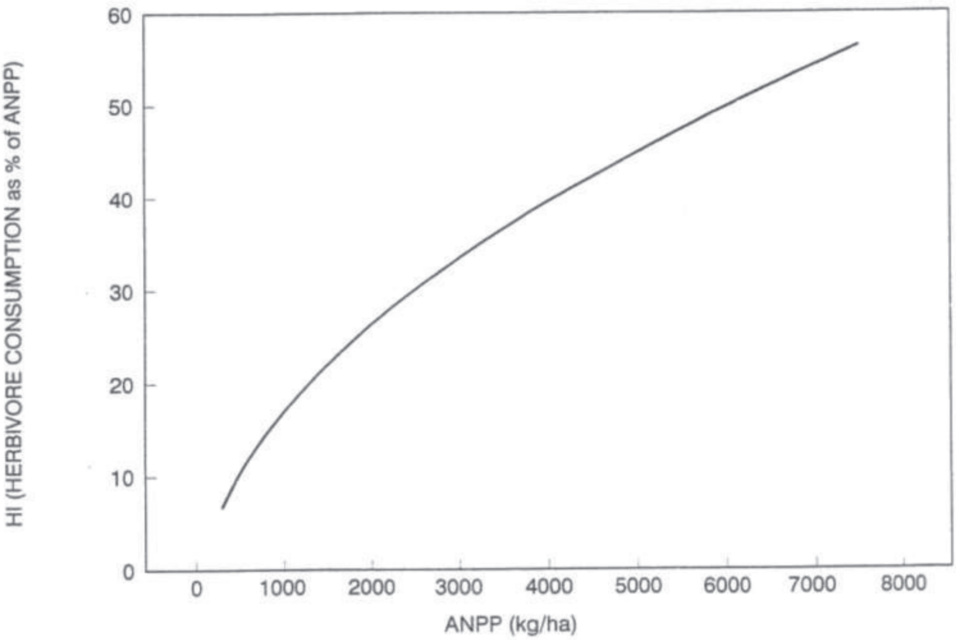

Figure 3. Harvest Index as a function of Annual Net Primary Production (ANPP). Harvest Index is the percent of ANPP consumed by domestic herbivores, calculated from the model of Oesterheld et al. (1992) (see Appendix 1)

This assumption is founded on empirical relationships developed at regional scale (Oesterheld et al. 1992). Another source of uncertainty is the impossibility of objectively estimate the carrying capacity of Patagonian ecosystems. The INTA Rio Negro and Chubut use information provided by the ranchers (Ayesa and Becker 1991 [Appendix 2], Elissalde et al. 1991 [Appendix 2], Somlo et al. 1995 [Appendix 2]), and the FAUBA methods use national censi data to estimate carrying capacity (Oesterheld et al. 1992, 1998) (See Appendix 1).

Several precautions must be observed, then, in defining stocking densities: (1) a careful selection of the best method for each particular objective and region, (2) a conservative attitude, (3) a continuous monitoring of vegetation and animals at the suggested stocking density, and (4) a flexible attitude to modify stocking density under particular climatic conditions, in order to promote regenerative processes or prevent transitions to more degraded states (Westoby et al. 1989, Paruelo et al. 1993 [Appendix 2]).

4. Resting periods

More than 40 years ago, Soriano (1956b) proposed resting as a necessary tool to reverse the degradation process of the Patagonian steppes. He argued that seedling recruitment would be almost impossible if sheep were continuously present. Huss (1973 [Appendix 2]) reinforced this suggestion by proposing resting periods to promote the recuperation of vigor of defoliated plants.

Recently, several authors reported preliminary results of rotational grazing experiments testing the effects of resting on vegetation and animal performance. These experiments were concentrated in humid areas: grass steppes of Tierra del Fuego and Southern Santa Cruz (Borelli, pers. comm.), and meadows of Río Negro (Becker et al. 1996 [Appendix 2], Giraudo et al. 1996 [Appendix 2], Siffredi et al. 1996 [Appendix 2]), Chubut (Nakamatsu et al. 1995 [Appendix 2]) and Santa Cruz (Clifton et al. 1995 [Appendix 2]). These experiments show auspicious results not only in vegetation recovery but also in animal production.

