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# Monitoring forage production for farmers' decision making

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**Abstract**

Objective management of grazing livestock production systems needs monitoring of forage production at the managerial unit level. Our objectives were to develop a system that routinely estimates forage above-ground net primary production (ANPP) at the spatial and temporal resolution required by farmers in the Pampas of Argentina, and to facilitate adoption of the system by end users as a managerial support tool. Our approach was based on the radiation use efficiency (RUE) logic, which proposes that ANPP is determined by the amount of photosynthetically active radiation absorbed by the canopy (APAR), and the efficiency with which that energy is transformed in above-ground dry matter (radiation use efficiency, RUE). APAR is the product of incoming photosynthetically active radiation (PAR) and the fraction absorbed by the canopy (fPAR). We estimated fPAR as a non-linear function of MODIS normalized difference vegetation index (NDVI). RUE was empirically estimated for the two principal forage resources of the region, yielding the following relations: $\text{ANPP} = 0.6 \times \text{APAR} + 12$, ($R^2 = 0.86$; $p < 0.001$; $n = 18$) for the upland sown pastures, and $\text{ANPP} = 0.27 \times \text{APAR} + 26$, ($R^2 = 0.74$; $p < 0.001$; $n = 18$) for the lowland naturalized pastures, with ANPP in g/m$^2$/60 days and APAR in MJ/m$^2$/60 days. The models were able to predict independent ANPP values with acceptable accuracy. Computational procedures were automated and run in a Relational Data Base Manager System that stored and managed all the information. The system is currently monitoring 212,794 ha in 83 farms and provides monthly ANPP values for the previous month and a history of the last 6 years. The data so generated show ANPP differences between the two major forage resources, considerable variability of a given month's ANPP among years and paddocks, and contrasting among-farm differences in the efficiency of conversion of ANPP and forage supplements into beef production. The system was well accepted by end users who utilize it mainly for making near real time decisions according to last month ANPP, and explaining results of previous production cycles by incorporating ANPP as an explicative variable. However, there were differences among farmers in the degree of utilization, apparently related to the advisor's attitude toward this new technology. Our results indicate that (1) forage production of large extensions can be monthly monitored at the paddock level by a small laboratory with capabilities in geographic information systems, and (2) advisors and farmers apply this information to their managerial decisions.


*Keywords:* Livestock production systems; Forages; Modeling; Decision support tool; Remote sensing; MODIS

## 1. Introduction

In temperate regions, grazing livestock production systems are primarily constrained, both biophysically and economically, by the amount, seasonality, and interannual variability of forage productivity (Oesterheld et al., 1992, 1998; Vallentine, 2001; Diaz-Solis et al., 2006). Setting stocking rate in these systems is the principal managerial decision (Walker, 1995; Diaz-Solis et al., 2003, 2006). Stocking rate is far more stable than forage productivity, which may lead to periods of both food scarcity and forage surplus that, if not corrected with the use of supplements and the production of reserves, reduce current and potential animal production. In this context, the forage balance, a systematic comparison of food offer and demand, and efficiency calculations are key diagnostic tools that allow

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farmers and advisors to plan and evaluate managerial decisions in a rational, objective way. However, precise diagnostic tools of this sort require a systematic quantification of forage productivity (above-ground net primary production, ANPP) as a key input (Stuth et al., 1993).

Biomass harvests through time and classical pasture simulation models are the major alternatives to face this critical need of quantifying forage productivity, but they have limitations to be extensively implemented at the managerial unit level. The large spatial heterogeneity and the seasonal and interannual variability of forage resources require intense sampling repeated through time. Thus, biomass harvests become extremely time- and labor-consuming if a representative spatial and temporal estimation of every – or even some – managerial unit is pursued (Sala and Austin, 2000; Hirata et al., 2005). Pasture simulation models have proven to be very useful for scientific development (Johnson and Thornley, 1983, 1985; McCall and Bishop-Hurley, 2003; Peri et al., 2003; Corson et al., 2006). However, they need detailed information on parameters and/or intermediate variables, like leaf area index or soil characteristics, which are, as biomass, very difficult to obtain in a representative way at the paddock scale under productive conditions (Donnelly et al., 2002; Diaz-Solis et al., 2003; Zhang et al., 2006).

Alternatively, the so-called radiation use efficiency (RUE) logic, based on Montheith (Monteith, 1972) ecophysiological model, can be used to quantify forage productivity (Hill et al., 2004; Piñeiro et al., 2006; Reeves et al., 2006). The RUE logic proposes that the amount of above-ground dry matter produced per-unit area during a period of time (ANPP) is determined by the amount of photosynthetically active radiation absorbed (APAR) by the canopy in that period, and the efficiency with which that energy is transformed in above-ground dry matter (radiation use efficiency, RUE):

$$\mathrm{ANPP}(\mathrm{kg\ DM/ha/month}) = \mathrm{APAR}(\mathrm{MJ/ha/month}) \times \mathrm{RUE}(\mathrm{kg\ DM/MJ})$$

APAR is the product of incoming photosynthetically active radiation (PAR) and the fraction absorbed by the canopy (fPAR). The RUE logic has been widely used from crop (Sinclair and Muchow, 1999) to global (Running et al., 2000, 2004) scales to estimate gross and net primary production because of the relatively conservative behavior of RUE within biomes and the possibility to estimate fPAR from simple vegetation indices calculated from remote sensing. However, monitoring fPAR with acceptable temporal resolution at the paddock level has been constrained by the low spatial resolution of the remote sensing information utilized (Di Bella et al., 2005; Paruelo et al., 2000; Reeves et al., 2001; Donnelly et al., 2002; Hill et al., 2004). The moderate resolution imaging spectroradiometer (MODIS) aboard the NASA earth observing system (EOS) Terra satellite combines high spatial and temporal resolution (<6 ha pixel size and almost daily overpasses) with improved geolocation, atmospheric correction, and cloud screening. These features are basic requirements to biophysically monitor pastures at the managerial unit level.

