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RELATION BETWEEN NOAA-AVHRR SATELLITE DATA AND STOCKING RATE OF RANGELANDS

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Abstract. Biomass of both wild herbivores and livestock in rangelands is correlated with rainfall at a regional scale. Thus, rainfall may be a good predictor of actual stocking rates. However, rainfall data are scarce in many regions, and their spatial resolution is usually much coarser than needed to set or to evaluate wildlife or livestock stocking rates. We here show a relationship between livestock biomass and an annual vegetation index (normalized-difference vegetation index-integrated value, NDVI-I) calculated from remotely sensed data on spectral properties of rangelands of Argentina. The relationship is as strong or even stronger than previously reported correlations between herbivore biomass and rainfall. This, together with the greater availability and higher spatial resolution of satellite data, makes remote sensing a potentially valuable tool to predict stocking rates for regions, landscapes, and different portions of a landscape. The form of the relationship between stocking rate and average NDVI-I was exponential, which, as previously shown, indicates an increasing herbivore load per unit of primary production as rainfall or productivity increases. This may be at least partially explained by the fact that the NDVI interannual variation and seasonality were negatively related with average NDVI-I. Thus, stocking rate may increase exponentially because of an increasing year-to-year reliability of the forage resource and a more even distribution within the year.

Key words: Argentine rangelands; herbivore biomass vs. primary productivity; herbivore biomass vs. rainfall; land-use management; livestock stocking rate; normalized-difference vegetation index, NDVI; primary productivity; remote sensing.

Introduction

Stocking rate, an important variable in rangeland management (Scarnecchia 1990), is partially determined by both primary productivity, which sets an upper limit to the energy flow to herbivores, and forage quality, which determines the proportion of that energy that will be assimilated. Primary productivity and forage quality are difficult to measure, and have a complex pattern of spatial and temporal variation (both annual and seasonal) that by itself may also affect herbivore carrying capacity. This makes it very difficult to derive a stocking-rate value or to evaluate current rates from the direct determination of both variables. A different approach is based on the utilization of empirical relations between stocking rate and one or more variables that are easy to measure. There is, for example, a strong correlation between herbivore biomass and annual rainfall in both African natural ecosystems (Coe et al. 1976, East 1984, Owen-Smith 1990) and South American rangelands (Oesterheld et al. 1992). The scale of the patterns revealed by these studies was regional, since each rainfall and herbivore-biomass data point corresponded to wide areas, such as national parks and game reserves in Africa or counties in South America. These relationships seem useful for the management of range livestock systems, but in most situations it may be necessary to predict stocking rates for areas that lack rainfall data or for purposes that require a much finer spatial resolution; ranches, paddocks within ranches, and transient subdivisions within paddocks are much smaller units than regions and may include a large portion of the whole regional variation. They may exhibit variation in rainfall and an even larger variation in soil moisture and fertility.

Aboveground net primary productivity (ANPP) can be estimated from an advanced very high-resolution radiometer (AVHRR) on board the National Oceanic and Atmospheric Administration (NOAA) polar satellites (Tucker et al. 1985*a*, *b*, Box et al. 1989, Kennedy 1989, Prince 1990). These authors demonstrated that ANPP was strongly correlated with the cumulative normalized-difference vegetation index (NDVI) derived from AVHRR channels 1 and 2 data (red and infrared bands, respectively). Furthermore, good correlations between NDVI and ANPP were also observed on a monthly basis (Taylor et al. 1985). More recently, Paruelo et al. (1997) have shown remarkable correlations between ANPP and NDVI for a wide range of North

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TABLE 1. Livestock stocking rates and normalized-difference vegetation index (NDVI) values for the 63 counties of Argentina used in this study. For each of these counties, animal husbandry was the main activity (>85% total area), and native grasslands and steppes were the dominant vegetation type (>85% total area). Livestock biomass included cattle, sheep, goats, and horses.