However, few experiences documented the use of similar techniques at the ranch scale (Soriano and Paruelo 1990, Paruelo et al. 1992, Paruelo and Golluscio 1994, Mercau and Deregibus 1997 [Appendix 2], Golluscio et al. 1998). In these ranches rotational grazing provides the possibility of implementing resting periods in different paddocks during the growing season. This grazing method had a positive effect on the recovery of palatable grasses and on animal production (Paruelo et al. 1992, Mercau and Deregibus 1997 [Appendix 2]; see details in the next section).

Some experiences of range management at the ranch scale

Management strategies based on the tools, techniques, and information presented above were successful in both improving sheep production and controlling degradation of the natural resources (Paruelo et al. 1992, Borelli et al. 1997, Golluscio et al. 1997 [Appendix 2], Oliva et al. 1998, Borelli et al. submitted). These management strategies include also several *flocks management techniques* out of the scope of this paper: pre-lambing shearing, control of the weight for the first mating of ewes, control of ewes' age through the teeth status, sanitary care, predator control (fox and puma cause severe economic losses), genetic breeding, and the selection of the category of animals to be assigned to each paddock on the basis of the climatic, predatory and robbery risks, and the marketing objectives of the ranch owner (Borelli et al. 1997).

Although these management strategies may require to adjust the stocking density of each paddock, only in some extremely degraded cases this adjustment would imply a decrease of the stocking density of the whole ranch. From an animal production point of view, the application of these techniques determined a consistent increase in the marking rate and a decrease in the mortality rate (Borelli et al. 1997). In addition, it caused an increase in the individual wool and meat production, with less variation among animals (Borelli et al. 1997). These results clearly increased the economic and social sustainability of sheep husbandry.

Ranchers of different biozones and social status of Patagonia adjusted the stocking density, separated homogeneous areas, improved the animal distribution through paddock division and water development, planned the grazing of different sites according to their phenology, and adopted the proposed flock management techniques. However, only some large ranches in NW Patagonia use rotational grazing methods. These ranches included areas characterized by a gradient of precipitations from 600 mm in the Western and high slopes to 150 nun in the Eastern and plain basins (Jobbágy et al. 1995, 1996). This range of precipitation determines a gradient of ANPP from *ca.* 2500 kg ha^{-1} in the wettest portion to 500 kg ha^{-1} at the driest extreme. An average of 5% of their area is covered by meadows, associated to rivers and streams varying from 3000 to 8000 kg há' of ANPP. Typically, these ranches have 10-15 large paddocks.

Because of the size of paddocks and the low density of the forage resources, the rotational grazing method implemented in NW Patagonia is not comparable to any of the classical textbook methods (Voisin 1959, Smetham 1994, Heady and Child 1994). Rotational grazing in Patagonia combines periods of almost continuous grazing, when plant growth is very slow, with periods of short duration-high stocking density grazing, when plant growth is rapid. The method minimizes sheep movements, by combining them with other sanitary and management activities (itch control, eye shearing, mating, shearing, marking, and weaning). Flexibility is an important attribute of the rotational grazing method. The general scheme should be adjusted on the basis of the proportion of grazed tussocks of several key species (Paruelo et al. 1993b [Appendix 2], Golluscio et al. 1998). The observation of the frequency of grass defoliation allows for an early detection of animal nutritional problems.

