The SAVANNA integrated modelling system: an integrated remote sensing, GIS and spatial simulation modelling approach

J. Ellis and M. B. Coughenour

Synopsis

This paper describes the modelling approach which was originally developed to describe and analyze the pastoral nomad system of the Turkana in Kenya. The SAVANNA modelling system was designed to address spatio-temporal variability by joining remote-sensed and Geographic Information System (GIS) databases with spatial simulations, in order to compute rates of plant production, forage intake by ungulates, and ecosystem function under varying climatic conditions. SAVANNA has subsequently been used elsewhere to model ecosystems dominated by wide-ranging grazer/browser populations.

Key points

1. *The spatially extensive nature of arid and semi-arid rangelands, coupled with the temporal variability of rainfall, complicate analysis and planning for economically sustainable management and development. There is need for a tool to address this spatio-temporal variability.*
2. *The SAVANNA model system uses Normalized Difference Vegetation Index (NDVI) data based on the National Oceanic and Atmospheric Administration (NOAA) Advanced and Very High Resolution Radiometer (AVHRR) to test model predictions of spatio-temporal patterns of plant production. NVDI data may alternatively be used to drive the plant growth submodel. Weather data serve as a primary driver for the model through the creation of monthly rainfall maps. GIS data layers include maps of topography, vegetation, soils, water distribution and land-use patterns.*

3. *The SAVANNA model has been used to simulate such diverse dynamics as the effects of winter snowfall on elk population fluctuations in Yellowstone National Park in the USA, and the implications of alterations in land-use rights among Turkana pastoralists in Kenya.*

1. INTRODUCTION

Temporal change in climate and vegetation is a fundamental property of arid and semi-arid grazing systems. Seasonal cycles between the wet and dry season or between summer and winter occur each year. Thus, adaptations and behaviours for coping with seasonality are among the most basic strategies of herbivores and humans living in arid and semi-arid lands. Longer-term inter-annual cycles, such as the El Nino-Southern Oscillation, cause intermittent extremes in rainfall, snowfall or temperature, and are the origin of some devastating natural disasters. Because inter-annual climate variability increases as ecosystems become drier (Nicholls and Wong, 1990), dry grazing lands are among the earth's most temporally variable and unstable ecosystems (Caughley et al. 1987; Ellis and Swift; 1988; Westoby et al., 1989). Both ecological models and laboratory experiments have established that spatial heterogeneity can theoretically compensate for temporal instability (Huffacker, 1958; DeAngelis and Waterhouse, 1987). And in nature, spatial heterogeneity acts as an important stabilizing property in highly-dynamic, temporally unstable grazing systems (Coughenour, 1992). Thus, changes over time and heterogeneity in space are, in some ways, compensatory forces balancing the dynamics of variable ecosystems.

The SAVANNA simulation model was developed to investigate the dynamics of a highly variable ecosystem in northern Kenya, inhabited by Turkana pastoral nomads. Because the ecosystem is both strongly seasonal and drought-prone, the Ngisonyoka Turkana nomads are among Africa's most mobile people (McCabe 1985; Ellis et al., 1987). At the same time, this region is characterized by landscape and vegetation heterogeneity, the result of strong elevational and climatic gradients (Coughenour and Ellis, 1993). In order to replicate the time-space dynamics of this ecosystem and the coping strategies of the nomads, SAVANNA needed to represent accurately both the spatial heterogeneity and the temporal instability inherent in the Turkana grazing system. The model was therefore constructed to simulate long-term dynamics of grazing system processes within the spatial framework of a GIS. Since the initial development of the Turkana version of SAVANNA, the model has been modified and adapted to several different grazing systems. It now exists in versions which are all spatially-explicit, process-oriented models of grassland, shrubland, savanna and forested ecosystems. The model has been implemented to simulate processes at local to regional scales, operating over years to multi-decadenal time periods (Coughenour, 1993).

