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The use of models in the analysis and management of aquatic and terrestrial animal production systems

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Abstract

Modelling of animal production systems as a whole is mainly used for extensively managed systems, such as fishing and hunting natural animal populations. This type of modelling is widely used in fisheries management, but has as yet found limited application in the modelling of extensive cultivation practices. Modelling of terrestrial animal production is concentrated on the breeding process and on growth and food conversion. For intensive fish culture, modelling concentrates more on growth of individual animals. There is a shortage of experience in modelling extensive and semi- intensive cultivation systems, both in aquatic and terrestrial animal production (pond culture, integrated farming). This paper provides a systematic overview of the types of models in use for animal production systems; these models differ in their control over production factors. The state of the art with respect to modelling subsystems is also sketched. Special attention is paid to the modelling and prediction of the environmental load caused by the output of present systems and to the search for alternative management strategies following this whole system approach.

Keywords: system analysis, animal production, fisheries, aquaculture

Introduction

Managing animal production systems entails the organization of resources in relation to their potential production: what is the best combination of available resources to produce the optimum range of products?

The production systems contain a number of complex and interacting elements and are embedded in larger biological ecosystems. Exploratory investigations are of an ecological nature, but also may include major economic links between processes.

Models can be used to evaluate different aspects and options for improvement of a production system in an integrated way. Examples of models that have been applied to various aquatic and terrestrial animal production systems are numerous. The objective of this paper is to discuss briefly biological models used in the analysis and management of animal production systems in their environment at different levels of control.

Production systems

Aquatic and terrestrial animal production methods may range from hunting in open systems to intensive cultivation in closed systems. Terrestrial animal production has almost completely changed to cultivation while retaining a large variation in the level of control. In the terrestrial environment the most extensive form of animal production is game cropping, while capture fisheries may be regarded as aquatic animal production with the lowest level of production control.

A generalized representation, as a relational diagram, of animal production systems based on the principles of population dynamics and population management (Berryman, 1981) is shown in Figure 1.

The principal state variable is the biomass of the animals in the stock. Biomass equals the sum of weights of each animal in the stock. Variables that change numbers and/or weights are therefore the most direct rate variables (production factors) affecting the biomass growth, reproduction, losses and harvest or offtake.

A classification of the production systems according to the level of controlling the rate variables is given in Table 1. Production based on hunting in open systems is restricted mainly to the aquatic environment: oceans, coastal areas, lakes, reservoirs and streams. The production control variable for capture fisheries is harvest. The main control variables in extensive aquatic and terrestrial production systems with private ownership are harvest, reproduction and to some extent losses (mortality). In intensive production systems growth has become the most important control variable to optimize the production level.

