ECOSYSTEM MODELING ADDS VALUE TO A SOUTH AFRICAN CLIMATE FORECAST

RANDALL B. BOONE [1], KATHLEEN A. GALVIN [1,2],
MICHAEL B. COUGHENOUR [1], JERRY W. HUDSON [2], PETER J. WEISBERG [3],
COLEEN H. VOGEL [4] and JAMES E. ELLIS [1*]

[1] *1499 Campus Delivery – B234 NESB, Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, Colorado 80523-1499, U.S.A.*
E-mail:rboone@nrelcolostate.edu
[2] *Department of Anthropology, Colorado State University, Fort Collins, Colorado, U.S.A.*
[3] *Department of Forest Sciences, Swiss Federal Institute of Technology, Zurich, Switzerland*
[4] *Department of Geography and Environmental Studies, University of Witwatersrand, Johannesburg, South Africa*

Abstract. Livestock production in South Africa is limited by frequent droughts. The South African Weather Service produces climate forecasts estimating the probability of low rainfall three and six months into the future. We used the ecosystem model SAVANNA applied to five commercial farms in the Vryburg region of the North-West Province, and five communal areas within the Province, to assess the utility of a climate forecast in refining drought coping strategies. Rainfall data from 1970 to 1994 were modified to represent a drought (225 mm of rainfall) in 1977/1978, and used in simulations. In a simulation on an example commercial farm we assumed a forecast was available in 1977 portending an upcoming drought, and that the owner sold 490 cattle and 70 sheep prior to the drought. Over the simulation period, the owner sold 31% more cattle when the forecast was used, versus when the forecast was ignored. Populations of livestock on both commercial and communal farms recovered more quickly following the drought when owners sold animals in response to the forecast. The economic benefit from sales is being explored using optimization techniques. Results and responses from South African livestock producers suggest that a real-time farm model linked with climate forecasting would be a valuable management tool.

1. Introduction

Periodic droughts occur in semi-arid areas of South Africa and neighboring countries during El Niño-Southern Oscillation (ENSO) events (FEWS, 1997). Droughts typically occur every three to six years (e.g., 1982–1984, 1986–1987, 1990–1992, 1994–1995 (Dilley, 2000; NOAA, 2002)). These frequent droughts can reduce range (veld or pasture) condition, crop yields, and livestock and wildlife populations (Ellis and Galvin, 1994; Dilley, 2000). Forecasts that predict the occurrence of droughts allow agricultural producers to modify their management and reduce losses (Mjelde et al., 1998; Stern and Easterling, 1999; Dilley, 2000), although

* Deceased.

Climatic Change **64:** 317–340, 2004.

other constraints on their responses to drought (e.g., access to credit or seeds) may still limit opportunities to respond (Roncoli et al., 2000; Vogel, 2000).

The South African Weather Service (SAWS) Long-term Operational Group Information Centre produces short-term weather forecasts (up to one week into the future, from the forecasting date), and long-term climate forecasts (biweekly, monthly, three months and six months). Three month and six month forecasts, called *Seasonal Outlooks* by SAWS, allow crop and livestock producers to plan well in advance for anticipated dry or wet seasons, and are the focus of our work. In Seasonal Outlooks, SAWS does not attempt to forecast the rainfall at a given location; such foresight and precision are not possible. Instead, the forecasts are for the entire country, sometimes divided into two or three regions. For each region, three probabilities are assigned representing the likelihood of a season that is: (1) wetter than normal, (2) normal, or (3) drier than normal (LOGIC, 2001). These probabilities (reported as percentages) must sum to 100, and the more confident SAWS are of their forecast, the more skewed the numbers they assign. For example, a rainfall forecast of '20 : 20 : 60' represents their forecasting a 20% chance of a wetter than normal upcoming season, 20% normal, and a 60% chance of a drier than normal season. A forecast of '30 : 30 : 40' suggests a drier than normal season as well, but lower confidence in the forecast.

Climate forecasts are steadily improving (Mjelde et al., 1998), and calls have been made for the assessment of drought responses using modeling (e.g., du Pisani et al., 1995). The general utility of ecological modeling in African savannas has been demonstrated (e.g., Stafford Smith and Foran, 1990; Wiegand et al., 1998; Boone et al., 2002), and ecological modeling using forecasts has been helpful in Australia (McKeon et al., 2000; Ash et al., 2000). We therefore sought to gauge the utility of ecological modeling when linked to climate forecasts, with a long-term goal of improving drought response by South African communal and commercial livestock farmers. We had two objectives in this portion of our work: to demonstrate the usefulness of an ecosystem model linked with climatic forecasts, and to survey potential users to see if the effort required to make a real-time farm-forecasting system for use in management would be well-spent. This paper focuses upon demonstrating the usefulness of modeling. We report the responses of potential users of a farm forecasting system in the Discussion.

2. Study Area

Data were collected throughout the western region (22°38′ E, 25°15′ S to 25°33′ E, 28°02′ S) of the North-West Province of South Africa (Figure 1). Red-yellow apedal soils dominate the region, with Glenrosa and Mispah soils in southern Vryburg 2, Taung, and northern Ganyesa (Department of Agriculture, 1999). Annual rainfall is about 500 mm in the eastern part of the region (eastern Vryburg 1, 2), 400 mm in eastern Ganyesa district, and 300 mm along the western border of

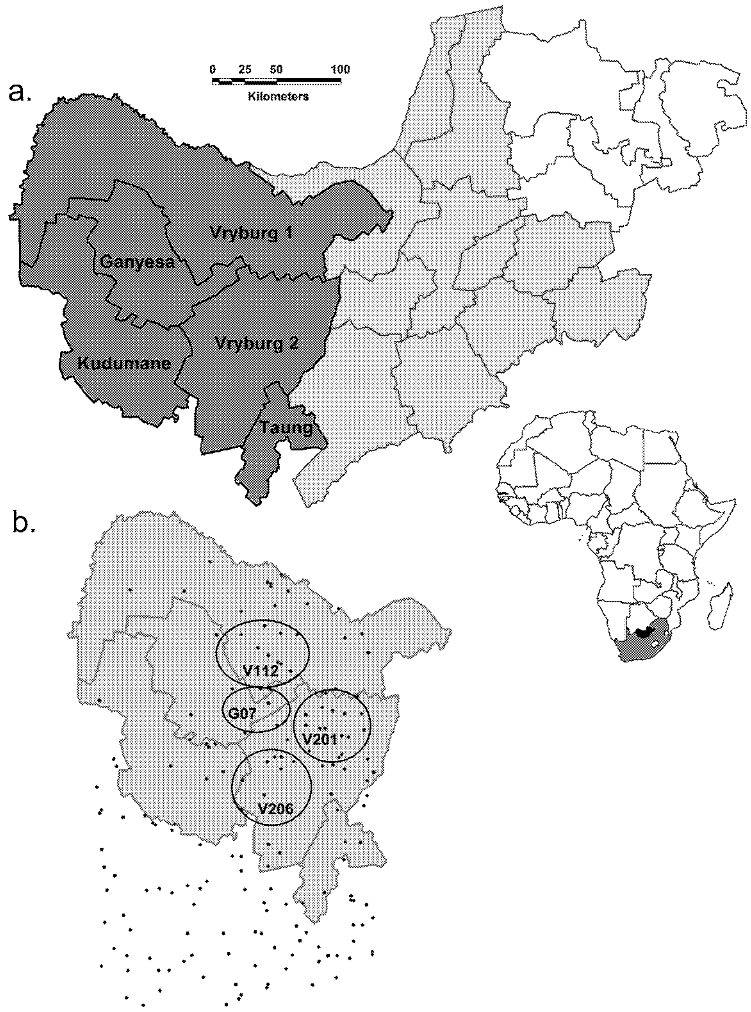

Figure 1. The (a) North-West Province of South Africa (shaded in inset). The North-West Province is divided into eastern, central, and western sections (shading on map). The study area is the western section, including Vryburg districts 1 and 2 with commercial livestock production, and the communal lands of Ganyesa, Kudumane, and Taung. Vryburg town is near the center of Vryburg 2, Potchefstroom is in the southeastern portion of the Province, and Johannesburg is 335 km to the east of Vryburg. Weather stations (b) used in modeling are shown as dots, along with the general locations of the three commercial farms (V112, V201, and V206) and the communal area (G07) used in examples.

the study area, abutting the Kalahari Desert to the northwest. However, rainfall in the area is extremely patchy, with adjacent areas sometimes having very different rainfall amounts. The region is within the savanna and grassland biomes of South Africa, and is classed as Kalahari thornveld and shrub bushveld (Acocks, 1975; NBI, 1976). Livestock production is the dominant land use, with some irrigated agriculture. Grazing capacity [the number of livestock that can be supported on a farm over the long term without degradation to the range (Society of Range Management, 1989)] in the area in 1999 was recommended at between 7 ha/LSU (large stock units) in the eastern Vryburg districts, to 25 ha/LSU in northern Ganyesa and 30 ha/LSU in central Taung (Department of Agriculture, 1999). Vryburg 1 and 2 (Figure 1) are commercial areas, where land owners produce livestock for markets. Ganyesa, Kudumane, and Taung (Figure 1) are communal areas, where herders raise livestock on shared lands.