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SAVANNA is unusual, or possibly unique, among grazing system models in that it:

(i) couples an ecosystem/grazing system simulation with remote-sensed and other spatial data-bases within a GIS format;

(ii) simulates at each time step, changes in vegetation quantity, quality and distribution in response to climate and other drivers (i.e. fire), as well as removal by herbivores;

(iii) simulates the spatial redistribution of herbivores in response to changes in vegetation quality and availability; and

(iv) simulates the production and demographic responses of herbivores to changes in vegetation.

Every simulation model has a certain level of trade-off between mechanistic detail and model simplicity. While highly aggregated or simplified models are easier to use, these are less realistic, less generalizable and less explanatory. On the other hand, highly mechanistic models are more difficult to implement and the marginal costs of added complexity are high.

Highly resolved models are more computationally demanding, which may prohibit their implementation at (very) large spatial or long temporal scales. Therefore, SAVANNA treats ecological processes at an intermediate level of resolution. The time step of the SAVANNA model is a week, which allows simulations over longer time scales and larger spatial scales (Coughenour, 1993). As computer technology has advanced, the scale and time frame of SAVANNA has expanded. Currently, the model simulates landscapes composed of 100-10 000 grid cells of any size and operates over timeframes of years to several decades, in reasonable computation time on a personal computer (PC) with the current generation of microprocessors.

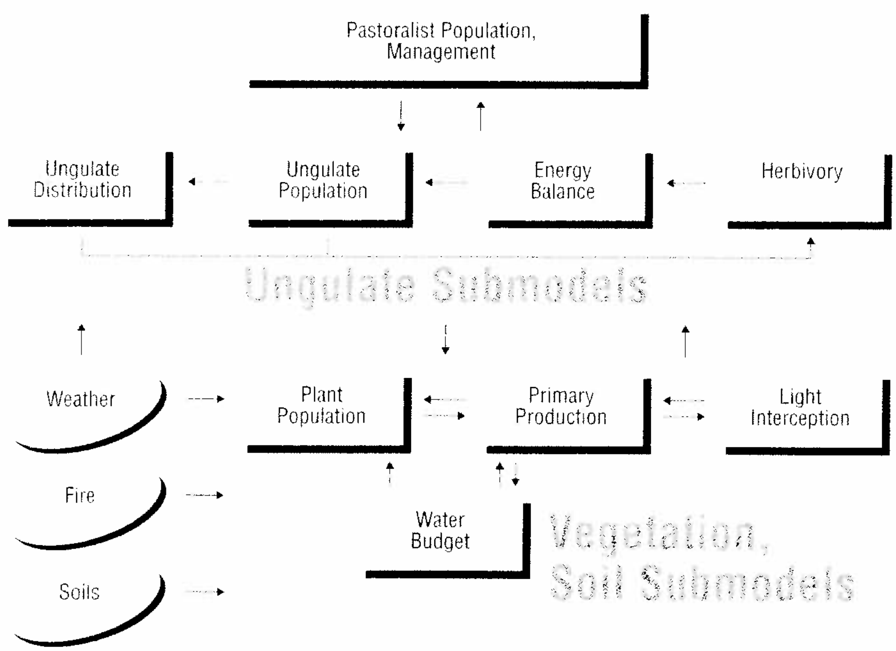
2. MODEL STRUCTURE

SAVANNA was designed to operate at a landscape or local level, i.e., it was envisioned to be applied to landscapes incorporating the entire spatial domain of a selected grazing system. In the Turkana case, the local grazing system covered a sub-tribal territory of approximately 10 000 km^2. Today, this grazing system could be simulated at a scale of one grid cell per square kilometre (km^2); when the model was first constructed, grid cells had to be considerably larger due to computational limitations. The spatial component of the model has a hierarchial structure. Grid cells may be of any size; each cell is simulated and changes in cell characteristics or redistribution of herbivores among cells is updated at selected time steps. Each cell has a subarea corresponding to the configuration of physical factors like topography and soils. For each subarea the model simulates vegetation patch cover (i.e. herbaceous, shrub, and tree cover) but this "within cell" patch structure is modelled as a proportion of the grid cell, rather than in terms of explicit patch structure.