Frequently, in most managed complex systems, the problem of scarcity of information and/or technology related to system functioning is solved not only by generating and providing that information or technology, but also by supporting the adoption process (Seelan et al., 2003). In fact, the incorporation of information or technology into the decisional framework of end users is sometimes as limiting as the lack itself (Campbell and Stafford Smith, 2000; Cros et al., 2004). The role of advisors and groups of farmers is critical in this process since farmers prefer to adopt technologies with technicians as intermediates, and working in groups makes the advisory and communication process more efficient (Donnelly et al., 2002; Seelan et al., 2003). For the research community, participating in the incorporation process could, in turn, provide critical feedback to refocus the objectives and improve the quality and format of the information or technology being generated (Jochec et al., 2001; Keating and McCown, 2001).

Because of all these difficulties, most livestock production systems worldwide are currently being managed without a routine quantification of forage productivity, one of the critical variables required for planning and for evaluating system efficiencies. The projects "Agrosat" (http://www.agrosat.info) in Spain and "GrassCheck" (http://www.ruralni.gov.uk) in Ireland present preliminary efforts in this sense but the spatial scale they use is not appropriate for planning at the farm scale, and their methods are not published. The CSIRO in Australia developed a per paddock monitoring system (http://www.pasturesfromspace.csiro.au), partially based on Hill et al. (2004), but results evaluating the degree of use of that system by farmers and advisors have not been published. A near real-time system to monitor forage production at the managerial unit level, accompanied by the know-how needed to integrate it into the decisional framework of end users, would constitute a novel managerial support tool that could help to reach the objectives of increasing livestock production and the sustainability of livestock production systems. In this context, the objectives of this paper are: (1) to develop the basis of a system that routinely estimates productivity of different forage resources at the spatial and temporal resolution required by farmers, (2) to show the type of information on forage productivity produced as system's output, and (3) to show adoption and utilization by end users as a managerial support tool.

## 2. Methodology

### *2.1. Region of study*

The study focused on the SW portion of the Pampas in Argentina. Climate is temperate subhumid. Mean annual precipitation ranges from 800 to 900 mm. Precipitation is more abundant in spring and summer (70%). Droughts are relatively common in winter, as a result of extremely low precipitation, but they may also take place in summer due to high evapotranspiration. Mean monthly temperature ranges from 7 to 9 °C in July to 21–22 °C in January. About 35 frost events occur between May and September, but both forage production and grazing occur year round. Mollisols are the dominant soils and they are often limited by a petrocalcic horizon, flooding, or alkalinity. Landscape-level heterogeneity consists of a mosaic of two topographical levels subjected to different water and salinity regimes, and concomitantly, to different land use. The upland position is typically under a $4 \times 4$ year pasture-crop rotation. Upland sown pastures are typically composed of *Festuca arundinacea*, *Dactylis glomerata* and *Lolium multiflorum* as grasses, and *Medicago sativa*, *Trifolium pratense* and *Trifolium repens* as legumes. During the cropping period of the rotation, winter crops are wheat and barley, and summer crops are sunflower, soybean and, to a lesser extent, corn. The lowland position is frequently occupied by Tall wheatgrass (*Agropyron elongatum* = *Elytrigia elongata*) naturalized pastures or by natural grasslands co-dominated by C3 and C4 grasses of the genus *Stipa*, *Piptochaetium*, *Briza*, *Paspalum*, and *Botriochloa*.

The farms under study are members of a national consortium of farmers (AACREA, Spanish acronym for "Argentine Association of Regional Consortia of Agricultural Experimentation", http://www.aacrea.org.ar) whose objectives are to achieve profitable and sustainable agricultural enterprises by exchanging experiences and testing technologies, and to transfer that knowledge to contribute to the country's development. This consortium is organized in groups with ~10 members (farms) each. Members of a group share an advisor that makes monthly 1-day visits to each farm, and organizes monthly group meetings in a host farm that rotates every month. Meetings have a standard format that basically consists of evaluating each farm in relation to animal nutrition (state of forage resources), crop condition, and the principal productive activities they are developing. Particular attention is paid to the host farm, including a thorough tour and further criticism. This intense interaction generally results in farms having similar management: in relation to livestock production, they use rotational grazing all around the year with variable outdoor supplementation during winter, especially for fattening steers.

### 2.2. The monitoring system

We designed a monitoring system that uses incident solar radiation, satellite-derived vegetation indices, calibrated values of RUE, and land-use information, which, through several computational procedures, generates forage productivity estimations at the paddock level with a monthly step.

We obtain daily incident solar radiation from an agrometeorological station centered in the region of study (37°24′17.8″ S, 61°26′27.4″ W, elevation 200 m ASL), which has an almost circular shape with a diameter of ~150 km. PAR is assumed to be 48% of incident solar radiation (McCree, 1972).

We utilize the normalized difference vegetation index (NDVI) from the MODIS project (Collection 4 of MOD 13, Vegetation Indices product, http://lpdaac.usgs.gov/main.asp) that consists of gridded-16 days composite images at four different spatial resolutions, from which we use the highest: 250 m pixel size (~6 ha). Per-pixel quality assessment (QA) information is included in the MOD 13 product, so we discard the pixel values that do not have the highest quality and replace them by simple linear interpolation from the previous and the following dates of the same pixels (less than 2% of the observations, mainly due to cloudy conditions).