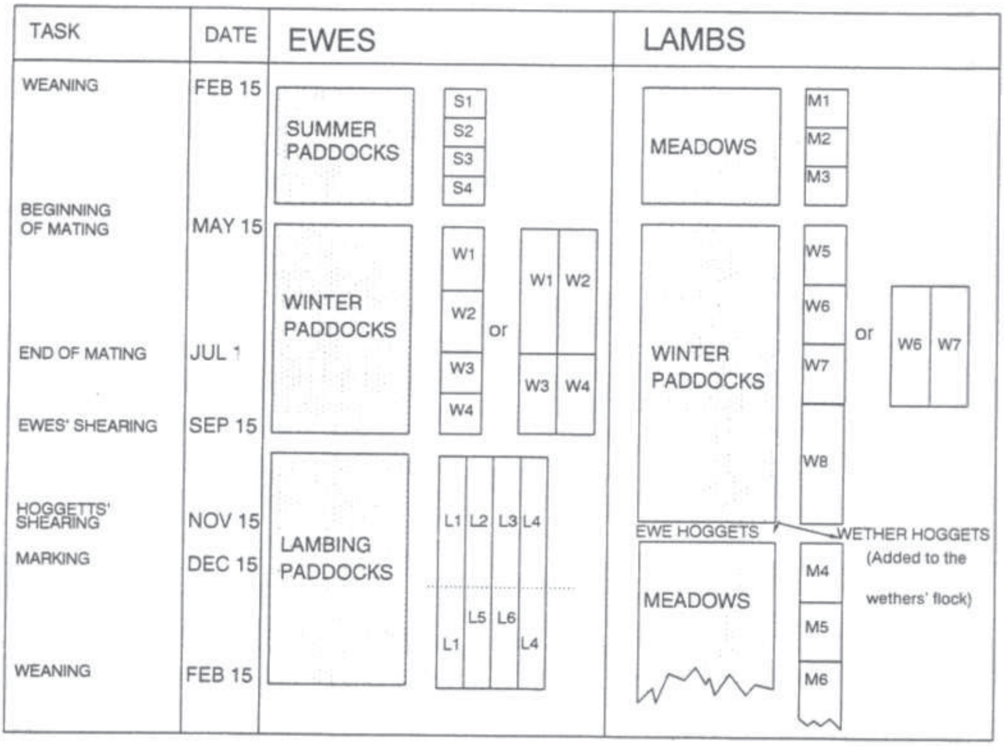

Figure 4. General scheme of the rotational grazing system developed in large ranches of NW Patagonia. The management of ewes and lambs is showed, emphasizing in the type of paddocks used along the year, and the flock movements related to sheep care activities. The types of paddock are represented as S (summer paddock), W (winter paddock), L (lambing paddock), and M (meadow paddock). Different subscripts indicate different paddocks within each paddock type. Wethers graze the paddocks recently used by ewes or lambs, immediately after they are left unoccupied.

Figure 4 shows a general scheme of a rotational method in Patagonia. Flocks are concentrated after weaning (February) in order to maximize the resting time of paddocks and to improve animal distribution when grazing the summer ranges. During winter, animals are distributed into several winter paddocks to reduce the risks of climatic catastrophes. Winter paddocks are usually located in areas with low altitude and towards the East. In these paddocks temperatures are warmer and the probability of snow storms are lower than in the rest of the ranch. This period of continuous grazing would not affect plant vigor because plant growth, and then reserves use, are very slow. Unfortunately the movement of sheep during the growing season of plants is difficult because ewes and lambs are particularly sensitive to movements over long distances from lambing to marking (Helman 1965, Spedding 1968). As a consequence, after pre-lambing shearing, ewes are placed in lambing paddocks and graze them continuously up to marking, or even to weaning (Figure 4). Three management tools are used to cope with such lack of resting of lambing paddocks during the growing season: (1) separation of steppe- from meadow-areas in each lambing paddock and movement of ewes and lambs from the first to the second at marking, (2) careful movement of ewes and lambs from one paddock to the neighbor one at marking, (3) to give a complete growing season of rest to one of the lambing paddocks each year.

A statistically robust evaluation of grazing treatments is very difficult, even in controlled experiments. Grazing experiments are in general pseudo replicated (explicitly or not) (Hurlbert 1984). Some precautions may be taken to minimize the impact of pseudo replication when it is logistically impossible to have true replications (Hurlbert 1984, Golluscio et al. 1998). One of them is to compensate the absence of true spatial replications by temporal pseudoreplications, and other is to demonstrate that two experimental areas that had changed along the implementation of different treatments were identical before those treatments begun. Adaptive Management theory (Walters 1986) provides an alternative intellectual framework, within which several ranches subjected to different grazing methods could be considered as true replications, and its results subjected to conventional statistical analysis. This approach was not used yet in Patagonia, but showed interesting results in the Flooding Pampa of Argentina (Deregibus et al. 1995).

One of these ranch-scale experiments involve two sections of the same ranch, which were subjected to the same historic management until 1987. Through a field vegetation survey based on aerial photographs performed in 1987 it was possible to identify similar ecological areas in both sections (Aguiar et al. 1988 [Appendix 2]). After this range assessment was performed, one of the sections was subjected to a rotational grazing method and the other continued managed under continuous grazing. To evaluate the effects of management on vegetation, Mercau and Deregibus (1997 [Appendix 2]) made two types of comparisons: present differences in originally similar areas (three years), and differences between the vegetation before and seven years after the grazing system begun.