County	Province	Stocking rate (kg/ha)	NDVI-I†	CV of NDVI-I‡	
				Interannual	Intra-annual
Pehuenches	Neuquén	5	0.092	0.321	0.331
Lago Argentino	Santa Cruz	13	0.094	0.392	0.809
Mártires	Chubut	8	0.095	0.439	0.439
Corpen Aike	Santa Cruz	9	0.096	0.428	0.549
Sarmiento	Chubut	12	0.099	0.476	0.533
Magallanes	Santa Cruz	8	0.099	0.523	0.518
Paso de indios	Chubut	10	0.099	0.399	0.458
Deseado	Santa Cruz	9	0.100	0.496	0.490
Gaiman	Chubut	10	0.106	0.349	0.501
Gastre	Chubut	11	0.106	0.299	0.455
Escalante	Chubut	5	0.109	0.412	0.485
Telsen	Chubut	9	0.109	0.285	0.381
Lago Buenos Aires	Santa Cruz	11	0.114	0.326	0.673
Río Chico	Santa Cruz	9	0.115	0.365	0.790
Florentino Ameghino	Chubut	11	0.115	0.357	0.415
Valcheta	Río Negro	7	0.116	0.259	0.277
Biedma	Chubut	10	0.119	0.285	0.364
San Antonio	Río Negro	7	0.126	0.234	0.284
Rawson	Chubut	12	0.137	0.279	0.391
Languiñeo	Chubut	14	0.137	0.231	0.566
Catan Lil	Neuquén	11	0.144	0.204	0.442
Collón Curá	Neuquén	8	0.145	0.209	0.300
Chical Co	Río Negro	19	0.149	0.204	0.286
Avellaneda	Río Negro	20	0.153	0.148	0.283
Río Senger	Chubut	18	0.164	0.252	0.636
Tehuelches	Chubut	22	0.166	0.220	0.647
Cura Co	Río Negro	9	0.167	0.137	0.244
Guer Aike	Santa Cruz	17	0.175	0.190	0.618
Limay Mahuida	Río Negro	11	0.177	0.133	0.306
Cushamen	Chubut	20	0.178	0.193	0.525
Chadileo	Río Negro	18	0.198	0.132	0.353
Adolfo Alsina	Río Negro	35	0.203	0.159	0.271
Pichi Mahuida	Río Negro	32	0.208	0.130	0.240
Ayacucho	San Luis	24	0.217	0.096	0.318
Lihue Calel	Río Negro	26	0.235	0.111	0.250
Belgrano	San Luis	22	0.237	0.071	0.313
La Capital	San Luis	35	0.245	0.104	0.325
Gobernador Dupuy	San Luis	59	0.246	0.091	0.351
San Martín	San Luis	67	0.253	0.076	0.355
Pringles	San Luis	85	0.260	0.092	0.343
Pedernera	San Luis	113	0.262	0.083	0.350
Puelen	Río Negro	14	0.263	0.132	0.127
Caleucaleu	La Pampa	54	0.284	0.072	0.138
Junín	San Luis	67	0.309	0.061	0.332
Toay	La Pampa	106	0.311	0.085	0.288
Las Flores	Buenos Aires	240	0.395	0.061	0.269
La Paz	Entre Rios	256	0.396	0.086	0.199
Laprida	Buenos Aires	239	0.403	0.088	0.214
Alvear	Corrientes	117	0.408	0.059	0.173
Magdalena	Buenos Aires	264	0.408	0.074	0.236
Castelli	Buenos Aires	285	0.409	0.066	0.267
Belgrano	Buenos Aires	241	0.410	0.062	0.262
Pila	Buenos Aires	178	0.414	0.058	0.258
Guido	Buenos Aires	250	0.416	0.055	0.257
Rauch	Buenos Aires	249	0.417	0.058	0.250
Feliciano	Entre Rios	193	0.419	0.082	0.176
Chascomus	Buenos Aires	302	0.422	0.061	0.251
Brandsen	Buenos Aires	291	0.422	0.071	0.235
Mercedes	Corrientes	191	0.423	0.068	0.171
Dolores	Buenos Aires	200	0.423	0.060	0.252
Federación	Entre Rios	196	0.429	0.075	0.179
Paso de los Libres	Corrientes	201	0.438	0.062	0.166
Monte Caseros	Corrientes	188	0.438	0.075	0.168