We estimate fPAR as a non-linear function of MODIS NDVI (Gallo et al., 1985; Potter et al., 1993; Sellers et al., 1996; Le Roux et al., 1997; Los et al., 2000; Piñeiro et al., 2006). NDVI is calculated as: $\mathrm{NDVI} = (\rho_{\mathrm{red}} - \rho_{\mathrm{nir}})/(\rho_{\mathrm{red}} + \rho_{\mathrm{nir}})$, where $\rho_{\mathrm{red}}$ is the red surface reflectance and ρnir is the near-infrared surface reflectance. NDVI is directly related to fPAR by green vegetation because it exploits the spectral properties of vegetation, which strongly absorbs visible (especially red) radiation, using that energy for photosynthesis, and strongly reflects near-infrared radiation (Sellers, 1985; Huete et al., 2002). The non-linear relation between NDVI and fPAR accounts for the widely described saturation of NDVI at high Leaf Area Index (LAI) > 3, and implies a linear relation between the simple ratio index ($\mathrm{SR} = (1 + \mathrm{NDVI})/(1 - \mathrm{NDVI}) = \rho_{\mathrm{red}}/\rho_{\mathrm{nir}}$) and fPAR. We parameterized the relation between NDVI and fPAR with local data assigning no absorption (fPAR = 0) to NDVI values corresponding to pixels that had no green vegetation (bare soil or senescent residues due to tillage) and maximum fPAR (fPAR = 0.95) to NDVI values corresponding to pixels with high amount of green biomass (sown pastures with LAI > 3 and high yielding wheat crops during anthesis). The resultant equation was:

$$\mathrm{fPAR} = \min[\mathrm{SR}/(\mathrm{SR}_{\max} - \mathrm{SR}_{\min}) - \mathrm{SR}_{\min}/(\mathrm{SR}_{\max} - \mathrm{SR}_{\min}),\ 0.95],$$

where $\mathrm{SR}_{\max} = 11.62$, and $\mathrm{SR}_{\min} = 1.55$.

RUE values were empirically estimated for the two principal forage resources of the region: upland sown pastures and lowland naturalized pastures. Ground measurements of ANPP were taken from October 2000 through October 2003 at eight sites (paddocks) within the region, four representing the upland sown pastures and four the lowland naturalized pastures. The agronomists that designed the harvest plan tried to resemble the regular intermittent grazing system to which the pastures are normally subjected. Thus, they harvested biomass with a 2 month regrowth period. At each site, eight cages (replicates) of $1 \times 1$ m were used. At the beginning of each regrowth period, vegetation was clipped to a height of 4 cm inside the cages and at the end of that period vegetation was clipped to the same height. ANPP was calculated as the increment of total (oven dry) biomass during the period. For each site and regrowth period, APAR was calculated as the product of PAR and fPAR for that period. fPAR was derived from MODIS NDVI for that period and paddock, represented by at least one 250 m-MODIS pixel. With this information, regression models of ground ANPP as a function of remotely sensed APAR were built for each forage resource as an estimation of average RUE (Demetriades-Shah et al., 1992; Le Roux et al., 1997).

To evaluate the models against independent data, we developed new regression models using only a part of the observed ANPP data set. We used these new regression models to make predictions that were then contrasted with observed ANPP data that were not used to generate the models. Fifteen values were used for model generation and three for model evaluation. We repeated this procedure five times with different random combinations of data used for model generation and evaluation (Manly, 1997; Piñeiro et al., 2006).

We built and maintain an updated geographic information system (GIS) with all the farms that participate in the project. The GIS consists of a very precise geolocated polygon (~20 m error) with paddocks as the minimum spatial unit. Each paddock is associated to a farm, its area, the land use (on yearly basis) from year 2000 to present, and a variable number of pixels that represent it. These pixels were selected by intersecting the paddock polygon with a grid in which each cell has exactly the same geolocation and shape of gridded MODIS image pixels. From this intersection, every pixel completely included in a paddock was selected as representative of it. Among the paddocks with at least 1 pixel, the percentile 25, 50 (median), and 75 was 1, 2, and 5 pixels per paddock, respectively. Since the shape of paddocks sometimes changes, and more importantly, the land use information should be loaded every year and corrected permanently, we are in close communication with farmers, which is clearly facilitated by their organization in groups with an advisor and a regional coordinator.

We built a Relational Data Base Manager System that stores and manages information and operates the monitoring system (Fig. 1). Computational procedures were automated as routines programmed in C++ and are operated by a specific user interface to load all the information described above: daily incident solar radiation, NDVI and QA information for those pixels representing paddocks, RUE values for different forage resources, and spatial information relating pixels to paddocks, paddocks to farms, and farms to groups. Then, intermediate procedures are run to calculate fPAR from NDVI, convert land use information from annual to monthly basis, and identify and correct low quality pixels. Finally, ANPP is calculated and presented as an output consisting of per-paddock and per-month ANPP values (Fig. 1).

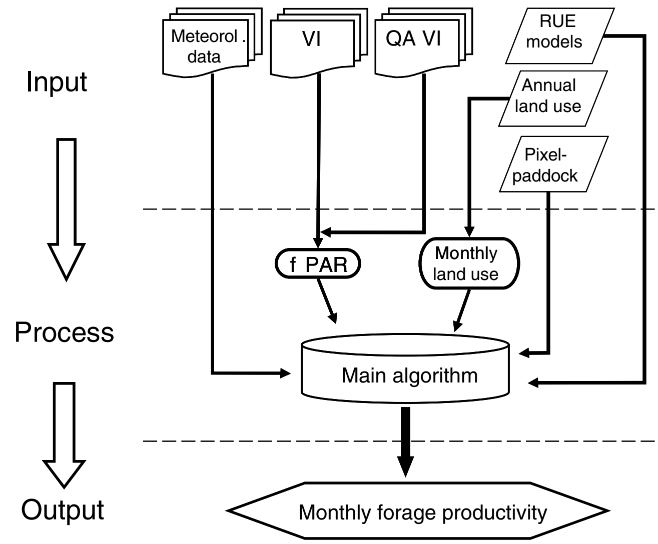


Fig. 1. Flow chart showing the principal calculation procedures of the monitoring system. The main algorithm is based on the radiation use efficiency (RUE) logic. Some inputs are updated every month (denoted by a multilayer icon) and others are updated with lower frequency (denoted by a one-layer icon), e.g. annual land use every year, and RUE models only if a new calibration is developed. VI, vegetation index; QA VI, quality assessment of vegetation index data.