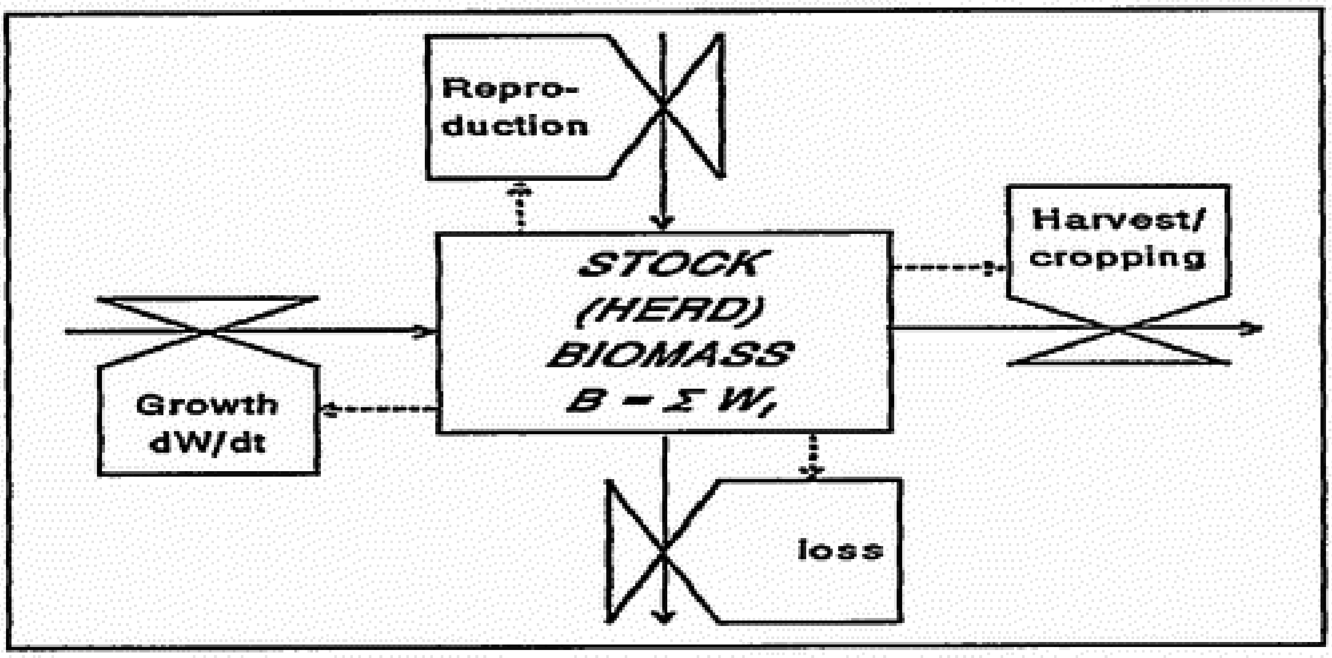

Figure 1. Schematic representation of the principal state and rate variables in an animal production system. B. Biomass; W_i, weight of individual animal.

Table 1. Classification of animal production systems based on their control

System	Control	Environment	
		Terrestrial	Aquatic
Open systems	Harvest	Hunting	Capture fisheries
Cropping/cultivation			
☐ Extensive	Harvest, reproduction, losses	Game ranching, nomad systems	Extensive pond culture
☐ Intensive	Harvest, reproduction, growth, losses	Integrated systems/ mixed farming	Integrated systems
		Specialized systems	Specialized systems

Production system models

The conceptualization of a production system into a system dynamic model is done according to the organizational level. The organizational levels relevant for animal production systems are communities, populations and individuals.

At the community level, trophic food web or ecosystem models are used. In a natural environment the autotrophic production of plants, e.g. phytoplankton and/or macrophytes, by photosynthesis is utilized by heterotrophic organisms at higher trophic levels. The modelling approach starts either at the lowest or at the highest trophic level. Bottom-up models start with the derivation of empirical relations between the structure of the lower trophic level populations in the community and their potential biological production based on solar radiation and nutrient concentrations. The production at higher trophic levels is modelled using assimilation efficiencies between successive trophic levels. Top-down models rely on information of the populations at the highest trophic level. These effects on populations at a lower trophic level are included to give an insight of the growth potential of the populations that are managed. Feeding habits and consumption rates are derived from stomach contents analysis, gut evacuation rates, and feed conversion efficiencies. The number of state variables may grow enormously when detailed food web relations and effects of abiotic factors are included in such models. Examples of these models are mainly applied to the aquatic production environment such as natural systems and extensive pond culture systems (DeAngelis, 1988; Christensen & Pauly, 1992).

Biodemographic models concentrate on the population as organizational level. Within the population, birth and death processes occur. The birth and death rates are related to the population size in numbers. The simplest population models consider the biomass as a single indicator for population size. The carrying capacity of the population is reached when the rate of increase in biomass is equal to the rate of decrease in biomass. The population is at equilibrium state in an unexploited situation. When the stock size is smaller than the carrying capacity, the difference between rate of increase and rate of decrease is called the surplus production. This surplus production is available for harvest, without changing the generating stock. The models resemble the traditional logistic ecological models. A model still widely used in fisheries management was formulated by Schaefer (1954).