American grasslands. NDVI is an index that reflects the difference between red and infrared radiation received from Earth by the satellite sensors. Since green canopies absorb differentially these two bands, the index integrates a measure of ''greenness,'' which is related to primary production. Considering that NDVI is sensitive not only to the amount of green tissue but also to the greenness of equivalent amounts of tissue (e.g., senescent vs. actively growing; Guyot 1990), the index may also reflect forage quality, but this relationship has not been clearly demonstrated.

If there were evidence that these satellite data are correlated with stocking rates, as previously proposed by McNaughton et al. (1989), they could become better predictors than annual rainfall because satellite information from NOAA-AVHRR sensors presents a greater spatial resolution than available annual rainfall data (up to 1 km^2) and may be better at detecting intra-landscape variations in water availability and primary productivity. We here show such evidence of a relationship between livestock biomass and annual integrated NDVI at a regional scale in Argentinean rangelands. Previous rainfall–herbivore relations are compared with this newly presented biomass–NDVI data as predictors of livestock biomass of these rangelands.

Methods

We compiled a data set that included both NDVI determinations and livestock stocking rates (Table 1). The normalized-difference vegetation index (NDVI) data were originated by a global area coverage (GAC, 7 × 7 km spatial resolution) AVHRR (advanced very-high-resolution radiometer) sensor of the NOAA satellite. The standard NOAA-AVHRR product is the GAC data produced by on-board processing of the raw 1.1 × 1.1 km LAC (large area coverage) data. Each GAC pixel is an average based on 8 LAC pixels taken systematically from a 4 × 4 pixel square. Thus, GAC images have a nominal linear spatial resolution of 4.055 km (an area of 16.5 km^2). The Global Inventory Monitoring and Modelling Systems (GIMMS) group at the NASA's Goddard Space Flight Center has developed a global data set where GAC data were reprojected onto an equal-area projection and resampled by continent to create a data base with spatial resolution of 7.6 km, which corresponds to a GAC pixel at a view angle of 35° off nadir. The final map projection is the Hammer-Aitoff projection. We chose images of Argentina taken monthly between January 1982 and December 1988. The images were composed by using the maximum value composite technique applied to the NDVI values. This technique minimizes the atmospheric and other degrading effects on the experimental values (Holben 1985).

Stocking-rate data were originated by a national census at the county level (Ministerio de Economía 1988). The counties included in the data set were selected following two criteria: (a) animal husbandry had to be the main activity (>85% of total area) and (b) native grasslands and steppes had to be the dominant vegetation type (>85% of total area). Sixty-three counties spread among nine provinces (La Pampa, 8; Buenos Aires, 11; Entre Ríos, 3; Corrientes, 4; Neuquen, 3; Río Negro, 5; Chubut, 14; Santa Cruz, 7; and San Luis, 8) were chosen according to these criteria. These study areas represent a broad range of environmental conditions: annual rainfall varies from 123 to 1611 mm and mean temperature from 7.7° to 20.2°C.

For each county we calculated a monthly NDVI spatial average. The 12 resulting NDVI values were averaged over each year to give an annual integrated value (NDVI-I) (Paruelo et al. 1997). We then averaged this integrated value for 7 yr (average annual NDVI-I, 1982–1988) and calculated the mean annual integrated NDVI for each county. The coefficient of variation of NDVI-I for the 7 yr was used to assess interannual variability, whereas the average coefficient of variation of the monthly NDVI data was used to estimate intra-annual variability.