3. Methods

3.1. ECOSYSTEM MODELING

To evaluate ecosystem responses (livestock production, range condition, and potential sales) to predictions in climate forecasts required a model complex enough to represent key interactions among ecosystem components (Hilborn et al., 1995); we used the SAVANNA Modeling System. Initial development of SAVANNA began in the Turkana District of Kenya, and improvements to the model were made in subsequent applications (e.g., Coughenour, 1992; Kiker, 1998; Boone et al., 2002; reviewed in Ellis and Coughenour, 1998). SAVANNA is a series of interconnected Fortran computer programs that model primary ecosystem interactions in arid and semi-arid landscapes, simulating functional groups for plants and animals (e.g., perennial and annual grasses, cattle, horses). The model is spatially explicit and represents landscapes by dividing them into a system of square cells. SAVANNA reads computerized maps that include, for example, the elevation, aspect, and soil type of each cell. The model predicts water and nitrogen availability to plants using rainfall and soil properties, for each of the cells. Based upon water, light, and nutrient availability, quantities of photosynthate are calculated for plant functional groups, using process-based methods. Photosynthate is distributed to leaves, stems, and roots using shoot/root ratios and other plant allometrics, yielding estimates of primary production. Plant populations are calculated from primary production. At each weekly time-step plants may, for example: produce seeds that become established; grow into older age classes; out compete other plant functional groups; or die.

A habitat suitability index (see Van Horne and Wiens, 1991) is calculated for each cell in the landscape, at weekly intervals and for each animal functional group, based upon forage quality and quantity, slope, elevation, cover, and the density of herbivores. Individuals in the population are distributed on the landscape based upon these indices. Animals will feed upon the available vegetation, depending upon dietary preferences and consumption rates. The energy gained is reduced by energy costs associated with basal metabolism, gestation, and lactation. Net energy remaining goes toward weight gain, with weights reflected in condition indices. Summaries of the status of vegetation, herbivores and climate are produced at monthly intervals. These summaries include both charts depicting temporal changes on the system, and maps depicting spatio-temporal responses across landscapes (e.g., Boone et al., 2002). However, we do not show mapped output here because, (1) the farms modeled are generally small and mapped responses not informative, and (2) we do not wish to disclose the identity of individual farm owners who provided personal information (e.g., livestock numbers owned) in surveys (Hudson, 2002), or the shapes or locations of their farms. For more detail about SAVANNA, see Boone (2000).

3.2. ADAPTING SAVANNA TO THE VRYBURG AREA

3.2.1. *Functional Groups*

Plant and animal functional groups must be defined for an area prior to adapting the SAVANNA model. Functional groups are defined based upon the questions to be addressed, balancing the need for detail in responses and the costs of model parameterization and execution. More functional groups may make responses more realistic, but add to model development. In this study, we focused upon range and livestock production and condition, and how they may relate to changes in rainfall. We, therefore, defined seven plant functional groups: (1–3) perennial grasses of high, moderate, and low palatability, (4) annual grasses, (5) acacia shrubs (e.g., *Acacia mellifera*), (6) camphorbush shrubs (*Tarchonanthus camphoratus*), and (7) acacia trees (e.g., *A. tortilis*). Grasses were grouped into palatability classes reflecting their general acceptance to livestock (general attributes of vegetation were from: Adams, 1976; Coates Palgrave and Drummond, 1983; Gibbs Russell et al., 1990; Shearing, 1994; Van Wyk and Van Wyk, 1997; Van Oudtshoorn, 1999).

Five animal functional groups were defined. Cattle, goats, and sheep groups represented the livestock in the Vryburg area. For completeness we added horses and donkeys, which are work animals in the region. However, the number of horses on any farm was ≤ 10 and the number of donkeys ≤ 5, and so were a minor component of the herbivores on any farm, and will not be discussed further. Commercial farmers do not own goats, whereas communal farmers may own goats, sheep, and cattle. Wildlife were a relatively minor component of the herbivore community outside protected areas, and so were not included in the model.

3.2.2. *Parameterizing the Model*

SAVANNA was first parameterized for the entire study area, then adjustments were made to represent individual farms. The model uses geographic layers describing elevation, slope, aspect, vegetation, soils, and water sources to model the growth of plants and distributions of animals. Elevation, slope, and aspect were derived from a digital elevation model produced by the U.S. Geological Survey and acquired from the African Data Dissemination Service (ADDS, 2001). Farms occurred within a given vegetation type that came from Low and Robelo (1996) and its related map (NBI, 1996), and included five types: Kalahari Plains Thorn Bushveld in Vryburg 1, Ganyesa, and Kudumane; Kalahari Mountain Bushveld in southern Kudumane; Kimberly Thorn Bushveld in Taung District; Kalahari Plateau Bushveld in Vryburg 2; and Dry Sandy Highveld Grassland in eastern Vryburg 2. The area has 39 soil types, taken from the Land Type database (Mac Vicar, 1984) available for South Africa and provided to us by the Department of Agriculture, North-West Province. All geographic data were generalized to 1 km $\times$ 1 km resolution cells.

Weather data were supplied by the South African Weather Service for 166 weather stations in the region. Records included precipitation and minimum and maximum temperature, and spanned from 1900 to 1995. The number of stations varied widely, with <100 prior to 1922, then climbing rapidly to 152–163 until 1982, then the number declining dramatically to 50–60 for the remaining years. In modeling we used the 25 year period from January 1970 to December 1994. SAVANNA uses a focal weather station for detailed information (relative humidity, wind speed, CO_2 concentration, active radiation) and only precipitation for the remaining stations; we used the Vryburg weather station as the focal site.

Parameters were set in the model, based upon an extensive literature review, previous SAVANNA applications (Coughenour, 1992; Kiker, 1998; Boone et al., 2002), field work associated with this project, and expert opinion. Individual parameters are too numerous to cite, but examples may be classified within groups of ecological processes: plant phenology and biomass (e.g., Ndawula-Senyimba, 1972; Theunissen, 1995; Veenendaal et al., 1996), plant allometrics and growth (e.g., Danckwerts, 1987; Fourie and Cox, 1987; Coughenour et al., 1990), livestock energetics and growth (e.g., Zeeman et al., 1983; Van Niekerk and Casey, 1988; O'Reagain and Owen-Smith, 1996), grazing effects and stocking (e.g., Barnes, 1989; O'Connor and Pickett, 1992; Kirkman, 1995), and effects of rainfall variability (e.g., Donaldson, 1967; Danckwerts and Stuart-Hill, 1988; Snyman and Fouche, 1991). Parameters controlling the distribution and relative balance of plant functional groups were set using vegetation data collected for the purpose (e.g., species lists and percent cover, height, biomass) and literature (e.g., Dörgeloh, 1999), and the management of farms (e.g., stocking rate, number of boreholes used, effects of drought) were from interviews of farmers (Hudson, 2002) and literature (e.g., Dean and MacDonald, 1994).

After the SAVANNA application to the region was producing results in general agreement to reference data, such as vegetation data we collected, the model was adapted to 5 commercial farms in Vryburg 1 and 2, and 5 communal grazing areas in Ganyesa, Kudumane, and Taung (Figure 1). Spatial layers were parsed to represent the farms of commercial owners. Communal owners do not graze within property limits, but their regions of use were delineated using interview results. The communal farms were represented by circular areas sized to be stocked at 125% the recommended level, a typical stocking intensity (Hudson, 2002). Changes to customize the application to individual farms were relatively minor, including some that were required to represent the area or management, such as the area of the farm and numbers of animals stocked as reported by herd owners. Boreholes were placed on each area, based upon the interviews of herd owners. Adjustments were made to the herbaceous plant groups to capture differences in the abundance of annual grasses and the dynamics in changes in biomass observed in past sampling. Changes in herbaceous plant biomass caused livestock populations to increase or decrease slowly over time. Small changes in the energy requirements of herbivores were made to ensure their populations were stable over the 25-year simulation (although they varied markedly across years). There was some redundancy in the ecosystem-level responses of the 10 areas. Here we used three farms and one communal area to demonstrate our findings in detail; the remaining areas yielded qualitatively similar results.

The SAVANNA modeling system (version 4L) was modified to represent the weaner livestock production system most common amongst Vryburg commercial farmers (Chris de Brouwer, Department of Agriculture, North-West Province, Potchesfstroom, Republic of South Africa, pers. comm.). In this system, herds are essentially 100% breeding stock (15% males), and weaned animals are sold at 7 to 10 months, for placement in feedlots. Stocking rates thought to be appropriate over the long-term (Department of Agriculture, 1999) or long-term stocking reported by farmers were included in SAVANNA. Animals were removed in SAVANNA using a culling module, with culled animals sold (markets are being incorporated in ongoing research, see Discussion). In SAVANNA, the number of livestock required to be culled to obey grazing capacity limits was calculated, the number of males required to be culled to maintain sex ratios was calculated, and finally the number of weaned animals was tallied. If enough weaners were to be culled to satisfy population and sex ratio limits, those animals were culled and the annual cycle was complete. If additional animals had to be removed to satisfy the requirements, the oldest animals were removed proceeding through younger and younger cohorts until enough had been culled. In general, a portion (12%) of the weaners was retained to replace older stock.