As a consequence of implementing such rotational grazing method, an increase in wool production was observed without variations in the *per capita* wool yield, nor in the marking or mortality rates (Paruelo et al. 1992). From the point of view of the forage resources, this grazing method significantly reduced the defoliation heterogeneity within plants of the same species (*Festuca pallescens*) in the summer paddocks (Paruelo et al. 1992), and increased the cover of two palatable forage species in winter paddocks (Bromus *pictus,* and *Poa ligularis;* Mercau and Deregibus 1997 [Appendix 2]).

Expansion of meadows and supplementation are presently used to increase the seasonal carrying capacity of different paddocks. The expansion of meadows area increases the summer carrying capacity because they produce almost five times the ANPP and have almost ten times the carrying capacity of the steppes (Lanciotti et al. 1993 [Appendix 2]). Improved management of meadows showed a significant effect on annual meat production (Durañona 1980 [Appendix 2]). The area occupied by meadows and their productivity can be increased by controlling water flow on valleys (Marcolin 1975 [Appendix 2], Horne and Morales 1981 [Appendix 2], Becker et al. 1990 [Appendix 2]). The use of urea and molasses blocks, allows for an increase in the voluntary intake of forage of poor quality by promoting the activity of ruminal bacteriae. These blocks showed to increase the defoliation of usually unpalatable dominant *Stipa speciosa* in the steppes, and caused a significant increase (15 percent) in the marking rate and in the weight of marked lambs when supplied in winter on paddocks with poor forage resources (Golluscio et al. 1998). Although costly, strategic supplementation allows for an increase in the winter carrying capacity (more available forage), and in the animal harvest efficiency of meadows in summer. As a consequence, urea supplementation promotes an increase in the growth rate of the population (natality minus mortality), increasing the overall sustainability of such range systems. However, it should be used with extreme care to avoid an excessive use of the dominant species of the steppe.

Constraints to the adoption of available technologies

Despite of the reported benefits of the techniques reviewed above, its adoption by ranchers is low as a consequence of several ecological and socioeconomic constrains. Borelli et al. (1997) claimed that the adoption of techniques of range assessment and flock management would be constrained only by social and cultural factors. The adoption of rotational grazing methods would have, additionally, economic and ecological constraints.

One of the most important *ecological constraints* against the adoption of rotational grazing methods is that, to obtain the expected results on vegetation recovery, resting periods should occur during the growing season. Resting periods promote an increase in plant vigor when growth is not constrained by another factor (Briske 1991). Plant growth in Patagonia is constrained by water availability (summer-fall) and temperature (winter) (Golluscio et al. 1982, Sala et al. 1989, Paruelo and Sala 1995, Paruelo et al. 1998b). Consequently, the growing season is confined to spring and early summer (Paruelo and Sala 1995, Jobbágy et al. in press). In addition, forage production is highly variable among years because of the interannual variability of precipitation (Jobbágy et al. 1995), which reflects in a highly variable NDVI (Oesterheld et al. 1998), á variable closely related with ANPP (Paruelo et al. 1997). The length of the growing season decreases (Paruelo and Lauenroth 1998, Jobbágy et al. in press), and the interannual variability of forage production increases as precipitation diminishes (Jobbágy et al. 1995, Oesterheld et al. 1998). Consequently, the more arid the area, the more difficult the device of a rotational grazing method. The development of warning systems (Sala et al. 1994 [Appendix 2]) that help to track changes in forage availability based on meteorological variables will remove some of the ecological constraints to the development of rotational grazing methods.

Another constraint to the use of these grazing methods are the restrictions to move ewes from the last weeks of gestation to lamb marking because these movements increase the probability of lamb mortality (Helman 1965, Spedding 1968). In NW Patagonia the period between the last weeks of gestation and lamb marking (late September to mid November) almost halves the growing season (Paruelo et al. 1998a). Research efforts are needed to find management alternatives to remove the impact of these constraints in designing sustainable rotational grazing methods.