ANPP estimations are run around the 10th of every month, after updating incident solar radiation, NDVI, and QA database with information from the previous month (two 16-day composites, in the case of NDVI and QA) and any other change introduced to the GIS. We distribute the report to each group of farmers by email. Additionally, regular meetings are held with farmers and/or advisors to explain the basis and capabilities of the system, the format and utility of the monthly report, and to obtain feedback from farmers and advisors and evaluate the degree of utilization of the system. In this regard, we performed an inquiry to the advisors of the eight groups that participate in the project after 1 year of receiving the monthly report. They answered eight questions on the degree of utilization of the monitoring system by themselves and by the farmers they advice.

## 3. Results

### 3.1. Basis of the system: RUE calibrations and evaluation

APAR calculated from MODIS NDVI and incident solar radiation mimicked variations of ground ANPP estimations (Fig. 2, average coefficient of variation of ground biomass estimates CV = 0.3). Average ANPP and APAR for each forage resource yielded the following relations: ANPP = 0.6 × APAR + 12, ($R^2 = 0.86$; $p < 0.001$; $n = 18$) for the upland sown pastures, and ANPP = 0.27 × APAR + 26, ($R^2 = 0.74$; $p < 0.001$; $n = 18$) for the lowland naturalized pastures, with ANPP in g/m$^2$/60 days and APAR in MJ/m$^2$/60 days (Fig. 3). These models are used by the main algorithm of the monitoring system to calcu-

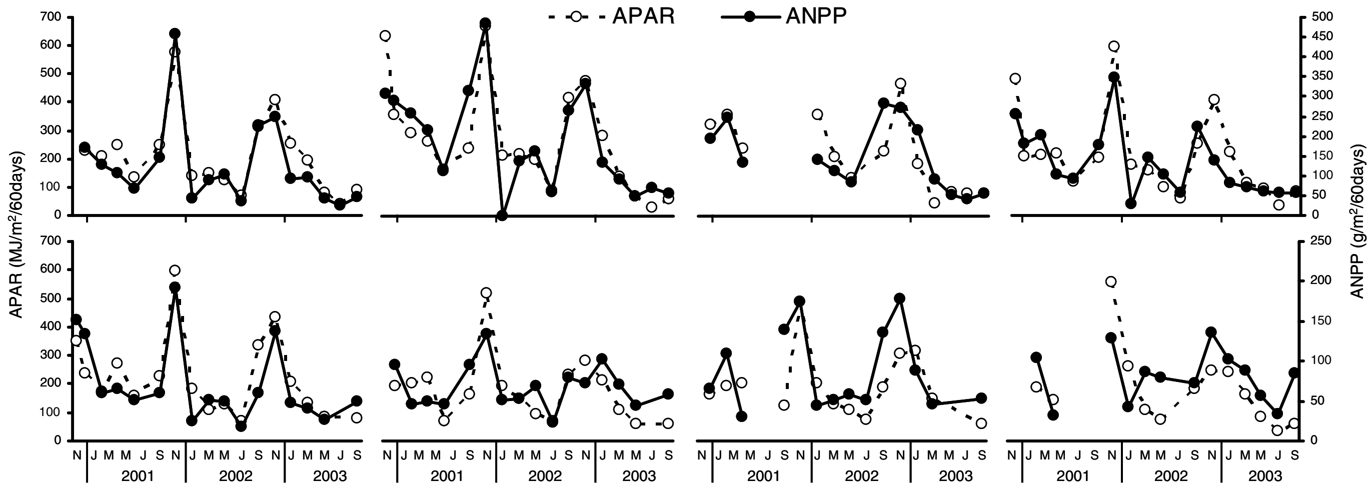


Fig. 2. Ground estimations of aboveground net primary production (ANPP) and absorbed photosynthetically active radiation (APAR) derived from both MODIS normalized difference vegetation index (NDVI) and incident photosynthetically active radiation (PAR) for four upland sown pastures (upper panel) and four lowland naturalized pastures (lower panel).

late ANPP for a given forage resource as a function of APAR. RUE models were able to predict independent ANPP values with acceptable accuracy (Fig. 4). Observed vs. predicted ANPP were closely related (upland pastures: $R^2 = 0.87$, root mean square error, RMSE, 49 g/m$^2$/60 days, average positive bias = 6%; lowland naturalized pastures: $R^2 = 0.72$, RMSE = 21 g/m$^2$/60 days, average negative bias = 8%).

### 3.2. Type of information on forage productivity produced

We are currently monitoring a total area of 212,794 ha, belonging to 83 members from 8 AACREA groups, who have requested to be part of this technological development. Each advisor receives the report of his group and distributes it among the farmers at the monthly meeting. The report consists of a MS Excel file that contains a spreadsheet and a partially pre-built query, in the form of pivot table and associated pivot chart. As an example, the report sent to Lamadrid group in June 2006, estimating ANPP for different forages resources at the paddock level from March 2000 through May 2006, is available as a supplementary file.

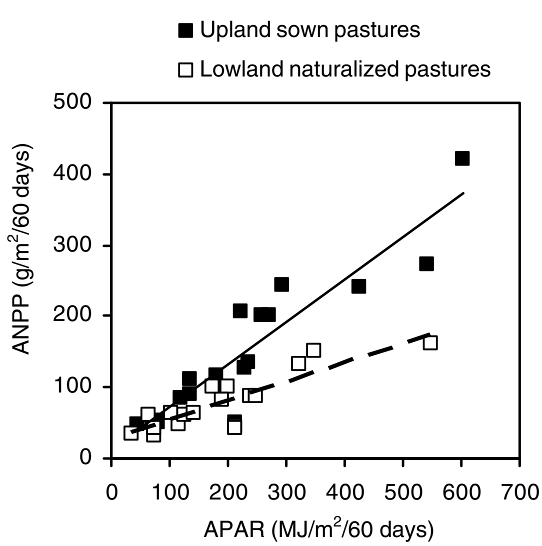


Fig. 3. Calibration between ground estimations of ANPP and MODIS-derived APAR. Each data point is the average APAR and ANPP, in each date, of the four sites of Fig. 2.