The most important difference in modeling commercial and communal holdings was the inclusion of selling (i.e., culling) on commercial farms, whereas selling was not used in the models for communal farms that were used as reference (i.e., control models). In general, commercial farmers seek to maintain a given level of grazing pressure on their lands (within climatic constraints). In contrast, communal farmers seek to build-up as many livestock as possible in wet or normal years (Galvin et al., 1994 reviews the trait for pastoralists, which is shared by the communal owners; Hudson, 2002), so as to have as many animals as possible survive during dry years. In essence, commercial farmers manage their herds to optimize profits or maintain an income. Communal farmers manage their herds to build security and meet short-term needs such as to pay school fees and for health care.

3.2.3. *Model Adjustment and Assessment*

Stocking rates at each farm were adjusted until they matched those recommended by the Department of Agriculture (1999). Farm models were then calibrated until the systems showed long-term stability in vegetation and livestock biomass over the modeled period of 25 years. We recognize that range condition has likely changed over the last 25 years, with declines in the communal districts, for example. However, documenting and modeling those changes was beyond the scope of this project. If detailed information is lacking, we find that comparing results from experiments to relatively stable ‘control simulations’ to be most revealing. Although stable over the long-term, over the short-term, the systems were dynamic. We strove to have those dynamics reflect real-world patterns. In interviews with herd owners we asked what proportion of the herd was lost in the last drought (Hudson, 2002), and we had long-term vegetation biomass estimates provided to us by the Department of Agriculture. We used these data to model system dynamics in response to drought. The resulting models were used as controls, to compare with responses in simulations where conditions were changed.

Our application demonstrates the utility of merging a climate forecast with ecosystem modeling, and is not intended to be used in management at this stage. Here, model validation is less critical than in the forecasting system used in management that this demonstration evokes (Rykiel, 1996, p. 240). Regardless, the overall structure and algorithms of the model have been validated extensively in a variety of contexts (e.g., Kiker, 1998; Boone et al., 2002). Here, comments from experts were collected and modeled herbaceous aboveground biomass was compared to Normalized Difference Vegetation Indices (NDVI) calculated from satellite images, produced by the U.S. Geological Survey and acquired from ADDS (2001).

We produced a figure similar to Figure 2 for a commercial farm in southern Vryburg 1 (V112), and presented our results to South African range scientists. Thirty experts in range science, livestock production, and climate forecasting saw our results during a two-day workshop, with mostly favorable feedback. The models were modified using the input from experts, yielding final control models and a comparison to NDVI (Figure 2). The modifications were mainly in the phenology of plants, and in the competitive balance between the plant groups. We judged that phenology and relative greenness of plants were being represented well by the final model (i.e., agreement in lines, Figure 2a; $r^2 = 0.42$ with an outlier removed).

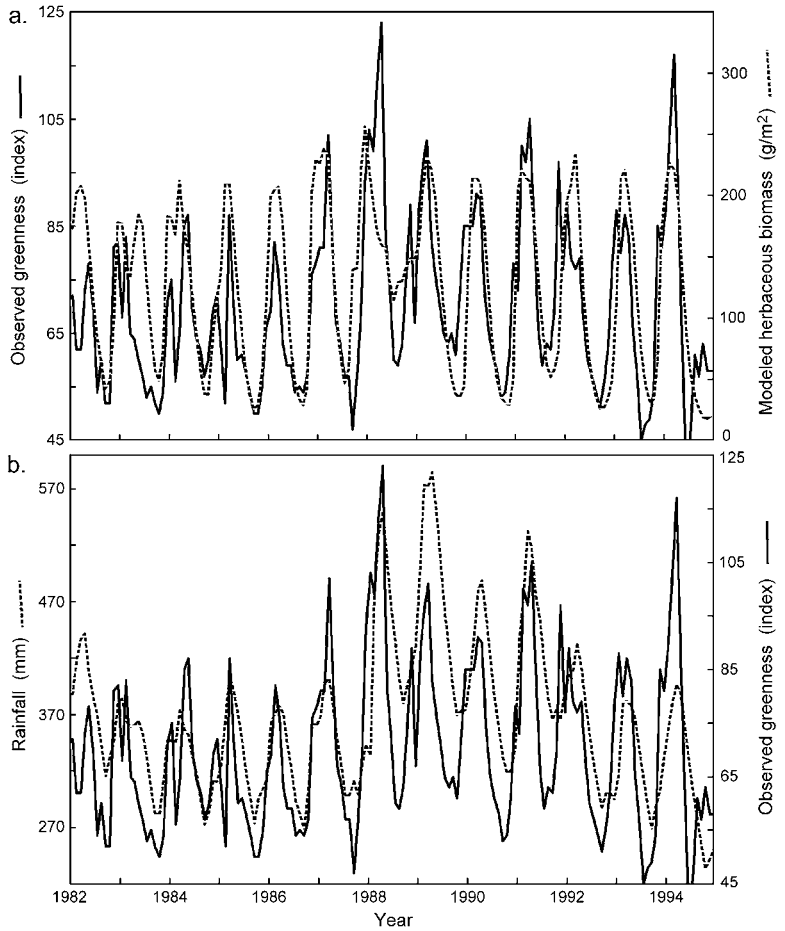

Figure 2. The agreement (a) between AVHRR NDVI images recorded from satellites (solid line) and simulated herbaceous biomass for farm V112 (dotted line) ($r^2 = 0.42$ with an April 1988 outlier, defined based upon statistical criteria, removed). This agreement is similar to that between (b) NDVI (solid line) and rainfall (dotted line), the main dynamic input into the ecosystem model ($r^2 = 0.41$ with a March 1994 outlier removed).

This evidence is stronger when placed in context, by comparing NDVI to rainfall. NDVI is not a perfect reflection of rainfall, which is the main dynamic input into the model (i.e., agreement in lines, Figure 2b; $r^2 = 0.41$ with an outlier removed), so the agreement between the observed NDVI and modeled response is similar to agreement between NDVI and observed rainfall (Figure 2a versus 2b, $r^2 = 0.42$ versus 0.41).

3.2.4. *Simulating Alternate Scenarios*

Our results begin with several scenarios intended to explore responses and show that the application is behaving reasonably. The main objective is then addressed, to demonstrate how using a seasonal climate forecast might aid in farm management. Our approach was artificially to create a dry or wet year in the rainfall record, and assume the availability of forecasts predicting those patterns. A real-time farm model using forecasts would provide estimates of farm status based upon a single, current forecast, and predict responses into the near future, from one to five years. Long-term responses to using or ignoring a forecast would not be helpful to a farmer interested in optimizing management over a coming season. However, ecosystem modeling provided the opportunity to explore responses over many years, with no differences between simulations in weather or management, except whether or not stocking was modified in response to a forecasted drought early in the modeled period. Within the 1970 to 1994 simulation period, we modified rainfall in 1977/1978, leaving a lengthy (16 year) period following the modified year to track responses. Summaries of annual rainfall from 1900 to 1994 (from August to July of the following year) showed that normal rainfall in the study area was ≈400 mm ($\bar{x} = 393.6$ mm, SD = 122.0 mm), a wet year was 650 mm, and a dry year was 225 mm. We maintained the pattern of rainfall from 1977/1978, but modified the quantity of rain, yielding three data sets (400, 650, and 225 mm rainfall in 1977/1978). Stocking rates were modified on farms or communal areas, if forecasts were used. Stocking rates for years when forecasts predicted drought were set using exploratory analyses that maximized animals that could be sold.

4. Results

4.1. TYPICAL MODEL RESPONSES

Annual rainfall for farm V112, and for the region in general, was above 600 mm in half of the years of the 1970s (Figure 3a), below 400 mm in the early and mid-1980s, and 500–600 mm in the late 1980s and early 1990s. This general pattern is reflected in the remaining figures. When simulated, high palatability grasses (Figure 3b, solid line) became more common during the mid-1970s when rainfall was heavy and relative grazing pressure reduced. In years with less rainfall, low palatability grasses (Figure 3b, dotted line) were more common than high palatability grasses. Annual grasses were generally a minor component of the herbaceous layer in the study area, but in some years may be dominant. In the simulation of farm V112, annual grass green leaf biomass was below 20 g/m^2 in all but the wettest years (Figure 4), but in the 1988/1989 rainy season annual grasses exceeded 90 g/m^2. That year the rains were earlier than normal (e.g., January rainfall in 1985 to 1990 was 40, 77, 38, 19, 107, and 55 mm) and perennial grasses were stressed from almost a decade of low rainfall (Figure 3a); the annual grasses grew more quickly in response to the heavy rainfall (Figure 4) and out competed the perennial grasses for light (Figure 3b, 1988/1989 season).