The model is composed of several interacting submodels (Figure 7.1). It is driven by monthly weather data, although NDVI values can be used to drive the model if climate data are not available. Monthly precipitation and temperature drivers may be entered as spatially explicit values or, if not available in that form, as mean values for the ecosystem. A snow submodel simulates snow depth and water content; snow crusting is related to temperature. The water submodel simulates soil moisture dynamics for each patch type within each grid cell. The model includes precipitation, interception, runoff, runon, infiltration, deep drainage, bare soil evaporation and transpiration. The light submodel simulates shading within and among plant canopies and provides information for competitive interaction among plant types and resulting change in vegetation structure.

Figure 7.1

SAVANNA model structure



Source: Coughenour (1993)

Plants are simulated in the net primary production (NPP) and plant population submodels. The NPP submodel is affected by light, water, temperature, soil properties and herbivory. Plant biomass is generated or lost in response to these drivers. The plant population submodel simulates establishment, size class and mortality of specific functional groups. The population submodel is linked directly to the NPP submodel.

Herbivore dynamics and impact are the outcome of several interacting submodels. The herbivory submodel simulates forage intake which is determined by species dietary patterns (i.e., diet selection) and by forage availability and quality. An energy balance submodel uses patterns of energy intake and expenditure to simulate the mean body weight of each sex and age class for each animal species. Body weight is used to develop a condition index which affects herbivore population dynamics. Birth rates and death rates are simulated in the population dynamics submodel, for each of five sex/age classes. Animals may also be removed from the population by sales, culling or other managerial means in a rule-based routine. A predator model interacts directly with the herbivore population dynamics submodel. Predation rate is density-dependent and predator dynamics are regulated by prey-intake rates. The herbivore spatial distribution submodel dynamically distributes animals among grid cells over the simulated region, on a monthly basis, in relation to habitat suitability. Suitability is determined by changing forage distributions as well as by the basic characteristics of the ecosystem and managerial inputs, such as herding and water distribution. For a more detailed description of SAVANNA, see Coughenour (1993).