The reports reveal key aspects of the forage resources. For example, Fig. 5 shows monthly patterns of ANPP from March 2000 through May 2006 for one of the groups of farmers. These patterns are the average of a large number of paddocks (~130, depending on the group dimension). Upland sown pastures are much more productive than lowland naturalized pastures, especially in spring, when usual good climatic conditions allow upland sown pastures to express their potential rate of growth. However, both forage resources show a similar seasonal pattern: a peak in spring, a drop through summer, then a year-dependent slight peak in autumn, and a less productive period during winter.

By selecting a farm of interest in the query, ANPP curves for each paddock can be seen (Fig. 6). There are differences related to type of forage resources but also differences among paddocks with the same forage resource. ANPP is only calculated for a paddock during the time period in which its land use corresponds to a forage resource; because of that, some paddocks in Fig. 6 do not have information during some months or years.

ANPP frequency distribution for a particular month allows both inter annual and inter paddock comparisons. Fig. 7 shows, for the last 6 years, ANPP frequency distribution for September, the month that usually marks the shift from typical winter to spring growth rates. Considerable variability can be seen both among years and paddocks, especially in the upland sown pastures. For example, in low productive years (2003 and 2005) average productivity

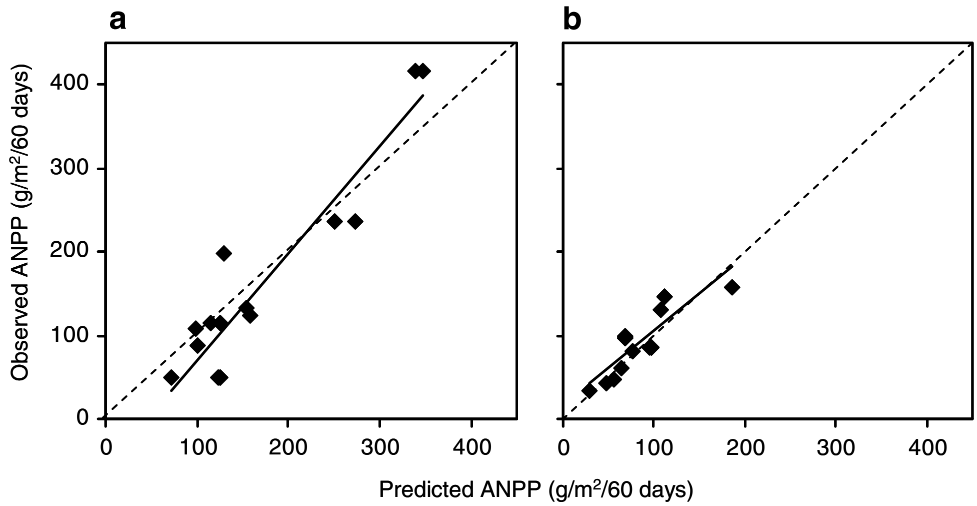


Fig. 4. Relationship between observed and predicted ANPP. Observed ANPP values were not included in the generation of the models to estimate Predicted ANPP. (a) Upland sown pastures and (b) lowland naturalized pastures.

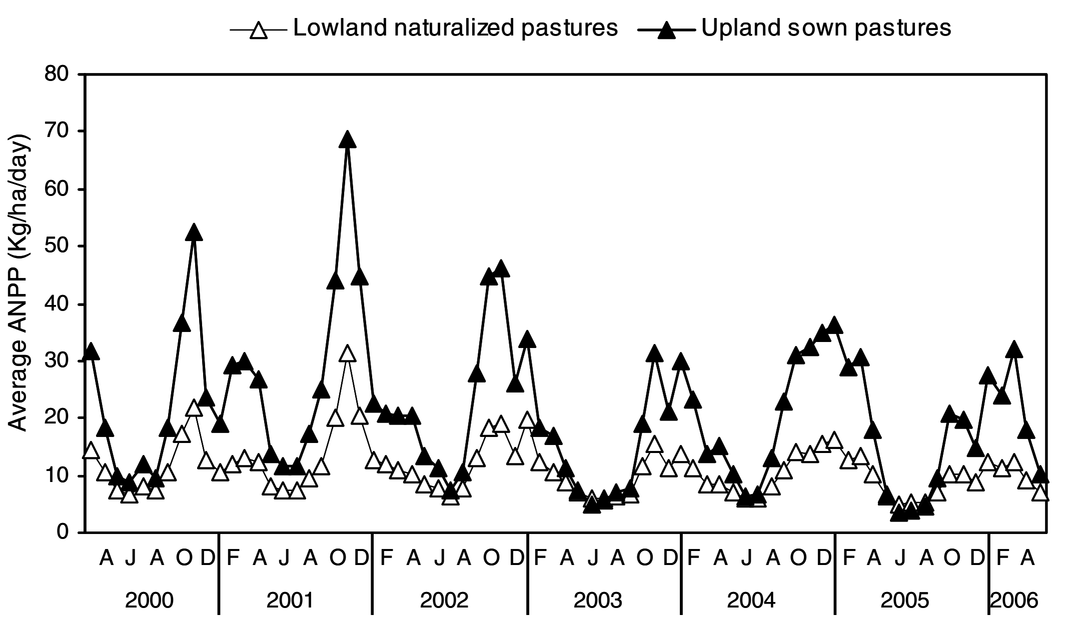


Fig. 5. Average monthly estimates of ANPP for all paddocks with upland sown pastures and lowland naturalized pastures of the Lamadrid AACREA group.

in September was 12 kg/ha/day, while in much more productive years (2001 and 2002) was around 30 kg/ha/day.

### 3.3. Utilization by advisors and farmers

Different users (advisors, farmers) analyze the monthly reports according to their objectives and creativity. These analyses, based on the forage balance approach, can be divided into those that aim at making near real-time decisions according to last month ANPP, and those that try to explain results of previous beef production cycles by incorporating ANPP as an explicative variable. Making decisions on animal movements according to last month ANPP is among the first group of analyses, and in these cases advisors combine the information on last month ANPP with the historical data on the current month to estimate ANPP for the following days or weeks.