When livestock on farm V112 were stocked at the level recommended by the Department of Agriculture, their populations (Figure 5a, cattle shown, solid line)

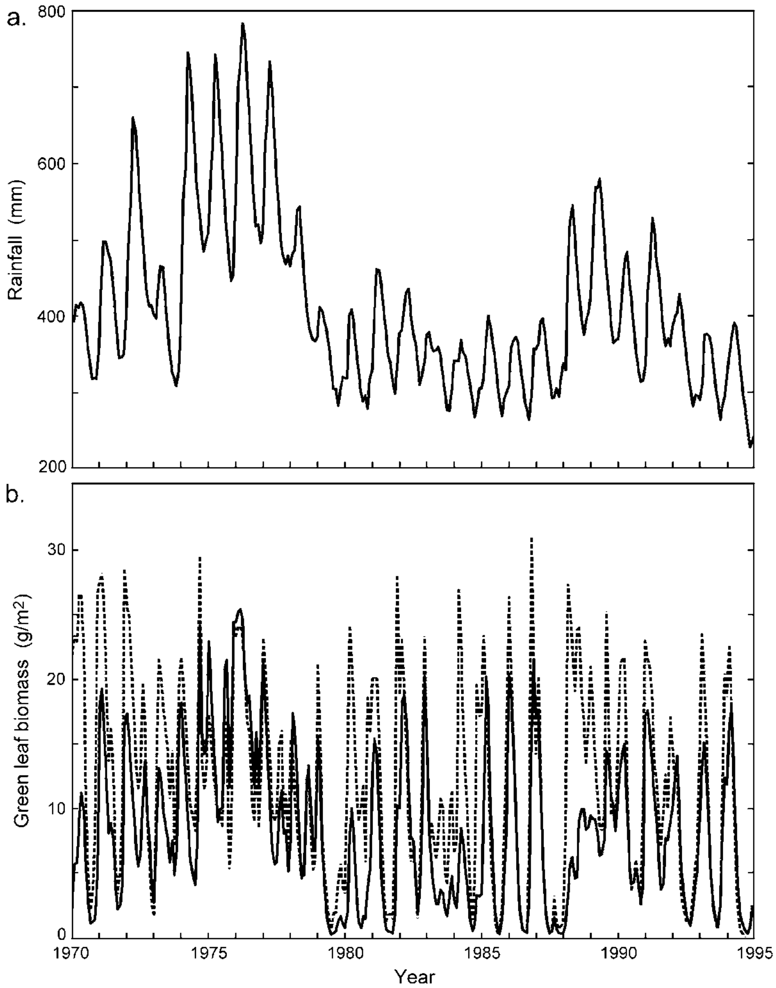

Figure 3. Rainfall (a) for farm V112 (and similar to the region in general) and changes in green leaf biomass (b) for high palatability grasses (solid) and low palatability grasses (dotted).

increased during the heavy rainfall years of the mid-1970s, then declined as rainfall totals dropped. At the peak of production in 1978/1979, 300 cattle were sold (Figure 5a, bars) to maintain the recommended stocking. In dry periods, <100 weaner cattle per year were sold to maintain desired age and sex ratios. The cattle population slowly rose and fell throughout the 1980s, then declined in 1988/1989 as perennial grasses were shaded by annuals, which were senescent and of low forage quality for part of the year. Then cattle population rose rapidly as perennial grasses recovered from the previous dry years and the unusual 1988/1989 year (Figure 5a).

An analogous simulation was run on a communal area used by owner G07, with livestock stocked at the recommended level and at the proportion of cattle,

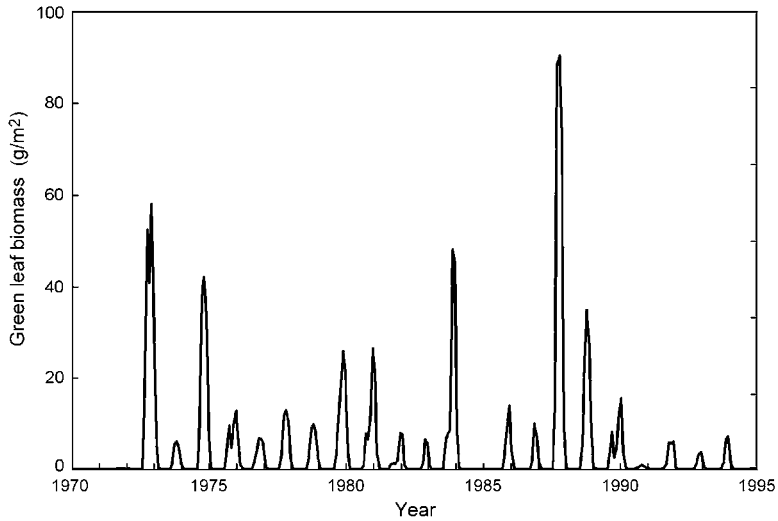

Figure 4. Annual grass green leaf biomass for farm V112.

goats, and sheep reported by the owner. In contrast to the commercial setting, animals were not sold by the communal owner. The cattle population (Figure 5b, upper solid line) increased more than three-fold in the years of heavy rainfall, then declined in succeeding dry periods. Goats (Figure 5b, dotted line) and sheep (Figure 5b, lower solid line) showed a similar response, although their populations did not decline as dramatically in response to lower rainfall.

4.2. SCENARIOS ALTERING STOCKING RATES OR ANNUAL PRECIPITATION

Commercial owners manage their lands with different production goals. Some stocked their lands heavily, relative to that recommended by the Department of Agriculture, and some stocked conservatively (Hudson, 2002). For example, farm V201 was stocked at 14% above the recommended level. When simulated at the observed stocking (710 cattle; solid line in Figure 6a) and at the recommended level (625 cattle, dotted line in Figure 6a), the higher initial population quickly dropped below the recommended level. Interestingly, the difference in the populations continued.

In contrast to the farm in Figure 6a, the owner of farm V206 managed extremely conservatively. When stocked at the reported level (667 cattle, solid line in Figure 6b), which was 55% of the recommended rate (1,211 cattle, dotted line in Figure 6b), cattle populations were essentially constant across years, regardless of rainfall amount. As might be predicted, the owner reported that over the years the herd had not been affected by drought.

The difference in cattle populations when simulated with greater than normal rainfall (dotted line) in 1977/1978 versus less than normal rainfall (solid line) in that year are shown for a commercial farm (Figure 7a) and communal area

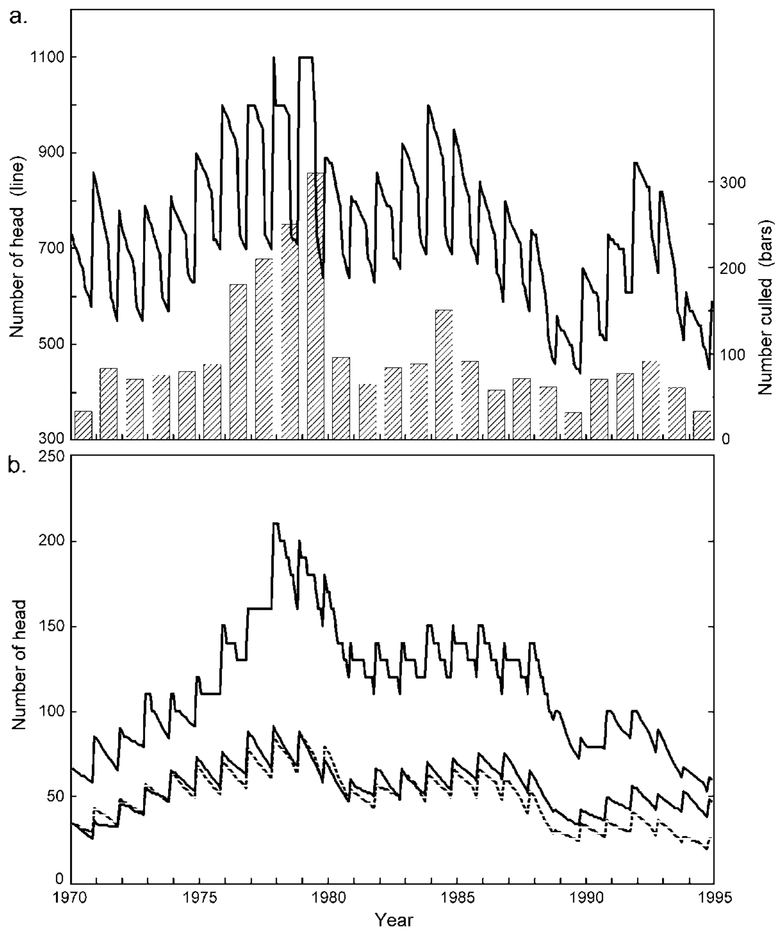

Figure 5. The (a) number of cattle (line) in a simulation of farm V112 under normal rainfall in 1977/1978 and with the initial population at the capacity recommended by the Department of Agriculture; the number of weaned cattle sold are shown in bars (a). The (b) populations of cattle (upper solid line), goats (dotted line), and sheep (lower solid line) of the communal area used by owner G07. Changes in populations within given years are due to births during the wet season, mortality in each month, and animals being sold prior to the dry season.

