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# Modelling the Development of Natural Pasture and its Sustainable Use

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**Abstract**

This paper reflects on the growing possibilities of interdisciplinary collaboration across the ecological and economic sciences in modelling the dynamics of complex ecological economic rangeland systems. The importance of interdisciplinarity in natural pasture research is obvious as most natural rangeland problems involve the interaction between social and ecological processes. Their causes lie in the behaviour of farms and households and consequences can be measured in terms of changing production potential of rangelands. Therefore feed back effects running in both directions have to be considered. This paper considers developments based on the inclusion of vegetation dynamics in models of rangeland utilisation. Here, a growing set of models deal with the link between economics and biology. These ecological-economic rangeland models are normally characterised by the fact that the economic optimisation problem is constraint by the vegetations dynamics of the natural pasture being exploited. The paper discusses the approach and related simulations. Possible future developments of natural pastures as sensible to a variable economic framework and the impacts of climate change are highlighted.

In particular the paper indicates new contributions to model the discontinuous and more event-driven response of semi-arid vegetation to utilisation in a case study on central Namibian rangelands. Within a typical optimal control approach in dynamic programming a state-and-transition matrix serves as an interface to relate the biological system to market prices and institutional constraints. Thereby resource quality is referred to as state variables within a multi-equilibrium system.

Keywords: environmental policy, state-and transition, ecological-economic, models

## 1 Introduction and objective

Because of an overuse of natural resources the range quality of most semi-arid savannahs has declined. The eco-system responds to selective grazing by domestic animals with a move towards woody plants and desertification. This indicates lower stocking potentials for domestic livestock and wildlife. Reconsidering long-term degradation processes and seeking of cures for environmental degradation are immediate requests, especially with respect to farmers' objectives. Dynamic ecological-economic models of natural pastures can show future developments and interdependences. In this regard a suitable interface for the ecological and economic system is a major methodological task.

## 2 Methodology

### 2.1 Dynamic optimisation of farm management

A central idea behind ecological-economic modelling is to combine the strengths of two approaches for the creation of a realistic tool of range land management, the vegetation dynamics of semi-arid ranges and the interacting economic behaviour of profit seeking farmers. The important advantage of an economic approach for the description of degradation is the formulation of an objective function and delineation of dependency of degradation on objectives. In this objective function preferences of decision-making units find their ranked representation, in particular the time preference. Strategies resulting in highest utility, as simple assignments, profit, are ranked with respect to the chosen objective function leading to the generally perceived pure profit-maximisation concept. For this approach the formulation of a productions function is essential.

It is obvious that for estimating reliable production functions, which should include eco-system components in continuous representation, an extensive data set is needed. But a broad set of empirical data is difficult to obtain. Hence other approaches to determine input-output relations for using them in a computer model are necessary. A commonly applied method to deal with problems of capturing the interaction of eco-systems and farming is to define discrete input-output combinations in programming modules that at least capture discrete modes.

These combinations can be considered as point data on an unknown continuous n-dimensional production function. However, since such points are introduced directly in a mathematical programming framework, there is no need to specify a production function (Kruseman, 2000). Then, the necessary information on the input-output relationships can be gained by farmer interviews. The obtained data set has to complemented by information taken from literature and experimental results of research stations on alternative management options.

The data gained from a farm survey has to be analysed for information on economic coefficients on farm practices and eco-system response, i.e. range quality as dependent on grazing intensity as an example. Also, most parameters such as overall farm sizes, labour needs, or calving rates, which are representative for a certain area, can only be seized conditionally by average. Here "best farmer practise" indicators serve as starting point for optimisation.

Typically, also accommodated in economic thinking, are constraints on the farming systems, such as limited resources of land or available water. As a consequence we came up to work with LP-structures, notably as the core tool module in modelling the farming system. Clearly defined activities assign specific requirements to scarce resource levels (e.g. biomass). Then, with the help of a mathematical algorithm, optimal solutions are found achieving highest values of the objective function. For this we used an extended programming-structure that is dynamic and in parts non-linear in GAMS.

Given a state-transition sub-module (presented below), investments in the range quality, as state, for instance like bush control measures can positively affect the biomass availability in the following periods. Acknowledging that bush encroachment is regarded as the most eminent ecological problem in the farming area (whereby no single successful strategy is identified and adopted by farmers so far) several different bush control measures are considered within the actual model. With respect to objective function an optimisation process finds management strategies obtaining highest utility levels in a framework of optimal utilisation of renewable resources (Pearce & Turner, 1993).