Livestock biomass included cattle, sheep, goats, and horses. Goat and horse biomass was estimated as the product between their density (Ministerio de Economía 1988) and individual mean mass (17 and 200 kg, respectively). Biomass for cattle and sheep, which accounted for more than 88% of total livestock biomass, was calculated considering the total number of individuals (Ministerio de Economía 1988), the distribution of individuals among sex and age categories (information only provided by a previous census of 1974, Ministerio de Economía 1974), and an estimate of the average individual mean body mass for each category: cows (400 kg), heifers (<2 yr old: 170 kg, 2–3 yr old: 260 kg), calves (120 kg), steers (<2 yr old: 200 kg, older: 300 kg), bulls (<2 yr old: 200 kg, older: 500 kg), sheep (37 kg), lambs (1-yr-old: 25 kg, younger: 12 kg), wethers (45 kg), muttons (50 kg). Animal biomass was translated into stocking rate on the basis of the county total area as reported by the census.

We compared the relationships between NDVI and

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† For each county, we calculated a monthly NDVI spatial average; the resulting 12 NDVI values were averaged over each year to give an annual integrated value, NDVI-I. For 1982–1988 these annual integrated values were averaged to get the average annual NDVI-I of each county.

‡ The coefficient of variation (CV) of NDVI-I for the 7 yr was used to assess interannual variability; the average CV of the monthly NDVI data was used to estimate intra-annual variability.

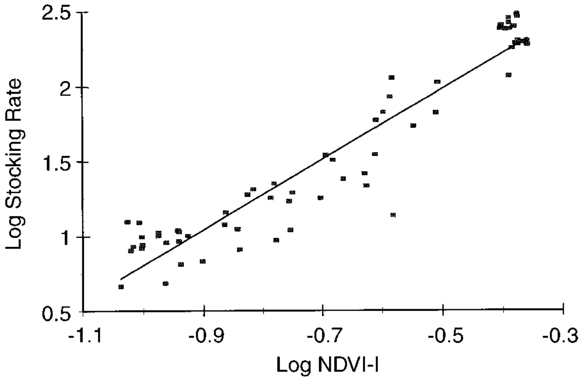

FIG. 1. Relationship between stocking rate (measured in kilograms per hectare) and mean annual integrated NDVI (normalized-difference vegetation index) for 63 counties of Argentina.

livestock with two other kinds of relationships: (a) livestock stocking rate–rainfall (or primary productivity estimated from rainfall) relationships reported in the literature, and (b) a livestock stocking rate–rainfall relationship observed in our own data set for 17 counties that had rainfall data (Servicio Meteorológico Nacional 1992).

RESULTS AND DISCUSSION

Livestock stocking rate (*B*, in kilograms per hectare) and mean annual integrated NDVI (normalized-difference vegetation index) were strongly related ($r^2 = 0.90$, $P < 0.001$, df = 61) on a log-log scale: $\log_{10}B = 2.35359 \log_{10}$ NDVI-I + 3.1593 (Fig. 1). This relationship is as strong or even stronger than previously reported cases in which wild-herbivore or livestock biomass was correlated with rainfall. Regressions between biomass of wild African herbivores reported by Coe et al. (1976) and East (1984) explained <76% of the variance and were based on many fewer data points, which tends to inflate r^2 values. Fritz and Duncan (1993) have also reported various relationships between both wild and livestock African herbivores and rainfall, with r^2 values ranging between 0.65 and 0.95, but with fewer than 10 data points in most cases. Livestock biomass of South American rangelands was associated with a linear transformation of rainfall with an r^2 value of 0.79 (Oesterheld et al 1992). In our own data set, we found that rainfall was related to stocking rate with an r^2 value of 0.85 and 17 data points.

The inclusion of two variables related with the temporal variation of NDVI (interannual and intra-annual coefficients of variation) in a multiple-regression model did not explain a significantly higher proportion of the variance in stocking rates (only 2% additional variance was explained). The reasons for this were that both variables were also related to NDVI-I. As previously shown for the Patagonian region (E. G. Jobbágy, *unpublished data*) and confirmed for a much broader range of habitats in our own data set, interannual variation in NDVI-I was strongly and negatively correlated with average NDVI-I (Fig. 2a, CV = 0.0202 × NDVI-I$^{-1.25}$, $r^2 = 0.92$, $P < 0.0001$). Intra-annual variability in NDVI (seasonality) was also negatively related with NDVI-I, (Fig. 2b, CV = 0.56–0.85 × NDVI-I, $r^2 = 0.47$, $P < 0.0001$).