(Figure 7b). When rainfall was less than normal, cattle populations declined dramatically in both areas. In the simulations on the commercial farm (Figure 7a), the populations were different more than a decade after the year when rainfall was varied. Differences in range condition in a drought versus a wet year led to large differences in the cattle population following the drought, and associated differences in animal condition. Populations recover in both scenarios when rains return to normal, but increases in the population modeled with a wet year were more rapid in part because animals were more numerous, and in part because of

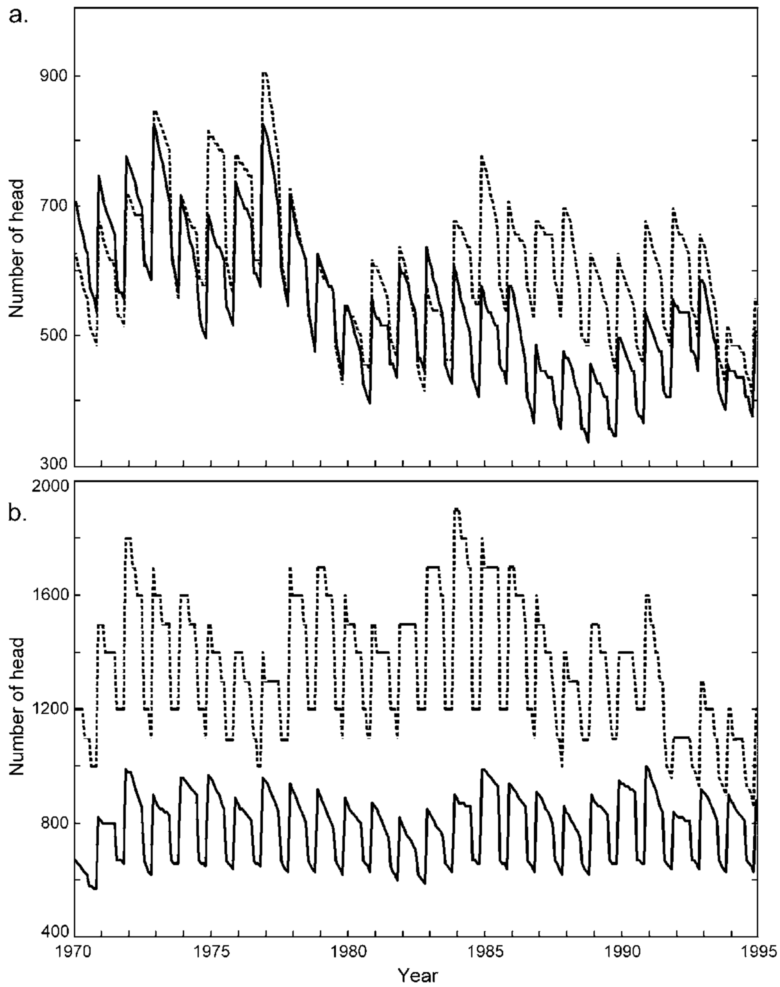

Figure 6. Cattle populations (a) on commercial farm V201 when stocked at the somewhat higher reported density (solid line) versus the density recommended as the capacity by the Department of Agriculture (dotted line). On commercial farm V206 (b), cattle are stocked far below (solid line) the capacity recommended (dotted line).

their better condition, which increases birth rates and reduces death rates in the simulation.

4.3. CLIMATE FORECASTS AND FARM MODELING

We have shown typical responses that suggest the model behaves reasonably, but now address how climate forecasts may be used in modeling and management. Imagine that in June of 1977 the owner of commercial farm V112 received a climate forecast that predicted that the next six months had a high probability of being drier than normal, akin to forecasts now made by SAWS (LOGIC, 2001). Assume

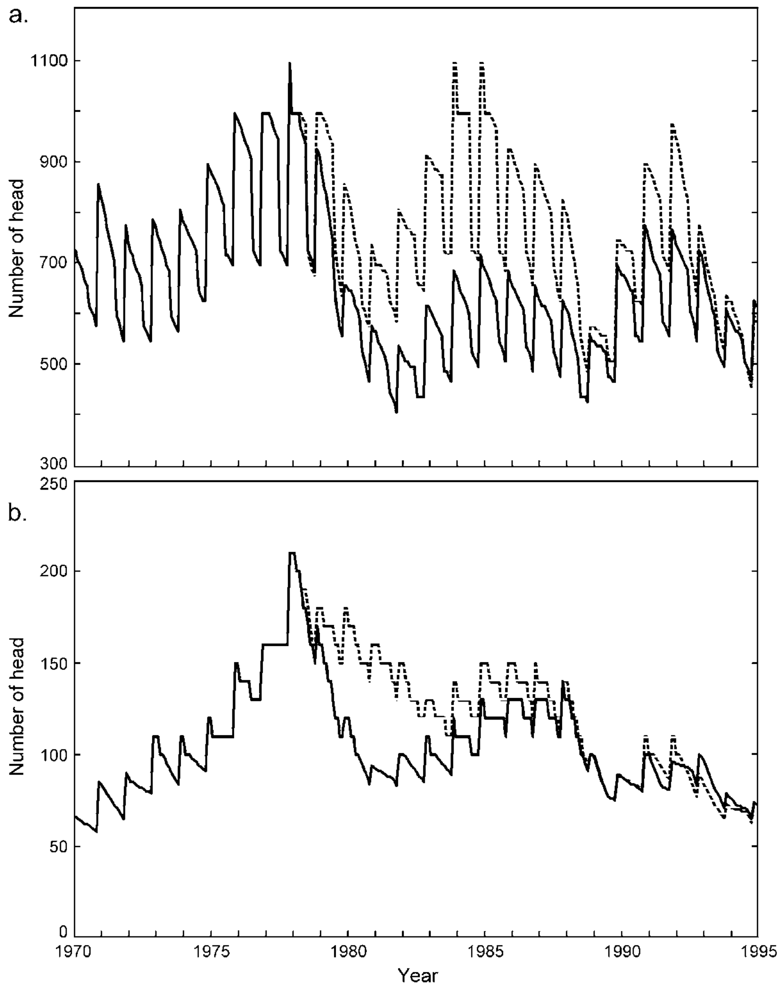

Figure 7. The (a) difference in cattle populations when rainfall in 1977/78 is below normal (solid line) versus above normal (dotted line) on farm V112 when stocked at the reported level. The same responses are shown (b) for the communal area used by owner G07, when the initial population is at the recommended level.

the farmer considered the forecast credible for use in management decisions, and considered a herd size of 490 cattle and 70 sheep appropriate stocking for a year of low rainfall, with excess animals sold.

The dotted line in Figure 8a is the simulated trend in the number of cattle when a forecast was not used and rainfall was low (225 mm) in 1977/1978, and the number of cattle sold are shown by lightly shaded bars in Figure 8b. The dark line and darker bars (Figures 8a,b) show the same responses, with a climate forecast available portending drought in 1977/1978. In 1977, 440 cattle were sold to reach the 490 target (Figure 8b), and sheep were already about at the target of 70 animals

(4 were sold). The cattle population declined somewhat in response to the decline in rainfall in the 1980s, but less than when animals were not sold (Figure 8a). More importantly, cattle did not overgraze the area, as they did when the forecast was ignored – the cattle population recovered quickly when rainfall stabilized (Figure 8a, solid line), whereas the population remained depressed when the forecast was not used (dotted line). Over the entire period modeled, 1,939 cattle were sold when the forecast was ignored, 2,546 when the forecast was used (i.e., sums of bars shown in Figure 8b).

A livestock farmer may ask what the loss in sales would be if animals were removed in response to a forecast of low rainfall, but in reality rainfall was normal or high. Given the assumptions of the model and the long-term pattern in rainfall, in the example farm (V112), if 440 animals were sold in 1977 but rainfall that year was above normal (625 mm), the condition of the remaining livestock (and hence their production) and range were high, so the cost of the incorrect forecast was relatively low. If the forecast was used and animals sold, 2,546 cattle were sold over the period modeled if a dry year, versus 2,913 if 1977/1978 was a year of normal rainfall, and 2,464 if it was a wet year (more animals were sold under the normal rainfall than the high rainfall because of excessive culling of breeding stock to meet stocking limits in the simulation with a wet year). For comparison, if the forecast was ignored and 1977/1978 was a wet year, 2,764 cattle were sold.

The benefit of using a forecast was similar for a communal farmer (G07 in Figure 9). In the simulation, 120 cattle, 33 goats, and 39 sheep were sold in 1977 in light of a forecast of low rainfall likely in the succeeding six months. Compared to when the forecast was ignored (Figure 9a, dotted line show cattle), the cattle population remained at about 120 (Figure 9a, solid line) and grew during the wetter years. Range condition improved when stocking was reduced during the dry 1977/1978 period, with high palatable grasses having greater biomass in the late 1970s (Figure 9b, solid line) than when the forecast was ignored (Figure 9b, dotted line). Under dry conditions in 1977/1978, when culling is ignored, high palatable grass biomass first declines, but is higher in later years because the cattle population is about one-third smaller than when the forecast was used to sell animals. The death of animals from drought allowed high palatable grasses to rebound to a biomass greater than when the forecast was used and more animals survived the drought.