The decision maker has to undertake adjustments in his management in every time step in order to reach his individual goals and consider actual resource developments. Therefore the models can be designed as an optimal control approach as characterised by Berg and Kuhlmann (1993).

## 2.2 Vegetation dynamics of a semi-arid rangeland

The vegetation dynamics of a semi-arid savannah are characterised as being highly non-linear. They are described by jumps and probabilities. Factors like natural resilience and conditional probabilities have to be considered. Scaling is another problematic issue as natural systems tend to be hierarchical with quick small processes embedded in slower larger processes (Levin, 1992). Moreover the appearance of ecological thresholds constitute a major challenge for ecological modelling approaches and for a ecosystem assessment.

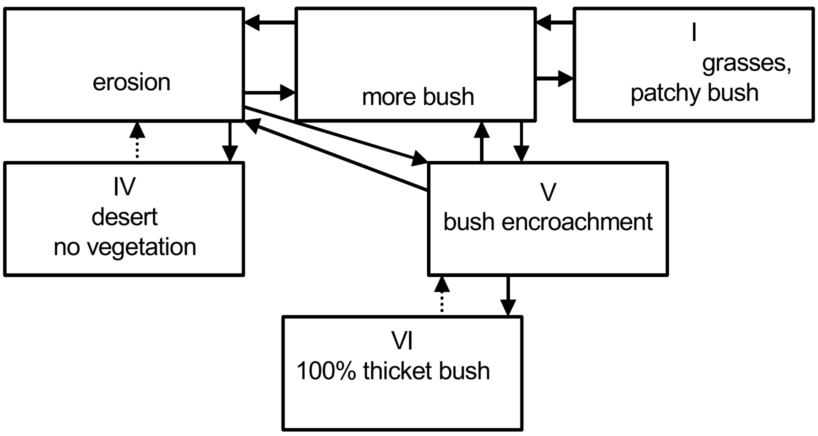


**Fig 1: State-and-transition model for a semi-arid rangeland (adopted from Westoby et al., 1989)**

Bioeconomic models often contain only one single logistic equation what is too simplistic by ecologists' standards. More complex representation of the vegetation dynamics might lower their suitability for their use directly as part of optimal control models (Cacho, 2000).

The recent state-and-transition-model as described by (Westoby, Walker, & Noy-Meir, 1989)), (Milton & Hoffman, 1994)) or (Rothauge, 2000)) provides some scope to deal with the situation. Tough the ecological system of an arid range land concerning all influencing factors as well as the time scale is not yet fully understood, these models replaced the former perception of an arid range land as continuously de- and up-grading from a climax vegetation to degraded land by utilisation. The state-transition model, as indicated in figure 1, is based on the idea of different states (I-VI) which can only be transferred by certain transition events. The transitions depend on factors like rainfall pattern, soil type, grazing, stocking, etc., and are therefore explicitly named "event-driven".

### 2.3 Integration, applied state-and-transition model and creation of an interface

One possibility to deal with this situation of ecological complexity is to link ecological and economic modules by transfer vectors. This concept works in such a way that, similar to the idea to replace n-dimensional production functions by point data on input-output relations of separate technology choices, unknown complex ecological functions on transition are replaced by point data on temporal input-output relations, whereas we use probability presentations.

Especially, one approach to deal with the highly complex dynamics in range ecology is to work with different range land quality states or frames as provided by the state-and-transition model. In that approach ecological thresholds are applied as in ecological state-transition model for range lands. This innovative approach is to integrate the inter-temporal interdependences of the agro-ecosystem by a transfer matrix. This transfer matrix determines which management options in a period t affects the state of the ecosystem (natural rangeland) in the period t+1. The picture for the entire farm results out of the summing over all states. The parts of land within the different states over time result consequently out of initial conditions t0, the optimal management and the intermediate states over time (Milham, 1994). Therefore the application of a transfer matrix (s. fig. 2) allows to integrate the dynamic interactions of management decisions and natural environment completely.