More complex models take into account the age, sex and size structure of the resource with their specific mortality and harvest rates and the growth rate of individual animals. The models commonly used to describe growth were developed by von Bertalanffy (1938) and Brody (1945). These models including the logistic growth model, were generalized by Richards (1959). Age- and/or size-structured biodemographic models include mortality, reproduction, growth and exploitation rates as model parameters. In the aquatic sciences, especially fisheries, numerous models are used: these have been reviewed by Megrey (1989). Recent applications have been described by Buijse et al., (1992) and Büttiker & Staub (1992). Recruitment is mostly excluded in such models, so the yield is predicted as yield per recruit. Biodemographic models have also been applied occasionally to extensive culture systems such as pond culture and game ranching (Tysso, 1987; Mace, 1989; Baptist & Sommerlatte, 1991). Production models for intensive culture systems usually include a biodemographic component which predicts the reproductive performance of the animal stock.

Using the individual animal as organizational level gives insight and explains the processes that occur at the population level. The models used are bioenergetic, using the energy flow from source to animal products in a balanced energy equation as a starting point to describe individual animal performance. Growth equals the energy consumed minus losses through respiration and excretion. The principal state variables in bioenergetic models are weight, protein and energy content of the animal and/or animal product. Rate variables are feed intake and energy requirement for maintenance, growth, activity and animal products. Respiration is controlled by temperature, body size and feed consumption rate. Major limiting factors are related to environmental quality, e.g. oxygen supply and food supply. The effect of food composition on growth, respiration and excretion is still rarely included. Bioenergetic models have been developed for the whole range of production systems. For terrestrial animal production the bioenergetic model is often an integrated part of the dynamic system model e.g. Udo & Brouwer (1993). Bioenergetic models for natural populations in the aquatic environment have been developed aiming to estimate the food consumption rates of fish (Hewett, 1989; Boisclair & Leggett, 1989). Examples of bioenergetic models developed for pond culture are provided by Cuenco et al., (1985) and Liu & Chang (1992). Recent applications of bioenergetic models for intensive fish culture systems have been made by Cacho (1990) and Schuur et al. (1991).

Model use in analysis and management

Making dynamic models are the first and most complex part of the analysis of production systems. Here the rules for predicting the change of state variables over time in relation to other variables are set. These models may be used in research to test hypotheses and in management to forecast system behaviour. Using a reductionist approach, the system is analyzed by studying underlying processes in detail. Models are used to hypothesize how state variables are related to observable quantities. Using a holostic approach, models are used to hypothesize how the performance of the system will be in relation to its state. Walters (1980) defined models using a reductionist or holistic approach as observation models and objective models respectively.

Models used for management of open access production systems, such as fisheries, are rather simple system dynamic biodemographic models. Management of the fish stocks in these systems is done indirectly by harvest control. The amount and the age or size distribution of the harvest is determined by the effort (number of boats, nets, fishermen) and the harvest method (gear type, mesh size). The model predicts, given a certain natural loss and growth of the animals in the population, the yield at a certain effort for a specific method. In this way the maximum yield is determined when the population is rationally exploited. The models can also serve as a policy analysis tool to determine the effects of the management options for a certain system. The main constraint on the use of these models is their dependence on elaborate observation models, which are used to estimate the parameter values of the system dynamic model. Carrying capacity, number and timing of new recruits, growth, mortality and the catchability efficiency of the harvest method cannot be estimated directly from the observations in the system. Another constraint on the use of models for these production systems is the uncertainty induced by the natural environment. The dependence on externalities can be quantified on the basis of historical data.

As well as by controlling the harvest, management of the stock can also be achieved by reproduction control. The number of recruits entering the system is controlled by protecting the spawning grounds or reproductive areas. Other management tools are introduction or stocking of the species in the system (Keto & Sammalkorpi,1989; De Silva et al., 1992). Also, losses through mortality might be influenced by culling a predator species.