Among the *socioeconomic constraints* that prevent the adoption of rotational grazing methods, the scarce subdivision of ranches is the most important. In ranches with only two or three paddocks, which is not a rare case, it would be impossible to separate animals of different categories. The use of electric fences would facilitate the subdivision of large paddocks and the isolation of most preferred areas. Strategic supplementation and development of drinking water points also would reduce the heterogeneity in the use of extense areas. Although some of these practices are financially impossible for most Patagonian ranchers under the present economic conditions, they may be profitable and should be considered in credit and subsidies programs.

In spite of the importance of the above-mentioned constraints, cultural seems be the most important constraint to apply alternative management systems in Patagonia. Tradition and the inadequate instruction of ranchers and range managers restrict the diffusion of techniques that involve major changes in the organization of ranches. Education is the key to modify this constraint.

Conclusion

Evidences suggest that it is possible to make an ecologically sustainable use of Patagonian forage resources. Such possibility would aid to increase the economic and social sustainability of animal husbandry in most of the Patagonian region. Increasing the ecological sustainability of Patagonian ranches not necessarily implies a reduction in stocking density. On the contrary, in several cases the stock density may even be increased, and, even when it must be reduced, the economic value of the produced goods may be often increased (Borelli et al. 1997).

Several technological and conceptual tools are now available to control and revert degradation in Patagonian rangelands, including satellite-based range assessment, controlled grazing, supplementation and diverse flock management practices. These tools can be extensively applied in most of Patagonia. Further research is needed to improve carrying capacity estimates, to develop warning systems, to increase the efficiency of use of the meadows (“mallines”), and to design grazing methods adapted to more arid areas or to poorly subdivided ranches. Economic support through loans and subsidies should encourage ranchers to adopt the proposed technology.

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Appendix 1. Methods for carrying capacity estimation in Patagonia

1. The INTA - Rio Gallegos method
Festuca pallescens and *F. gracillima* are tussock grasses which dominate the grasslands of south and West Santa Cruz (Boelcke et al. 1985). The space among tussocks (locally named “coirones”) is occupied by a group of short grasses and forbs (locally known as “intercoironal”), dominated by *Poa dusenii* (Borelli et al. 1984 and 1988). The method to estimate carrying capacity developed by INTA Rio Gallegos is based on the measurement of the biomass of grasses and forbs in these “intercoironal” patches (Borelli et al. 1990 [Appendix 2]). Sheep prefer these patches over *Festuca sp.* tussocks, because of their higher nutritive value (Wernli 1988 [Appendix 2], Borelli et al. 1990 [Appendix 2]). The carrying capacity of each paddock is calculated by dividing the “intercoironal” biomass by the annual forage intake of a sheep (350-400 kg DM sheep^{-1} yr^{-1} for a 40-kg sheep; ARC 1980). An additional element of the Rio Gallegos method is the measurement of the height of the *Poa dusenii* plants, which was found highly correlated with the intensity of recent grazing (Borelli et al. 1990 [Appendix 2]). An empirical relationship between the height of *Poa dusennii* and the intensity of recent grazing is used to monitoring short term effects of grazing and weather on forage availability (Borelli et al. 1990 [Appendix 2]). This method to calculate carrying capacity showed a good agreement with the average regional stocking density values (Cibils 1993 [Appendix 2]).

This technique is restricted to steppes formed by a matrix of scattered tussocks, and short grasses and forbs growing among them. To extrapolate this method to other ecological zones of Santa Cruz where the identification of the “intercoironal” is not clear, Cibils (1993 [Appendix 2]) proposed dividing the “intercoironal” biomass by a coefficient termed “allowance” (equation 1).

$$\text{Carrying capacity (sheep ha}^{-1}\text{)} = \frac{\text{Intercoironal biomass (kgDM ha}^{-1}\text{)}}{\text{Allowance coefficient (kgDM sheep}^{-1}\text{)}} \qquad \text{Eq.1}$$

The lower limit of this allowance coefficient is 100 kgDM sheep^{-1} yr^{-1}, in the shrub steppes of San Jorge Gulf dominated by *Trevoa patagonica* and *Colliguaya integerrima* (Somlo et al. 1997, based on Baetti et al. 1991 [Appendix 2]). The upper limit of the allowance coefficient is 500 kgDM sheep^{-1} yr^{-1}, in the shrub steppes of the center (W-E) and the Atlantic coast of central (N-S) Santa Cruz, dominated by *Nassauvia glomerulosa* or *Verbena tridens* (Somlo et al. 1997, based on Baetti et al. 1991 [Appendix 2]).