5. Discussion

Simulations demonstrated that seasonal forecasts from the South African Weather Service linked with an ecosystem model applied to farms may help improve range condition and livestock production for owners. Rangeland condition was improved if livestock stocking was reduced prior to a forecasted drought. A workshop was held in the Vryburg region of South Africa where these results were presented and

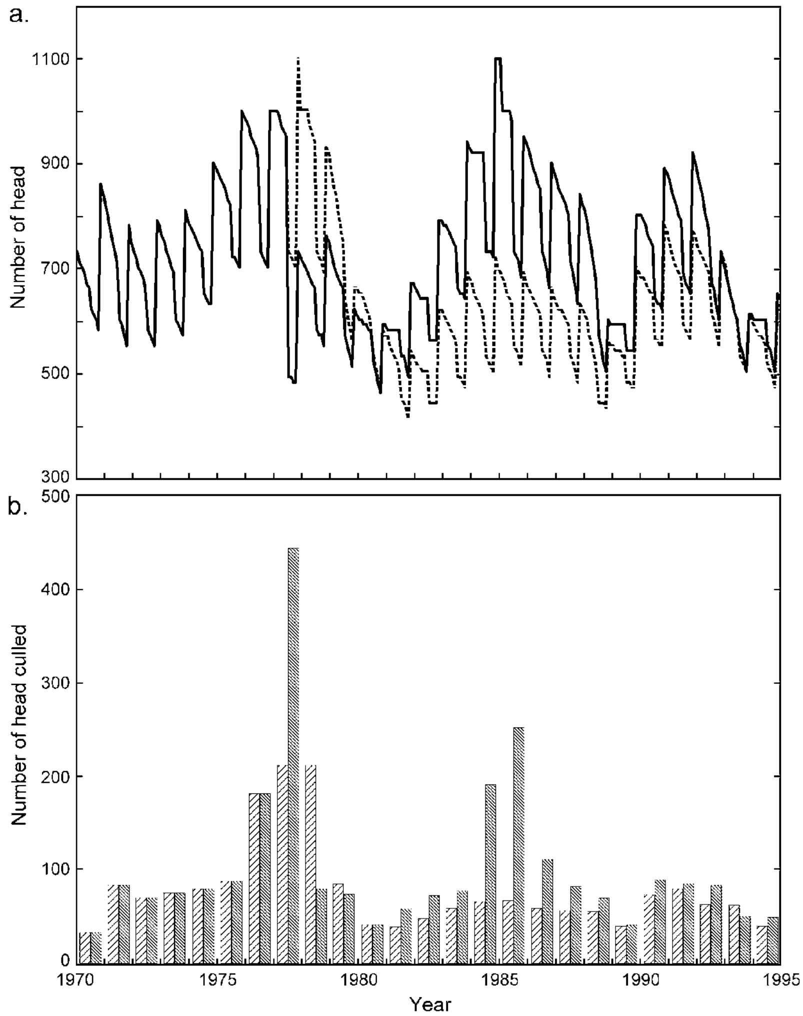

Figure 8. The difference (a) in cattle populations when animals were sold in 1977 because of a forecast of below average rainfall, for farm V112 stocked at the reported density. The trend (dotted line) if the forecast was ignored may be compared to the trend (solid line) if culling was done. The number of animals sold (b) if the forecast was ignored (light bars) may be compared to animals sold if the forecast was used (dark bars).

discussed. Feedback from farmers, managers, and scientists suggests that a system to model farm responses to seasonal forecasts, to be used in management, would be useful. How spatially specific that system would need to be remains a question; whether a generalized farm response for a given district, such as Vryburg 1 or Taung, would suffice, or if individual farms would need to be modeled is not clear.

The economic expectations for farmers using forecasts are not included in these results, but will be important (Mjelde et al., 1998; Stafford Smith et al., 2000).

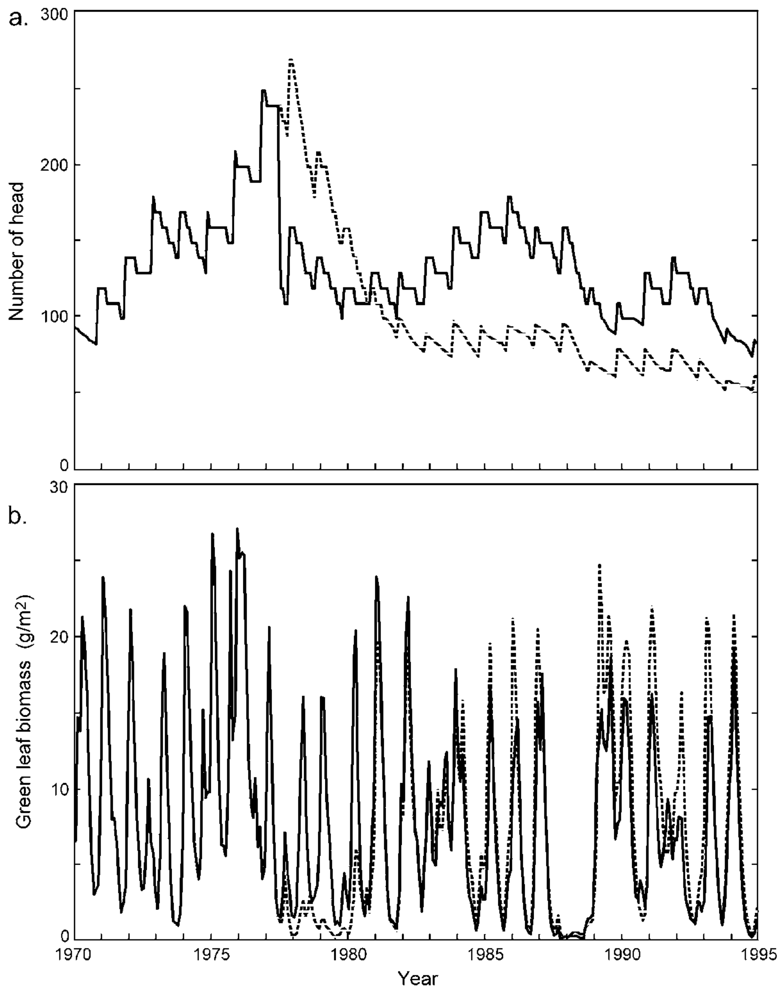

Figure 9. The difference (a) in cattle populations when animals were culled in 1977 because of a forecast of below average rainfall, for the communal area used by owner G07 at the density reported. The trend (dotted line) when the forecast was ignored may be compared to the trend when the forecast was used (solid line). Culling is not shown because animals are not regularly sold; there was a single selling event of 120 cattle in response to the forecast. The difference (b) in high palatability grasses when the forecast was ignored (dotted line) and when culling occurred in response to the forecast (solid line). High palatability grasses declined if the forecast was ignored, but then rebounded following a decline in the cattle population.

If forecasts improve to the degree that their release to the public causes many farmers to sell animals, the market cost per animal will decline. We are conducting economic analyses using this study area, and have linked the SAVANNA modeling system and a module doing mathematical programming to estimate the economic benefits and costs associated with using seasonal forecasts (Thornton et al., in press). Numbers of animals to sell annually are optimized using climate forecasts and considering long-term economic gains. Early results suggest that the economic benefits from the use of forecasts would be small in most years, but would be large in years of severe drought.

Our methods and results do not focus upon model assessment, beyond comparisons to observed data and correlations with normalized difference vegetation indices (Figure 2). These results are not intended to be used in practice, making assessment secondary (Rykiel, 1996), but to demonstrate the potential utility of a real-time farm modeling system. A follow-up project developing the farm modeling system for use in management would require a significant assessment component.

A single culling event prior to a drought (e.g., Figure 8) led to >100 more cattle in the population more than a decade following the event. When forecasts were ignored and extra animals left on the farm, range condition declined (as in McKeon et al., 2000) as did animal condition, and populations failed to recover for many years. In contrast, when excess animals were sold, the range was not degraded, and populations increased when rains returned. The magnitude and duration of this compensatory effect was surprising to us. Our model application may be termed a 'consequence model' (N. T. Hobbs, pers. comm., interpreted from Starfield, 1997), where data and assumptions are combined to model consequences of perturbations ('what if ... ' models). The effect many not be as extreme in reality, but given that the model and assumptions we have used yield reasonable responses in general, this consequence – decade-long compensatory population differences – appears reasonable and worthy of further research.

Another consequence of interest is the relatively low decline in sales associated with selling animals in response to an incorrect forecast of drought (2,764 cattle sold if a wet year and the forecast was ignored, versus 2,464 sold if animals were removed prior to an incorrect forecast of drought). When an incorrect forecast was used, farmers benefitted directly from selling animals, and the remaining livestock production improved through density dependent responses, so the cost of the incorrect forecast was minimized. This response cannot be generalized across years, however. If animals were removed in response to several incorrect forecasts over a span of years, production would decline markedly.

Our results underscore the utility of destocking heavily stocked grazing lands prior to a forecasted drought (Toulmin, 1994). In our model, livestock production in a given year lagged behind initial declines in vegetation biomass by several months. Offspring produced following a decline in vegetation biomass further stressed the forage base, until livestock populations precipitously declined. In areas where equilibrium dynamics appear more important than non-equilibrium dynamics (Ellis and Swift, 1988; Illius and O'Connor, 1999), using forecasts to adaptively modify stocking may increase the likelihood of a sustainable forage base.