Management of production systems based on cultivation, with a higher level of control, usually deal with a specific process like culture space, feed, oxygen supply, water and temperature. At this control level the potential harvest or offtake is directly related to the growth of the stock biomass in terms of weight, because reproduction and survival are controlled. Growth can be controlled directly through feeding or indirectly. In extensive culture systems growth is often controlled indirectly by stocking density and production of natural food by fertilization. In intensive culture systems, animals are supplied with complete feeds. Therefore production manipulation is primarily concerned with providing adequate levels of nutrients by feeding management. The quantity and quality of feed used determines the conversion efficiency from feed to animal product.

Bioenergetic observation models deal with estimating the terms of the balanced energy equation. The system boundary used is an individual animal. Estimation of model parameters is based on experiments in respirometers, monitoring the heat and gaseous exchange, consumption rates and collection of faecal and urinary waste. Protein and energy dynamics are simulated in relation to temperature, body weight, ration size and diet quality. Reviews on models for aquaculture are given by Fridley (1987), Piedrahita (1988) and Cuenco (1989). Bywater (1990) reviews terrestrial animal production system models, which can be applied at farm level. The last decade has seen a move to develop explanatory models based on underlying biochemical processes in the growing animal, such as pigs (Black et al., 1986) or fish (Machiels, 1987).

Biological models include the response and interaction of the cultured animal and its environment. Models that are developed specially to design, manage or control the culture environment have been applied on intensive culture systems in the aquatic (Wallin et al., 1991) and terrestrial environment (Dewhurst & Thomas, 1992).

Discussion

A comparison between models developed for aquatic and terrestrial animal production systems shows similarities in the basic concepts. The differences between models for the aquatic and terrestrial environment are the result of production control level, environmental, historical, and bioenergetical dissimilarities.

Early domestication of terrestrial animals suitable for production resulted in 10-15 cultured species. Aquatic species, which are caught in natural systems or cultivated surpass this number at least a hundredfold. Much practical knowledge and experience has been accumulated on culturing aquatic species, but scientific research for model development in the aquatic environment still concentrates more on natural systems in food web and population models.

The estimation of parameter values used in models for animals in the terrestrial environment is relatively easy. The observable quantities such as number and total biomass of animal population can be directly incorporated in the models. Observable quantities in the aquatic environment are related to size distribution and age estimates. Model parameters like stock size and growth and mortality rates are indirectly derived from these observable quantities. These estimates are always based on sampling a population, and therefore information on the variability of the estimated parameters in the individual animal is lacking. Bioenergetic observation models rely on transfer of heat and material between the animal and its environment. The heat exchange of aquatic species, being poikilothermic, with their environment, cannot be measured directly because the heat production is relatively low and the heat capacity of water is high in comparison with air. Feed for aquatic animals must be supplied through the water, while excretion products are immediately polluting the water the animal is living in. Estimation of parameters like feed intake and urinary or faecal excretion is more difficult for the aquatic environment. Intensive terrestrial production systems require collection and processing of waste produced by the animal. In an intensive aquatic production system, water quality control is an integrated part of management.

Comparison between simulation results and reality is easier for a terrestrial production system. Domestication of aquatic species is only starting now. The number of species that are possible candidates for culture in the aquatic environment is large. For each species, model parameters must be adapted by integrating the observable quantities and models. Widespread access to computer facilities makes it possible that aquaculture will follow the techniques already developed for animal production systems: data acquisition in a database, statistical software to support reductionist analysis and dynamic simulation software to develop or adapt the system dynamic models (Udo & Brouwer, 1993). Improved knowledge on the dynamics of production systems enables improvement of the sustainable utilization of natural resources.

A common objective of most production systems is to maximize growth. Models which have been developed reflect this common objective because these models take growth and motality of individual animals as a starting point, evaluating at which input or effort growth is maximized and mortality is minimized. Once additional objectives are defined, available models have to be adapted to the in- and output parameters coinciding with the new objectives, which might be conflicting (e.g. to improve survival, production and food conversion efficiency; reduce costs; maintain environmental quality; minimize loss and risks). Therefore, biological models should be integrated with economic and engineering models to manage and control the environment, site selection, facility design, operation and control.

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