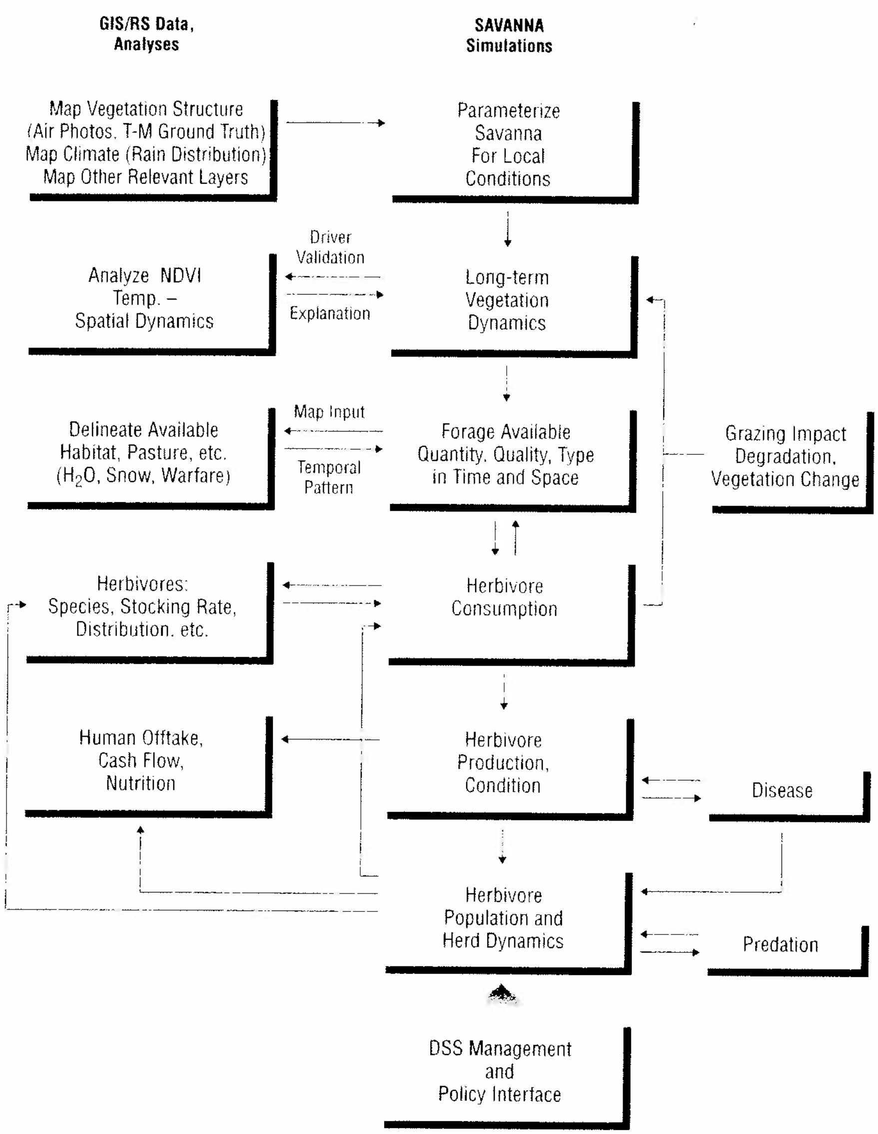
3. SAVANNA OPERATIONS

Utilization of the SAVANNA integrated system generally involves a series of linked GIS operations and model simulation runs (Figure 7.2). In order to run the system in such a way as to take advantage of the precision inherent in SAVANNA, the physical and dynamical characteristics of the selected ecosystem must be specified at a commensurate level of resolution. Spatial databases needed to meet research or management objectives are entered into a GIS system (SAVANNA interfaces with ARC-INFO, GRASS and IDRISI).

Regional soils, climate patterns and vegetation are generally required; vegetation structure can be entered from aerial photos, T-M or other R/S imagery, or from other sorts of maps. When basic information (e.g., vegetation, climate, soils), is accumulated in the GIS, SAVANNA is parameterized to fit the local conditions. The model can then be run to replicate the vegetation dynamics of the selected region, based on extant seasonal and long-term climate patterns. At this stage, it is useful to compare model output to observed NDVI dynamics.

Figure 7.2

SAVANNA operations and output files



The model demonstrates how the system should behave under the given climate regime, and it explains at the process-level why system dynamics followed the simulated pattern.

Comparison with observed NDVI dynamics provides a validation test for the model; if results match, the ecosystem and the model are in synchrony. If results

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differ, the ecosystem is not reacting to climate dynamics as expected, indicating that there is a mismatch between real ecosystem characteristics and those used to parameterize the model. For example, an undiscovered shift in plant species composition or overgrazing might cause a mismatch between simulated and observed NDVI trends.

Simulation of vegetation dynamics provides the information needed to specify the spatial distribution and temporal dynamics of forage for herbivores, within the region of interest. If some of this forage is unavailable to herbivores for reasons such as poor water distribution, unsuitable terrain, and warfare zones, these areas can be eliminated within the GIS. Information on herbivore species, sex and age classes, stocking rate and distribution are then entered in GIS format. SAVANNA then simulates herbivore consumption based on the forage and herbivore inputs, and updates forage conditions and herbivore condition for simulation at the next time step.

These SAVANNA operations provide, (among other things), numerical values for, and spatial distribution of:

(i) grazing impact on vegetation and resulting changes in vegetation;
(ii) herbivore production and condition;
(iii) herbivore production translated into human offtake; and
(iv) herbivore population and herd dynamics.