Workshop participants in South Africa doubted that communal livestock owners would be willing to sell animals in response to a forecast. Interviews by Hudson (2002) echoed this view, with 44% of commercial farmers citing the selling of animals as a primary strategy to cope with drought, whereas only 3% of communal farmers used that strategy. Like pastoralists, a goal of communal farmers is to own as many livestock as possible (Galvin et al., 1994) to spread the risk in a variable climate, a means of retaining wealth, and insurance of some animals surviving droughts. These long-held traditions can change, however, if human population growth stresses food security and demands increased production (e.g., Galvin et al., 1994 contrasts pastoral groups that sell animals or do not). For example, Norton-Griffiths (1998) cites a 4% per year increase in livestock sales in Kenya (with livestock numbers remaining relatively constant), and calls this a 'fundamental change in pastoral production strategy' (Norton-Griffiths, 1998, p. 288). There is potential therefore for communal livestock holders in South Africa to market animals. There is also a gradient in communal owner's ties to the market economy (Hudson, 2002), with some termed 'emerging commercial farmers' who are more likely to make use of forecasts. At the other extreme, communal owners with very few livestock may be unable to tolerate the risks inherent in using forecasts (Vogel, 1995; Roncoli et al., 2000).

Our analyses have focused upon selling livestock in response to forecasts of droughts, but livestock producers may respond in many ways to potential drought (Roncoli et al., 2000). Owners may supplement animal feed using hay, practice fodder banking (e.g., rest range longer or purchasing concentrates), rent extra land, or change the proportions of livestock species they hold (e.g., more goats, which are more resistant to drought than are cattle) (Vogel, 1995; Hudson, 2002). Behaviors within households may be modified in droughts as well, such as getting outside work, reducing expenses, or conserving water (Roncoli et al., 2000). Also, management of droughts are often constrained by other factors, such as access to credit, seeds, or forecast information itself, and so responses should not be viewed in isolation. The constraints that resource-poor farmers face need to be considered; this remains an area of ongoing research in the Province and elsewhere in the country (Vogel, 1995; Roncoli et al., 2000; Vogel, 2000). The SAVANNA modeling system may be used to address effects of some of these actions, such as supplemental feeding, changes in herd composition, or renting land, and can incorporate the constraints cited.

Climate forecasts in South Africa are still of limited accuracy. SAWS estimates, for example, that about 30% of the variation in their climatic patterns may be associated with ENSO events. Climate forecasts are improving, however (Mjelde et al., 1998), through the inclusion of other global weather patterns, such as the North Atlantic Oscillation and Indian Ocean sea surface temperatures (Mjelde et al., 1998; Dilley, 2000). We have demonstrated that these forecasts, linked in essentially real-time with ecosystem models at the district or farm level, would potentially aid livestock producers in optimizing their drought response strategies.

Acknowledgements

We extend thanks to Y. Otsuki and M. Kneeland for assisting in this research. Special thanks go to T. Meyer of the Department of Agriculture, North-West Province, South Africa, for providing vegetation data. Discussions with M. Stafford Smith were helpful. We also thank participants in workshops for their feedback. Comments from anonymous reviewers improved the manuscript. This research is supported by the U.S. National Oceanic and Atmospheric Administration, Contract NA86GP0347 to Galvin, Ellis, and Vogel.

References

Acocks, J. P. H.: 1975, 'Veld Types of South Africa', *Memoirs of the Botanical Survey of South Africa* **40**, 1–128.

Adams, J.: 1976, *Wild flowers of the Northern Cape*, Department of Nature and Environmental Conservation, Provincial Administration of the Cape of Good Hope, Cape Town, South Africa.

ADDS: 2001, *African Data Dissemination Service, Site Version 2.3.2*, U.S. Geological Survey/EROS Data Center, Sioux Falls, South Dakota, U.S.A., http://edcsnw4.cr.usgs.gov/adds/

Ash, A., O'Reagain, P., McKeon, G., and Stafford Smith, M.: 2000, 'Managing Climate Variability in Grazing Enterprises: A Case Study of Dalryple Shire, North-Eastern Austrailia', in Hammer, G. L., Nicholls, N., and Mitchell, C. (eds.), *Applications of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems*, Kluwer Academic, Dordrecht, The Netherlands, pp. 253–270.

Barnes, D. L.: 1989, 'Reaction of Three Veld Grasses to Different Schedules of Grazing and Resting. 2. Residual Effects on Vigour', *South African Journal of Plant and Soil* **6**, 8–13.

Boone, R. B.: 2000, *Integrated Management and Assessment System: Balancing Food Security, Conservation, and Ecosystem Integrity – A Training Manual*, Global Livestock Collaborative Research Support Program, Univ. California, Davis, CA, U.S.A. URL: http://www.nrel.colostate.edu/projects/imas/prods/rboone/Workshop.html

Boone, R. B., Coughenour, M. B., Galvin, K. A., and Ellis, J. A.: 2002, 'Addressing Management Questions for Ngorongoro Conservation Area, Tanzania, Using the SAVANNA Modeling System', *African Journal of Ecology* **40**, 138–150.

Coates Palgrave, K. and Drummond, R. B.: 1983, *Trees of Southern Africa*, C. Struik Publishing, Cape Town, South Africa.

Coughenour, M. B.: 1992, 'Spatial Modelling and Landscape Characterization of an African Pastoral Ecosystem: A Prototype Model and its Potential Use for Monitoring Drought', in McKenzie, D. H., Hyatt, D. E., and McDonald, V. J. (eds.), *Ecological Indicators*, Vol. 1, Elsevier Applied Science, New York, NY, U.S.A., pp. 787–810.

Coughenour, M. B., Ellis, J. E., and Popp, R. G.: 1990, 'Morphometric Relationships and Development Patterns of *Acacia tortilis* and *Acacia reficiens* in Southern Turkana, Kenya', *Bull. Torrey Botanical Club* **117**, 8–17.

Danckwerts, J. E.: 1987, 'Growth Analysis of *Themeda triandra* and *Sporobolus fimbriatus* Tillers in Semi-Arid Grassveld', *Journal of the Grassland Society of Southern Africa* **4**, 7–12.

Danckwerts, J. E. and Stuart-Hill, G. C.: 1988, 'The Effect of Severe Drought and Management after Drought on the Mortality and Recovery of Semi-Arid Grassveld', *Journal of the Grassland Society of Southern Africa* **5**, 218–222.

Dean, W. R. J. and MacDonald, I. A. W.: 1994, 'Historical Changes in Stocking Rates of Domestic Livestock as a Measure of Semi-Arid and Arid Rangeland Degradation in the Cape Province, South Africa', *J. Arid Environments* **26**, 281–298.

Department of Agriculture: 1999, *Atlas Products of the North West Province*, Technical Supportive Services GIS Section, Department of Agriculture, North West Province, Potchefstroom, Republic of South Africa.

Dilley, M.: 2000. 'Reducing Vulnerability to Climate Variability in Southern Africa: The Growing Role of Climate Information', *Clim. Change* **45**, 63–73.

Donaldson, C. H.: 1967, 'The Immediate Effects of the 1964/66 Drought on the Vegetation of Specific Study Areas in the Vryburg District', *Proceedings of the Grassland Society of Southern Africa* **2**, 137–141.

Dörgeloh, W. G.: 1999, 'Diversity of the Herbaceous Layer in Mixed Bushveld', *J. Range Management* **52**, 519–524.

du Pisani, L. G., van Themaat, R. V., and Roux, F.: 1995, 'Drought Monitoring and Information Centre Established for Arid Zone of South Africa', *Drought Network News* **7**, 32–33.

Ellis, J. E. and Coughenour, M. B.: 1998, 'The SAVANNA Integrated Modelling System: An Integrated Remote Sensing, GIS and Spatial Simulation Modelling Approach', in Squires, V. R. and Sidahmed, A. E. (eds.), *Drylands: Sustainable Use of Rangelands into the Twenty-First Century*, IFAD Series: Technical Reports, Rome, Italy, pp. 97–106.

Ellis, J. E. and Galvin, K. A.: 1994, 'Climate Patterns and Land-Use Practices in the Dry Zones of Africa', *Bioscience* **44**, 340–349.

Ellis, J. E. and Swift, D. M.: 1988, 'Stability of African Pastoral Ecosystems: Alternate Paradigms and Implications for Development', *J. Range Management* **41**, 450–459.

FEWS (Famine Early Warning System): 1997, *El Niño's Effects on Rainfall in Eastern and Southern Africa*, U.S. Agency for International Development, FEWS Bulletin, AFR/97–10. URL: http://www.info.usaid.gov/fews/fb971027/fb971027.html

Fourie, J. H. and Cox, J. R.: 1987, 'The Distribution, Growth Characteristics, and Utilization of Lehmann Lovegrass in Southern Africa', in Frasier, G. W. and Evans, R. A. (eds.), *Proceedings of Symposium 'Seed and Seedbed Ecology of Rangeland Plants'*, Agricultural Research Service, U.S. Department of Agriculture, Washington, D.C., U.S.A.

Galvin, K. A., Coppock, D. L., and Leslie, P. W.: 1994, 'Diet, Nutrition, and the Pastoral Strategy', in Fratkin, E., Galvin, K. A., and Roth, E. A. (eds.), *African Pastoralist Systems: An Integrated Approach*, Lynne Rienner Publishing, London, U.K., pp. 113–131.