Within the second type of analyses, Fig. 8 shows that the maintenance of beef production levels in production cycles of low ANPP is accompanied by an increase in the use of corn supplementation. The production cycle 2004–2005 shows low efficiency in the use of supplements: even though ANPP was high, more supplements were required to obtain a beef production level similar to previous years. Considering that the type of pastures and livestock categories remained constant across years, a more detailed – monthly – analysis would be necessary to identify the unbalances within the year that led to such a low efficiency. Another

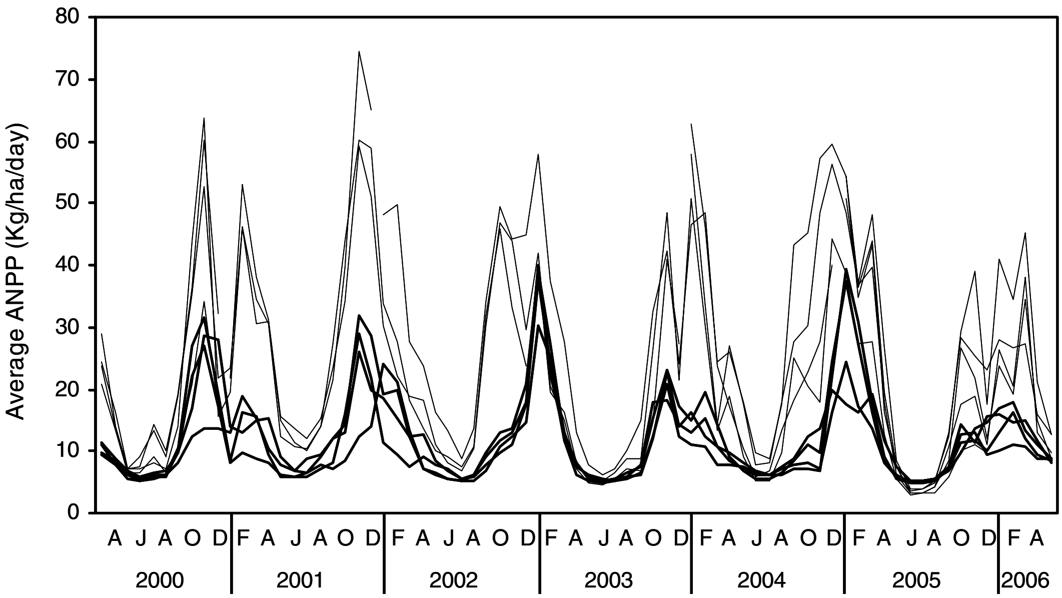


Fig. 6. Per paddock monthly ANPP for a particular farm ("San Juan"). Thin lines represent paddocks with upland sown pastures, and thick lines represent paddocks with lowland naturalized pastures.

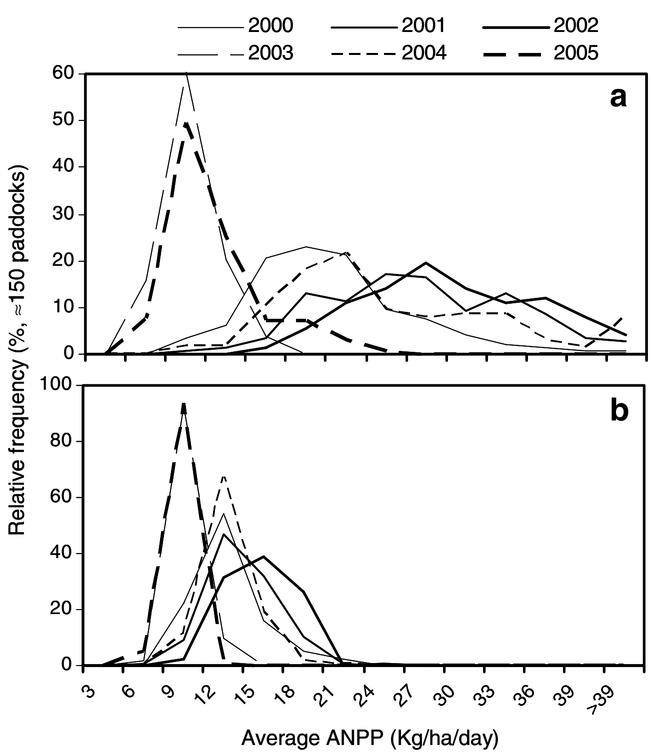


Fig. 7. Frequency distribution of September per paddock ANPP for the last 6 years. (a) Upland sown pastures and (b) lowland naturalized pastures.

example of this second type of analyses is the comparison of system efficiencies for different farms (Fig. 9): the rate with which ANPP is transformed into beef production is highly variable among farms. From this diagnosis, straight forward managerial priorities can be derived to increase beef production: some farms need to increase forage production while others need to increase the utilization efficiency and/or the quality of the forage produced.

With the double purpose of facilitating the use of this technology by end users and to monitor how they are using it, we participated in 35 extension meetings in the last two years. This intense interaction and an ad hoc poll revealed that this near real-time monitoring system was well accepted and used by farmers and advisors (Table 1). However, there are differences among groups and between advisors and farmers: while all advisors frequently utilize the monitoring system (at least once every 3 months) for performing, controlling, or correcting the current year forage balance, a lower proportion of the farmers did that. Additionally, most, but not all, advisors also utilize the system once a year for the analysis of the previous production

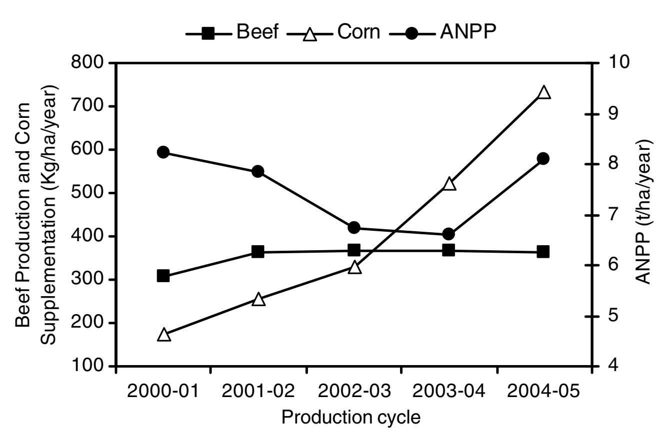


Fig. 8. Beef production, corn supplementation and annual ANPP on average for all forage resources for "San Juan" farm for the last five production cycles.