However ¿what is the ecological significance of such allowance coefficient? Carrying capacity can be calculated as the ratio between available forage, and the individual demand of each sheep (equation 2).

$$\text{Carrying capacity (sheep ha}^{-1}\text{)} = \frac{\text{Available Forage (kgDM ha}^{-1}\text{)}}{\text{Individual annual intake (kgDM sheep}^{-1}\text{)}} \qquad \text{Eq. 2}$$

From equations 1 and 2, it can be deduced that the allowance coefficient results from the product of the Individual annual intake, and the proportion of the available forage explained by the “intercoironal” biomass (ICB % = Intercoironal biomass / Available forage) (equation 3):

$$\text{Allowance coefficient (kgDM sheep}^{-1}\text{)} = \text{Individual annual intake x ICB\%} \qquad \text{Eq. 3}$$

Equation 3 suggests that the Allowance coefficient is lower than the Individual annual intake (Gulf shrub steppes) when sheep consume forage items that do not pertain to the “intercoironal”, as shrubs or “coirones” (ICB% < 1), and is higher than the Individual annual intake (Central Santa Cruz shrub steppes) when not all the “intercoironal” biomass is grazed by sheep (ICB% > 1). This suggests that the estimation of carrying capacity by the INTA - Rio Gallegos method in communities other than the *Festuca* spp. grasslands would gain in precision from better knowledge of the relative importance of the “intercoironal” biomass in the diet.

2. The INTA - Trelew and Bariloche method

The estimation of carrying capacity developed by INTA for some plant communities of the provinces of Rio Negro, Neuquén and Chubut is based on a regression model between the Pastoral Value (Daget et Poissonet 1971) of each paddock and their carrying capacity (Elissalde et al. 1991 [Appendix 21, Somlo et al. 1995 [Appendix 2]). The Pastoral Value of each paddock is calculated as the average Pastoral Value of the different vegetation units included in it, weighed by its relative area. The Pastoral Value of each vegetation unit is calculated as the sum of the products of the frequency of each species by its Pastoral Value. The frequency of each species is estimated by using the Step Point Method (Evans and Love 1957), modified by Elissalde et al. (1991 [Appendix 2]). The Pastoral Value of each species ranges between 0 and 5, and is empirically stated on the basis of the sheep preference and the phenology of each species. A table of Pastoral Values is available for the arid zone of Chubut (Elissalde et al. 1991 [Appendix 2]), and other for the Pre-Cordilleran grasslands of Río Negro and Neuquén (Ayesa and Becker 1991 [Appendix 2]). In both regions the regression curve relating carrying capacity and Pastoral Value are based on carrying capacity data obtained from ranchers. The implicit assumptions of this method are that rangelands have attained their carrying capacity at the time when those enquiries were done, and that ranchers provide a reliable estimate of carrying capacity.

As with the INTA - Rio Gallegos method, carrying capacity estimated from Pastoral Value can be repeated through time in order to monitor the dynamics of vegetation in response to the climatic conditions and the grazing management. However, both methods are difficult to extrapolate to wide areas, and the regressions they use are not automatically applicable for other ecological zones.

3 The FA UBA - Buenos Aires method

This method is based on equation 2. It assumes that Individual annual intake vary from 350 to 400 kg $sheep^{-1}$ yr^{-1}, according to the nutritional status and the age- by sex- structure of the flocks (ARC 1980), and calculates the Available Forage as the product between the Aboveground Net Primary Production (ANPP) and Harvest Index (HI). The Harvest Index is defined as the proportion of ANPP that can be grazed on average management conditions. Then carrying capacity can be expressed then as:

$$\text{Carrying capacity (sheep ha}^{-1}\text{)} = \frac{\text{ANPP (kgDM ha}^{-1}\text{ yr}^{-1}\text{) x HI (\%)/100}}{\text{Individual annual intake (kgDM sheep}^{-1}\text{)}} \qquad \text{Eq. 4}$$

Harvest Index can be empirically determined. However, the experimental design and the logistic of such large scale experiments needed to estimate it are not simple. Moreover, the results of a single experiment will be valid only for the particular community, stocking density, climatic conditions, and management under which the experiment was done. Finally, such reductionist approach to derive HI values will have enormous problems to be aggregated in order to generate general models. On the basis of these considerations, a"top-down" approach is used. Oesterheld et al. (1992) found that the herbivore biomass is linearly correlated with the Annual Net Primary Production (ANPP), both variables expressed in a log scale and energy units per unit surface. The data used to develop such regression were obtained from censi at the county level across Argentina (Ministerio de Economía 1974) and Uruguay (Ministerio de Agricultura y Pesca 1980). The use of this model to estimate carrying capacity has the underlying assumption that Patagonia had attained its carrying capacity in 1974.