There are a few potential explanations for the better fit of herbivore biomass data to NDVI-I than to rainfall. First, the NDVI data coverage of each county is much greater than rainfall data coverage. Each county usually has no more than a single data point for rainfall, whereas, depending on its size, it has between 50 and 500 NDVI data. Although only one single average NDVI-I value was entered per county in our equation, this value is a much more accurate spatial integration of the productivity of the county than the single point coming from a single rain gauge located somewhere in the county. Second, several studies found significant correlations between integrated annual NDVI and aboveground net primary productivity (ANPP) (Goward and Dye 1987, $r^2 = 0.9$; Box et al. 1989, $r^2 = 0.9$; Paruelo et al. 1997, $r^2 = 0.92$), which are stronger than relationships between ANPP and precipitation (Sala et al. 1988, $r^2 = 0.75$). Thus, this ''greenness'' index has a better area coverage and a closer association with ANPP than rainfall.

In addition to a closer relationship with livestock

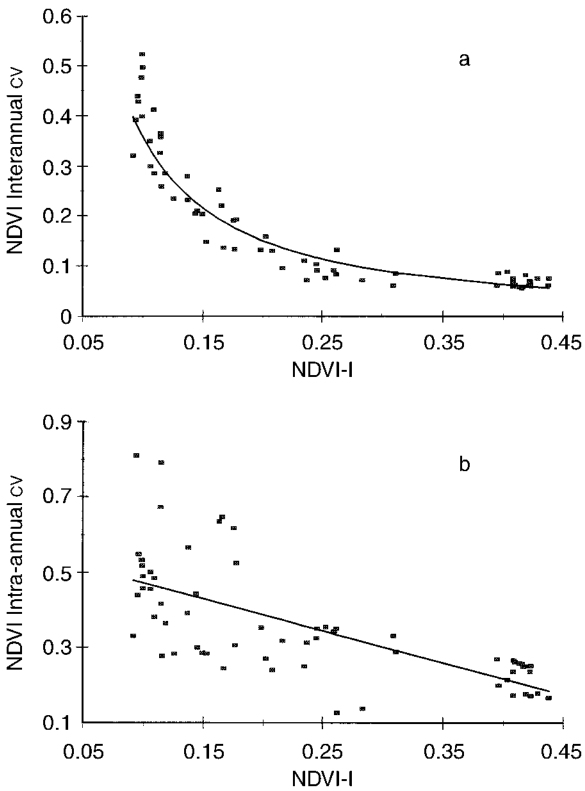

FIG. 2. Relationship between the coefficient of variation of NDVI and mean annual integrated NDVI: (a) NDVI among years; (b) NDVI within a year.

biomass, the predictive ability of NDVI-I is strengthened by its finer spatial resolution and wider availability than rainfall. NDVI data are available for virtually any area of the world, whereas rainfall data are scarce. Also, NDVI data have a resolution that is unthinkable for rainfall data: 7 km in the case of the images used in this study, or 1 km in the case of NOAA-AVHRR Local Area Coverage data. Decision makers counting with NDVI-I maps could translate NDVI-I into stocking rate for different large areas, as shown by this study, or perhaps smaller areas such as landscape units.

However, we have two cautionary remarks about the utilization of these results. First, extrapolation of our equation to other regions or to different scales should not be done directly without previous investigation. Other regions may have different technological and socio-economic constraints and possibilities that may modify the relationship between livestock biomass and NDVI-I. For example, a lower reliance on native forage and an increasing importance of forage imports from other areas, a common practice in many developed areas of the world and in particular areas of Argentina not included in this study, may weaken the relationship between stocking rate and NDVI-I. Also, we do not know if the relationship observed at the regional level will be the same at local or landscape levels. Our relationship is a strong suggestion that NDVI-I may be correlated with livestock biomass at smaller scales, but the shape and significance of that relationship has to be investigated on the basis of livestock data taken at that same high spatial resolution. The second cautionary remark is that the relationship revealed by this paper should not be used as an indicator of carrying capacity as ''the maximum number of animals which an area of land can support without degradation of plant or soil resources'' (Scarnecchia 1990:553). We do not know whether the stocking rates utilized in Argentinean rangelands are close to that definition of carrying capacity.