4. SAVANNA APPLICATIONS

The exact operation of the SAVANNA integrated system depends upon the objectives at hand and the characteristics of the ecosystem/grazing system under investigation. SAVANNA has been used in a research context to evaluate the long-term dynamics of the Turkana grazing system mentioned above. The model has also been used to assess management options for several North American national parks, where questions of ungulate carrying capacity, grazing impact and appropriate management techniques have been addressed. Currently, the modelling system is being adapted to evaluate climate and land-use interactions and their joint effects on the production characteristics, stability and resilience of a very large grazing region encompassed by the Mongolian Steppe in east Central Asia. An early prototype of the integrated system was first developed to evaluate patterns of energy flow from plants, through livestock to Turkana pastoralists in northern Kenya. In this study, we used a primitive GIS application and a static ecosystem model to trace the seasonal and spatial dynamics of energy in this large (10 000 km^2), unstable and highly seasonal ecosystem (Coughenour et al., 1985). Through this analysis, we were able to identify critical paths of energy flow, the relative importance to pastoralists of various plant types and herbivore species, and we identified that livestock removed an extremely small portion of the total forage produced over the ecosystem as a whole. From this beginning, we developed a dynamic ecosystem model (SAVANNA) and, among other objectives, coupled it with NDVI data to evaluate ecosystem recovery rates following a severe drought (Coughenour, 1992). In addition, we used the SAVANNA system to conduct a retrospective analysis of drought dynamics and livestock production over a 67-year period (1923-1990) covered by historical climate data (Ellis et al., 1993).

SAVANNA has recently been used to assist in research and management of ungulate populations in several national parks and conservation areas in North America. A general concern in parks and conservation areas is the question of natural regulation of ungulates versus intense management, in order to keep populations within levels perceived to be compatible with ecosystem vegetation and other properties. In this context, SAVANNA has been used to provide park biologists and managers with simulation studies of winter-range carrying capacity, ungulate impact on forage plants and riparian zones, and ungulate population responses to fire and climate change.

Yellowstone National Park is one of the largest parks in the US (i.e., about 8 900 km^2) and supports a high diversity of native ungulates and high densities of some species. Since the early years of the park, elk were culled in the belief that they would otherwise become too abundant, as they were protected from both human hunting and natural predation. In the late 1960s, the culling policy became a point of public controversy and since 1968 the northern Yellowstone elk herd has been managed under the concept of natural regulation. SAVANNA was used to test the concept of natural regulation in northern Yellowstone and to evaluate the potential effects of a massive 1988 fire on winter-range carrying capacity and elk population dynamics (Coughenour and Singer, 1996a,1997b). Using climate data from 1968 to 1990 and the Yellowstone GIS habitat and vegetation map, SAVANNA simulations closely matched the numbers of elk observed over that time period. It correctly simulated four die-offs occurring between 1968 and 1989, both in terms of the year of occurrence and the magnitude of elk mortality. SAVANNA predicted that if conditions were to remain generally the same over the period 1992-2011, elk populations would rise to the levels achieved before the 1989 die off, then fluctuate with climate conditions around a long-term mean of about 25 000 animals. The model suggested that the 1988 fire would have only limited effects on range forage; would result in slightly depressed elk numbers in the first decade after the fire, and would lead to slightly (10%) higher numbers for the second decade after the fire.

At present, GIS data are being organized and SAVANNA is being adapted to address questions of climate and land use interactions on the Mongolian steppe. Throughout central and east Asia, there is concern about degradation of grazing lands resulting from socio-economic changes, land tenure changes, expansion of livestock numbers and alterations in spatial patterns of grazing exploitation (Kerven et al., 1996). In this research programme SAVANNA, simulations will be linked with NDVI analyses at broad regional scales to identify subregions and/or locations (i.e., sums or small aimags in Mongolia) which appear to be performing poorly, given extant climate regimes. The model will then be adapted to selected 'suspect' degradation locations and finer scale information on land use intensity, livestock numbers, plant cover, etc. will be entered. Model simulations will explore: (i) whether extant land use practices are compatible with the current climate regime; (ii) how land use might be altered to achieve better ecosystem performance; and (iii) potential degradation trajectories if improper land use continues (Ellis et al., 1995).

5. NEW FEATURES

Over the next several months we hope to make several improvements and additions to the modelling system. The current socio-economic submodel will be revised to better represent monetary flows resulting from sales of animals or other activities undertaken at the firm or enterprise level. A disease interaction submodel will be developed to address the effects of disease on ungulate production. We are particularly concerned about disease transmission and its implications where livestock and wild ungulates utilize a common environment. A decision support system was developed for one version of SAVANNA, aimed at making the modelling system more user-friendly for biologists and managers at one national park (Buckley et al., 1993). We plan to develop a more general user-friendly interface which will serve as a shell, amenable to modification to suit the objectives and conditions at any location.

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