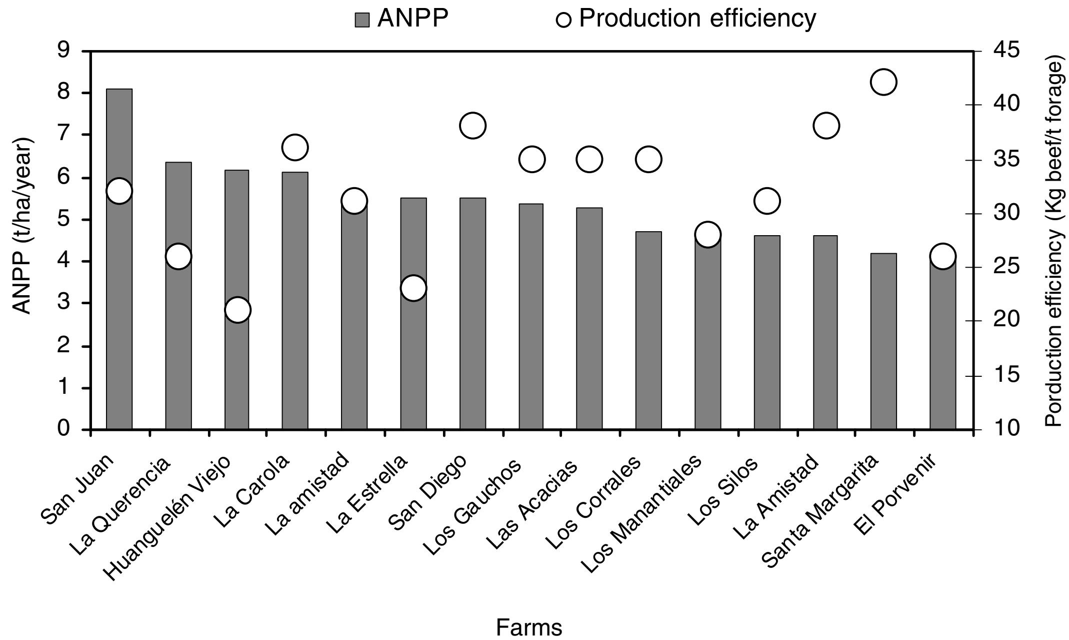


Fig. 9. Annual ANPP and production efficiency (defined as kg of beef produced per ton of forage produced, discounting the amount of beef produced from supplementation) for Lamadrid AACREA group farms in the production cycle 2004–2005.

Table 1
Inquiry answered by the advisors of the eight groups that compose the AACREA South West region (Utilization of ANPP reports in the South West region of AACREA*)

| Percentage of farmers or advisors that: | % of advisors | % of farmers |
|---|---|---|
| | Total number: 8 | Total number: 83 |
| Opened the report at least once | 100 | 77 |
| Frequently (at least once every 3 months) utilize the report to perform/control/ correct the forage balance of the current production cycle | 100 | 19 |
| Utilize the report every year to analyze the performance of the previous production cycle | 88 | 35 |
| Only occasionally used the report to perform a particular analysis | 0 | 30 |
| Utilize the report with additional objectives | 88 | 8 |
| *Do not utilize the report because of* | | |
| 1. High complexity | 0 | 34 |
| 2. Low precision | 0 | 6 |
| 3. Difficulties in utilizing information on pasture growth rate to make decisions | 0 | 40 |

* Values are not additive within columns because alternatives in the inquiry were not excluding.

cycle. In contrast, this was one of the most frequent uses among farmers (Table 1).

## 4. Discussion

We designed a monitoring system that produces monthly estimates of forage productivity at the paddock level, and delivers the information to advisors and farmers who utilize it as a managerial support tool. The system is based on the RUE logic, a MODIS vegetation index, and a consortium of farmers. The RUE logic, simple and mechanistic, provided the framework to combine (1) remote sensing information of continuously-monitored vegetation with (2) detailed ground measurements of ANPP to produce a calibration model for each type of forage resource. The 250 m-MODIS vegetation indices have overcome the trade-off between spatial and temporal resolution present in previous sensors. As a result, the system may provide a detailed temporal monitoring of small areas (e.g. paddocks), a key feature if information is to be used by farmers. Finally, the organization of farmers in consortia guided by an advisor constitutes an efficient way for interchanging data (e.g. land use rotations of thousands of paddocks) and receiving feedback (e.g. suggestions from the farmers). As a result, grazing production systems are now under a more rational managerial scheme, both in relation to past production cycle analysis and to planning.

The use of the RUE logic for the monitoring system was facilitated by the conservative behavior of RUE among seasons and years. Considering ANPP values for the region

(Paruelo et al., 2000; Piñeiro et al., 2006), the 3-year time series we used for calibration was very convenient since it included both high-and-low-production years (2001 and 2003, respectively, largely determined by differences in the amount and timing of precipitation). In spite of this wide range of ANPP values, which likely includes much of the variation expected in other years, APAR followed ANPP very closely. This conservative behavior of RUE both among seasons and climatically distinct years could be a consequence of the time scale at which ANPP was calculated (Medlyn, 1998), and the fast response of leaf area to environmental factors that these pastures show (Posse et al., 2005). For example, a relatively short drought period probably reduces RUE for a few days, but such a stressful condition would also rapidly restrict leaf area expansion, which (added to leaf rolling and increased senescence) would reduce fPAR and, concomitantly, APAR. Integrated over a longer period, such as two months, most of the variation in ANPP would be explained by these changes in APAR and only a marginal portion by changes in RUE. This agrees with the resource balance hypothesis, which states that light harvesting is downregulated by plants to redirect investment in acquiring any other resource limiting growth (Field et al., 1995; Joel et al., 1997). The effect of time scale on RUE calculations under stress conditions needs further study. However, regardless of the mechanism underlying the conservative behavior of RUE, the strong empirical relation observed in this study between ground ANPP estimates and satellite-derived APAR is useful for locally monitoring ANPP at monthly to bimonthly steps, a time scale relevant for on-farm decision making.