Our relationship between stocking rate and NDVI-I, as well as all the other relationships between herbivore biomass and primary productivity or rainfall reported in the literature (Coe et al. 1976, East 1984, McNaughton et al. 1989, Oesterheld et al. 1992), was linear on a log-log scale with a slope >1, which indicates an exponential form. This means that herbivore load per unit of forage resource increases as primary production increases, a pattern observed both at landscape (McNaughton 1985, Frank and McNaughton 1992) and regional scales (McNaughton et al. 1989, Oesterheld et al. 1992). Both previous work (E. G. Jobbágy, *unpublished data*) and our results show that as NDVI-I increases its interannual variability decreases. We also showed that the distribution of NDVI values within the year becomes more even. This suggests that herbivore biomass may be responding not only to the total amount of forage resource but also to its year-to-year reliability and to its seasonal distribution.

The livestock production systems encompassed by this study are strongly based on the direct utilization of native vegetation. Animals are rarely fed silage or grain, and management practices that tend to increase primary productivity, such as fertilization, irrigation, and forage-species replacement, are rare (Oesterheld et al. 1992). Thus, the amount of productive livestock biomass that can be sustained by a given area must be strongly coupled with the amount of forage it can produce. The decisions on stocking rates are entirely made by the managers of the individual ranches. However, the intellectual process by which these decisions are reached is not entirely clear. Data on primary productivity, which should be the basis of that process, are scarce: a recent review reported only 14 published data points for the entire country (McNaughton et al. 1993). Good, long-term rainfall data are also scarce and, in any case, most decision makers are not aware of the published quantitative relationships between ANPP and precipitation (e.g., Sala et al. 1988). Instead, managers rely upon a non-explicit coarse tunning of stocking rate according to previous experiences: good years with apparently low stocking rate are contrasted with bad years with apparently high stocking rate to reach a value of stocking rate that is reasonably safe and efficient. Since selling stocks in years with low ANPP may be economically inconvenient, because of lower prices, it is likely that a manager's perception of the year-to-year variability of ANPP has a strong impact on stocking-rate setting. Seasonality may also play an important role: since production systems in these areas generally have low technological input, practices that result in storage and transfer of forage from a productive season to an unproductive season are not usually feasible. Thus, stocking rate is likely set on the basis of the likelihood of surmounting the limiting season rather than making an efficient use of the productive season. Stocking rates are usually set at the scale of entire ranches or large paddocks, which include an environmental heterogeneity that is ignored for this purpose. This generates a heterogeneity of under- and overutilization of environments, with strong consequences for the function of the system.

Our empirical relationship between livestock stocking rates and NDVI-I reflects all these decision-making processes and perhaps some more that we are not aware of. The relationship could be used to (1) understand what variables may be controlling actual stocking rates, (2) infer the ''average'' stocking rate that would be expected for a given site according to an empirical regional pattern, which might be a better tool than the costly trial-and-error process just described, (3) indicate potential cases of overgrazing or underutilization of particular habitats, (4) provide an indicator of production capacity that may guide policy makers to make decisions about the spatial distribution of different policies, such as tax rates or technological developments, and (5) stimulate further research on potential relationships at finer scales, which would have strong impacts on management decisions at that scale. Our results confirm the strong association between herbivore biomass and the basis of the energy flow, ANPP, for systems dominated by wildlife or by livestock supported by natural vegetation (Coe et al. 1976, East 1984, McNaughton et al. 1989, Oesterheld et al. 1992). They suggest potential explanations for the exponential nature of that association: the pattern of interannual and seasonal variation of ANPP. They present NDVI-I as the best predictor of stocking rates because of its close fit to actual data, wide availability, and high spatial resolution.

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