Gibbs Russell, G. E., Watson, L., Koekemoer, M., Smook, L., Barker, N. P., Anderson, H. M., and Dallwitz, M. J.: 1990, 'Grasses of Southern Africa', *Memoirs of the Botanical Survey of South Africa*, No. 58.

Hilborn, R. et al.: 1995, 'A Model to Evaluate Alternative Management Policies for the Serengeti-Mara Ecosystem', in Sinclair, A. R. E. and Arcese P. (eds.), *Serengeti II: Dynamics, Management, and Conservation of an Ecosystem*, University of Chicago Press, Chicago, IL, U.S.A., pp. 617–637.

Hudson, J. W.: 2002, *Response to Climate Variability in the Livestock Sector in the North-West Province, South Africa*, MA Thesis, Colorado State University, Fort Collins, CO, U.S.A.

Illius, A. W. and O'Connor, T. G.: 1999. 'On the Relevance of Nonequilibrium Concepts to Arid and Semiarid Grazing Systems', *Ecol. Appl.* **9**, 798–813.

Kiker, G. A.: 1998, *Development and Comparison of Savanna Ecosystem Models to Explore the Concept of Carrying Capacity*, Ph.D. Dissertation, Cornell University, Ithica, New York, NY, U.S.A.

Kirkman, K. P.: 1995, 'Effects of Grazing and Resting on Veld Productivity', *Bulletin of the Grassland Society of Southern Africa* **6**, 9–11.

LOGIC (Long-term Operational Group Information Centre): 2001, *Seasonal Outlook for Southern Africa August 2001*, South African Weather Service. URL: http://www.weathersa.co.za/Forecasts/forecast.htm

Low, A. B. and Robelo, A. G. (eds.): 1996, *Vegetation of South Africa, Lesotho and Swaziland*, Department of Environmental Affairs and Tourism, Pretoria, South Africa.

Mac Vicar, C. N.: 1984, *Land Types of the Maps: 2522 Bray; 2622 Morokweng; 2524 Mafeking; 2624 Vryburg*, ARC-Institute for Soil, Climate, and Water, Memoirs on the Agricultural Natural Resources of South Africa, No. 1.

McKeon, G., Ash, A., Hall, W., and Stafford Smith, M.: 2000, 'Simulation of Grazing Strategies for Beef Production in North-East Queensland', in Hammer, G. L., Nicholls, N., and Mitchell, C. (eds.), *Applications of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems*, Kluwer Academic, Dordrecht, The Netherlands, pp. 227–252.

Mjelde, J. W., Hill, S. J. H., and Griffiths, J. F.: 1998, 'A Review of Current Evidence on Climate Forecasts and their Economic Effects in Agriculture', *Amer. J. Agric. Econ.* **80**, 1089–1095.

NBI (National Botanical Institute): 1996, *Vegetation Map of South Africa, Lesotho, and Swaziland*, Deon Marais, Department of Environmental Affairs and Tourism, Pretoria, South Africa.

Ndawula-Senyimba, M. S.: 1972, 'Some Aspects of the Ecology of *Themeda trianda*', *East African Agricultural and Forestry Journal* **38**, 83–93.

NOAA (National Oceanic and Atmospheric Administration): 2002, Climate Prediction Center: El Niño/La Niña Home. URL: http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/

Norton-Griffiths, M.: 1998, 'The Economics of Wildlife Conservation Policy in Kenya', in Milner-Gulland, E. J. and Mace, R. (eds.), *Conservation of Biological Resources*, Blackwell Science, London, U.K., pp. 279–293.

O'Connor, T. G. and Pickett, G. A.: 1992, 'The Influence of Grazing on Seed Production and Seed Banks of some African Savanna Grasslands', *J. Appl. Ecology* **29**, 247–260.

O'Reagain, P. J. and Owen-Smith, R. N.: 1996, 'Effect of Species Composition and Sward Structure on Dietary Quality in Cattle and Sheep Grazing South African Sourveld', *Journal of Agricultural Science, Cambridge* **127**, 261–270.

Roncoli, C., Ingram, K., Kirshen, P. H., and Flitcroft, I.: 2000, *Opportunities and Constraints to Using Seasonal Precipitation Forecasting to Improve Agricultural Production Systems and Livelihood Security in the Sahel-Sudan Region: A Case Study of Brukina Faso, CFAR – Phase I*, International Forum on Climate Prediction, Agriculture, and Development, International Research Institute for Climate Prediction, New York, New York, U.S.A.

Rykiel, E. J. Jr.: 1996, 'Testing Ecological Models: The Meaning of Validation', *Ecol. Modeling* **90**, 229–244.

Shearing, D.: 1994, *Karoo: South African Wild Flower Guide No. 6*, Botanical Society of South Africa and the National Botanical Institute, Kirstenbosch, Claremont, South Africa.

Snyman, H. A. and Fouche, H. J.: 1991, 'Production and Water-Use Efficiency of Semi-Arid Grasslands of South Africa as Affected by Veld Condition and Rainfall', *Water South Africa* **17**, 263–268.

Society of Range Management: 1989, *A Glossary of Terms Used in Range Management*, Denver, CO, U.S.A.

Stafford Smith, D. M. and Foran, B. D.: 1990, 'RANGEPACK: The Philosophy Underlying the Development of a Microcomputer-Based Decision Support System for Pastoral Land Management', *J. Biogeogr.* **17**, 541–546.

Stafford Smith, M., Buxton, R., McKeon, G., and Ash, A.: 2000, 'Seasonal Climate Forecasting and the Management of Rangelands: Do Production Benefits Translate into Enterprise Profits?', in Hammer, G. L., Nicholls, N., and Mitchell, C. (eds.), *Applications of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems*, Kluwer Academic, Dordrecht, The Netherlands, pp. 271–289.

Starfield, A. M.: 1997, 'A Pragmatic Approach to Modeling for Wildlife Management', *J. Wildlife Management* **61**, 261–270.

Stern, P. C. and Easterling, W. E. (eds.): 1999, *Making Climate Forecasts Matter*, National Academy Press, Washington, D.C., U.S.A.

Theunissen, J. D.: 1995, 'Biomass Production of Different Ecotypes of Three Grass Species of the Semi-Arid Grasslands of Southern Africa', *J. Arid Environments* **29**, 439–445.

Thornton, P. K., Fawcett, R. H., Galvin, K. A., and Boone, R. B.: 'Evaluating Management Options that Use Climate Forecasts: Modelling Livestock Production Systems in the Arid and Semi-Arid Zone of South Africa', *Clim. Res.*, in press.

Thornton, P. K., Galvin, K. A., and Boone, R. B.: 2003, 'An Agro-Pastoral Household Model for the Rangelands of East Africa', *Agricultural Systems* **76**, 601–622.

Toulmin, C.: 1994, 'Tracking through Drought: Options for Destocking and Restocking', in Scoones, I. (ed.), *Living with Uncertainty: New Directions in Pastoral Development in Africa*, Intermediate Technology Publications, London, U.K., pp. 95–115.

Van Horne, B. and Wiens, J. A.: 1991, *Forest Bird Habitat Suitability Models and the Development of General Habitat Models*, U.S. Department of Interior Fish and Wildlife Service, Fish and Wildlife Research Number 8, Washington, D.C., U.S.A.

Van Niekerk, W. A. and Casey, N. H.: 1988, 'The Boer Goat. II: Growth, Nutrient Requirements, Carcass and Meat Quality', *Small Ruminant Research* **1**, 355–368.

Van Oudtshoorn, F.: 1999, *Guide to Grasses of South Africa*, Briza Publikasies, Arcadia, South Africa.

Van Wyk, B. and Van Wky, P.: 1997, *Field Guide to Trees of Southern Africa*, C. Struik Publishing, Cape Town, South Africa.

Veenendaal, E. M., Ernst, W. H. O., and Modise, G. S.: 1996, 'Effect of Seasonal Rainfall Pattern on Seedling Emergence and Establishment of Grasses in a Savanna in South-Eastern Botswana', *J. Arid Environments* **32**, 305–317.

Vogel, C.: 1995, 'People and Drought in South Africa: Reaction and Mitigation', in Binns, T. (ed.), *People and Environment in Africa*, John Wiley and Sons, New York, NY, U.S.A., pp. 249–256.

Vogel, C. H.: 2000, 'Usable Science: An Assessment of Long-term Seasonal Forecasts amongst Farmers in Rural Areas of South Africa', *South African Geographical Journal* **82**, 107–116.

Wiegand, T., Jeltsch, F., Bauer, S., and Kellner, K.: 1998, 'Simulation Models for Semi-Arid Rangelands of Southern Africa', *Afr. J. Range Forage Sci.* **15**, 48–60.

Zeeman, P. J. L., Marais, P. G., and Coetsee, M. J.: 1983, 'Nutrient Selection by Cattle, Goats, and Sheep on Natural Karoo Pasture. 1. Digestibility of Organic Matter', *South African Journal of Animal Science* **13**, 236–239.

(Received 31 August 2003; in revised form 12 November 2003)