From this model, and assuming that herbivores eat daily 3 % of their fresh weight in dry matter forage, it can be deduced that harvest index increases with ANPP, according with the following equation:

$$\text{HI (\%)} = -5.71 + 0.7154 \text{ x } (\text{ANPP (kgDM ha}^{-1}\text{ yr}^{-1}))^{0.5} \qquad \text{Eq. 5}$$

Equation 5 indicates that the rate of increase of the Harvest Index with ANPP decreases with ANPP (Figure 3). As the ANPP gradient is associated to a precipitation gradient (PPT) (Sala et al. 1988), the increase of HI with ANPP reflects an increase in PPT that would be associated to changes in drinking water availability, and/or forage quality (Milchunas et al. 1988). The change of both nutritive value and drinking water as a function of precipitation is greater in the arid extreme of the gradient than on the humid one. Because the model was developed at a regional scale, it ignores the differences in forage quality, and then HI, within sites of the same ANPP.

ANPP can be estimated from biomass harvesting methods (Singh et al. 1975, Lauenroth et al. 1986), from models relating ANPP with precipitation (Noy Meir 1973, Sala et al. 1988, Me Naughton et al. 1993) or from satellite data (Paruelo et al. 1997). The biomass clipping is the reference method to calibrate both empirical models or satellite estimates. However, the *estimation of* ANPP by *biomass harvesting* at the paddock level share the same advantages and disadvantages of the estimates of both "intercoironal" biomass (INTA-Santa Cruz method) and Pastoral value (INTA-Rio Negro and Chubut method).

Estimations of ANPP derived from precipitation data are very easy to obtain and provide a reasonable description of the spatial heterogeneity of ANPP with a well-developed PPT gradient (Jobbágy et al. in press). The model developed for the central grasslands of United States of America by Sala et al. (1988) was validated for South American (Me Naughton et al. 1993, Paruelo et al. 1998b). However, a shortcoming of this model is that it will provide estimates of ANPP for undisturbed sites. Additional problems of this approach arise in areas where PPT data are scarce or landscapes are composed by several units with different water budget each one (Paruelo et al. 1998b). To cope with these two problems Paruelo et al. (1998b) assumed that sites with the same plant community have similar water budgets, as suggested by Jobbágy et al. (1996). This implies that sites corresponding to a particular community will have the same water budget than floristically similar sites of known precipitation located on flat areas, where lateral water fluxes (run on and run off) are absent, and precipitation is the only water input to the system (Noy Meir 1973). This approach can be useful only for areas where the relationships between floristic composition and precipitation has been documented (i.e., W Chubut, León and Facelli 1981, Jobbágy 1993, Jobbágy et al. 1996).

The main advantages of *ANPP estimates derived from satellite data* are that they have no extrapolation problems, and they would reflect the present degradation status of vegetation. The available models relating the NDVI integral and ANPP, calibrated for North America (Paruelo et al. 1997) or the Sahel (Prince 1991), were not validated for South America. However, some indirect evidences suggest that calibrations developed for temperate grasslands can be applied with caution to Patagonian rangelands (Paruelo et al. 1998a).

Additional support to the use of satellite data (NDVI) to estimate carrying capacity is provided by the linear regression model between stocking density and NDVI (both variables in log scale) found by Oesterheld et al. (1998). Stocking density was calculated from the 1988 census for 63 counties of Argentina (Ministerio de Economía 1988), and NDVI was calculated as the average of seven years of monthly NOAA-AVHRR data of NDVI integrated along each year. A similar model of carrying capacity as a function of NDVI was developed from Landsat MSS images for the shrub steppes of Central Santa Cruz (Oliva et al. 1995 [Appendix 2]). This approach provide a good alternative to directly estimate carrying capacity at the ranch scale, without the above-mentioned uncertainties about the estimation of ANPP and Harvest Index.

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