| Demand/Transfer | Activity1 | Activity2 | Activity3 | |
|---|---|---|---|---|
| Demand State1 | | 30 | 10 | <= Land State1(t) |
| | 25 | | 20 | <= Land State2(t) |
| Demand State3 | | | 30 | <= Land State3(t) |
| | | | | |
| Transfer State1(t+1) | | 30 | 10 | |
| Transfer State2(t+1) | 20 | | 50 | |
| Transfer State3(t+1) | 5 | | | |

**Fig 2: Simplified example of a LP-structure and a transfer matrix**

Each discrete management activity or technique, which is bounded to a specific state of range quality, has a transfer vector (technically combined in a matrix when different activities are considered), which determines to what extent land shifts from an initial state to a different quality state. By that, complex ecological systems with respect to their corresponding bundle of functions are represented as point data in dynamic matrices. As a result ecological dynamics can be treated most easily within an economic modelling approach using simply coefficients.

The coefficients of transfer matrix are in our actual models are mainly based on expert knowledge, and they are to be worked out further in close co-operation with local range land scientist and botanists.

Moreover in the simulations the rainfall patterns appear stochastically. This emphasises the event-driven character of the vegetation dynamics. Moreover the biomass production is a function of both, the actual rainfall and the coefficient for biomass productivity, for the latter again assuming dependency on the specified range quality state In mathematical formulation this phrasing means for instance, that if a particular threshold is exceeded the system would transform itself into another state (frame) as well as different rules and mathematical equations would apply differently in states. Also the model contains a possibility to transfer biomass surplus from one period to the next period. To provide options to secure biomass availability under poor rainfall conditions, farmers can opt for storage in stems of mature grass.

**3. Results from a case study on Namibian rangelands**

Initial model runs are set off to show how the economic environment, i.e. prices, wages, time preferences implemented by different interest rates, etc., influence the decision-making of the farmer. Especially the impact of the labour costs on the land use intensity (i.e. exploitation of the natural, slowly renewable, resource) can be examined. The decline in cattle production is caused by a range land degradation process which takes place if little investment in the environment (i.e. range land quality) is undertaken. Model runs show how economic conditions influence decision-making (Fig 3).

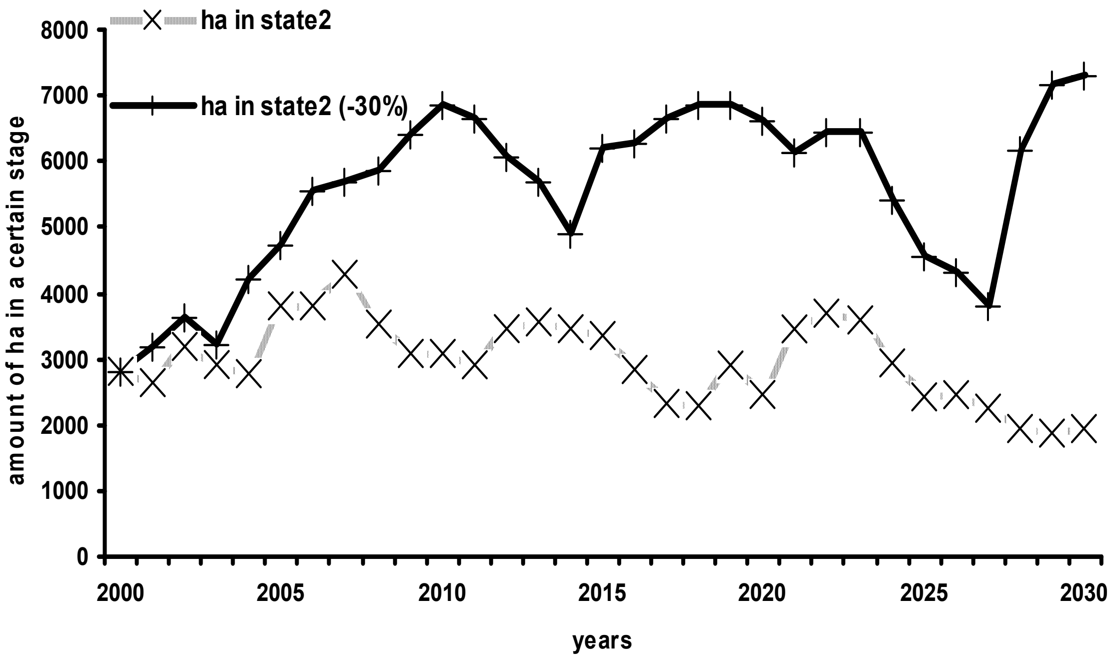


**Fig 3: Impact of reduced labour costs (-30%) for bush control activities on the amount of hectares being in a good state (state 2)**

In particular the impact of interest rates and labour costs on land use can be examined. Although these models do not yet illustrate all vegetation dynamics sufficiently, results from first model runs indicated the importance of the time preference for farmers. For instance, the biomass production tends to decrease over time (interest rates of more than 10%) as range land degradation take place.