Stocking rate is the managed variable that most heavily impact on animal production per hectare and per year in grazing livestock production systems (Walker, 1995; Diaz-Solis et al., 2003). Additionally, ANPP is the principal variable that limits stocking rate (especially if supplements are not used). From the combination of these two variables, a risk function can be defined: increasing stocking rate is associated to an increasing productive risk, but that function highly depends on the pattern of ANPP variability, which in turn depends on the combination of forage resources and the agroclimatic conditions of a farm. Thus, the risk level associated to a given stocking rate is usually unknown because of lack of information on the variability of forage production (Kaine and Tozer, 2005). Information provided by the monitoring system presented in this paper clearly solves this problem because it provides this quantification for a large combination of forage resources, soil types, and managerial systems, for a time series of – at present – more than 6 years. When supplements are used to avoid food scarcity, beef production levels can be sustained even in years with low ANPP (Fig. 8), but with higher production costs. In these cases, the productive risk (probability of ANPP not meeting livestock demand) may be applied to an economical perspective: how frequently the economic results will be negative for different scenarios of stocking rate within the real ANPP time series?

Our project had the explicit objective of making the monitoring system a managerial support tool for end users. The frequent interaction with advisors and farmers guided the design and implementation of the system to meet the needs of end users. Examples of these adjustments are the segregation of forage resources into different types of pastures, the definition of a standard relation between yearly to monthly land use, the time step of productivity estimates, and the format and time of distribution of reports. In relation to the format, for example, end users preferred the report as a worksheet with which they could perform calculations, instead of as a map, which was considered as a more qualitative description. Although both advisors and farmers were the end users of the monitoring system, as expected from previous works (Seelan et al., 2003), advisors had an additional role as facilitators of the adoption of this new technology by the farmers. As a result, the extent with which the system was used in a group was largely influenced by its advisor's attitude toward the project. The inquiry revealed that most advisors regularly utilize the system while only a minor part (19%) of farmers does that (largely those that are also professional agronomists). It is more likely that advisors and professional agronomist farmers have the conceptual framework required to include quantitative estimates of forage productivity in grazing management. In fact, planning the forage balance is one the aspects of management for which farmers need more advice, both for a yearly basis and for the fine-tune adjustments of animal movements and supplementation that they monthly perform during the advisor visit. The organization of farmers in consortia was also relevant in the adoption process because it contributed to a more fluent communication process among farmers and between farmers and both advisors and our research team.

Our approach aims to balance the robust mechanistic background of the RUE logic with certain degree of empiricism required to operationally monitor productivity at the time and spatial scales needed by farmers. This situation could limit our estimates. First, an empirical relation between NDVI and fPAR derived from the literature and parameterized for local conditions was used. Although the shape of that relation could be different for different biomes (Myneni et al., 2002), our work is restricted to natural and sown pastures, which mitigates that potential limitation (Fensholt et al., 2004). We recently satisfactorily evaluated (data not shown) our NDVI-fPAR model in some canopies from farms that participate in the monitoring system. Second, the estimation of RUE from calibrations between ground estimates of ANPP and APAR limits its use to local conditions and to a minimum time step: it is not possible to have, for example, specific daily or weekly estimations. We are conducting field experiments to test the utility of including a more mechanistic computation of daily RUE. This approach, based on the general logic of the MOD 17 algorithm (Heinsch et al., 2003), will assume a potential RUE that would be then downregulated by scalars accounting for water, temperature, and light stresses. Third, both respiration and below-ground productivity are integrated in the empirical RUE estimations. This would not be a problem if both variables were a constant proportion of above ground net primary production (Hanan et al., 1995; Nouvellon et al., 2000). While this assumption seems reasonable for respiration, it may not hold for belowground production, which appears to be modified by grazing. However, measuring and considering a differential belowground productivity for different periods after grazing events would not be possible in practice in the context of the monitoring system.

The spatial and temporal scale of the estimates generated by the monitoring system could limit its utility in some highly intensive production systems. Since the 6 ha pixels are fixed on the ground, in general each paddock has to have a minimum of ~20 ha in order for a pixel to be completely included in it. In Argentina, however, only some dairy systems have a significant number of their paddocks under this area threshold. It is worth noticing that we are referring to paddocks and not to strips, since from a managerial perspective it is necessary to quantify the ANPP of the whole grazing circuit. The temporal scale could be limiting in systems where decisions are fine-tuned at intervals shorter than a month. Again, this type of farms is uncommon outside the highly intensive dairy systems. However, the monitoring system may still be useful because in most of these cases farmers have no ANPP information at all, and because the monthly estimates are sufficiently detailed for analyzing past production cycles.

The availability of monitoring systems such as the one here described has several implications for the sustainability of rangelands and for ecological and agricultural research. A spatially and temporally detailed knowledge of forage production allows farmers to set stocking rates with more precision, which may translate into a more efficient use of resources and a lower risk of overstocking them. The near real-time nature of the system and the included monthly history allow the farmers to anticipate decisions in the event of extreme situations of either low or high forage production. Additionally, the RUE logic of the system, with its strong emphasis on fPAR as determinant of forage production, makes the farmers and advisors more conscious of the value of remnant leaf area after grazing or drought events, with positive consequences in terms of further productivity and conservation of the rangeland. The extraordinary increase of availability of ANPP data with relevant temporal and spatial resolution opens the way to the research of the environmental and managerial controls of ANPP at group, farm and paddock levels, which may also include experimental manipulations and evaluation at those same levels. Global perspectives of livestock production systems for the next 25 years predict a strong increase of intensification that will require improved management (Bouwman et al., 2005). Better monitoring of forage production appears as a key element of such a change.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.agsy.2007.01.001.

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