As the vegetation dynamic is represented by a state-and-transition model, one can follow up the amount of hectares in a particular quality state at a certain point of time. Then we simulated variations in labour costs for combating bush encroachment. For instance the amount of hectares in state 2 (i.e. an average good rangeland condition) would increase by roughly 100% with an assumed cut in labour costs of 30%.

By the fact that discounted value added of different technology choices over time lead to different optimal strategies, high time preference becomes the crucial issue for an incentive for long-term investment in the environment (i.e. sustainability). We found, there is little chance to pay off the invested money from a lower stocking rate (i.e. an income renunciation) this year by an increased biomass availability in the next years. For instance, with an actual time preference of 7.5% (i.e. interest rate minus prevailing inflation rate) investments in bush control at current prices are too expensive. These findings are in line with considerations of the Namibian government to provide cheap loans for farmers for bush control activities.

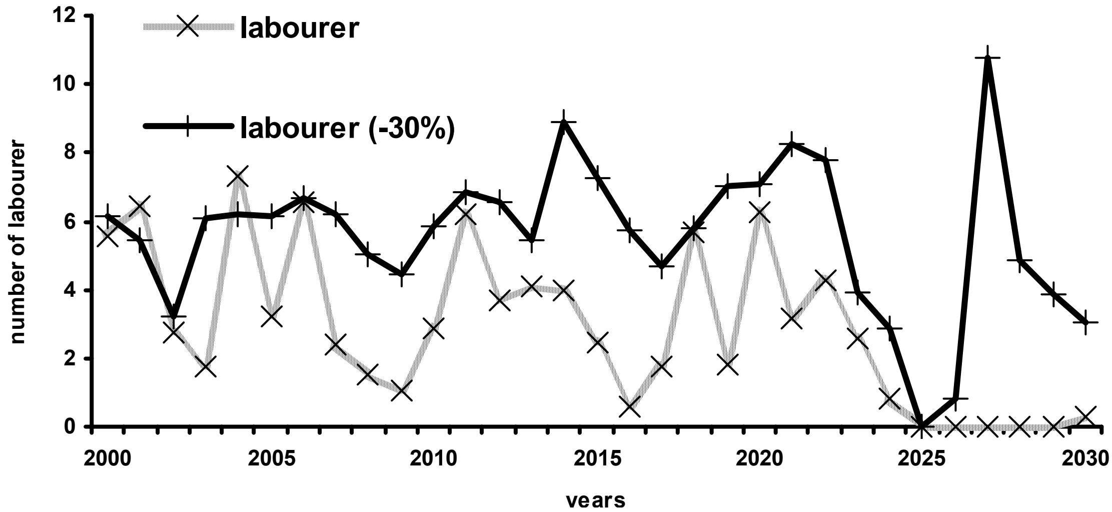


**Fig 4: Impact of reduced labour costs (-30%) for bush control activities on the number of employed labourers on a sample farm**

Other possibilities would be to subsidise labour for more labour intensive bush control measures (e.g. manual spot treatment). As the model can show a reasonable desire at low costs, effects on the environment are positive. Further note Namibia faces a serious unemployment problem which could be approached In average more workers would be employed on a sample farm (Fig 4).

**4 Summary**

We can give first hints how the state-and transition perception of a semi-arid rangeland might be applied as an interface between ecological models and farming system models. This can be achieved by the application of transfer matrices.

Moreover, in a case study on Namibian farms we are capable to show how improved and better adapted management practices can lead to a more sustainable use of semi-arid rangelands. To approach our objective we built a farm model that includes ecological-physical aspects on the interaction of different domestic livestock and game with the environment by a state-and-transition-model. The models are designed around the maximisation of discounted value added of different activities for sustainable rangeland use. Furthermore, the possible impact of policy measures on land degradation can be investigated.

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