A MODELLING APPROACH FOR PREDICTION AND CONTROL OF GRASSLAND ECOSYSTEMS

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ABSTRACT

A grassland ecosystem is a field where energy flows and various materials, such as nitrogen and potassium, circulate from component to component. This ecosystem usually depends on a large number of environmental, biological and, often, agricultural factors, which control the productivity in the ecosystem and the interactions between them are intricately entangled. Moreover, studies of a grassland ecosystem require such a large area of land, even in an experiment, that it is difficult, in most cases, to replicate the experiment. For these reasons, this problem should be best solved by a system approach instead of a series of field experiments.

The system approaches to grassland ecosystems have been considered for the following purposes:

1) To analyse various factors and their interactions which affect grassland productivity,

2) To forecast short-term grassland productivity for a year or one season, and to make decisions for short-term grassland management, such as grazing intensity and amount of fertilizer to apply.

3) To analyse the conditions under which high and stable grassland productivity can be maintained on a long-term basis i.e., 10 years or more, since grassland plants are perennial and since theoretically, land should be utilized for many years continuously.

4) To seek optimal grassland conditions and to evaluate the conversion efficiencies of solar energy, including both solar radiation and fossil-fuel, to biomass including plant and animal products.

5) To compare efficiencies among various livestock production systems from the viewpoints of energy and economics, and to decide which system or which combination of systems should be adopted.

For solving these problems, in this study, a system model of grassland ecosystem, with emphasis placed on energy flow and nitrogen cycle, will be proposed and several results of system simulation will be reported.

Introduction

The development of grasslands is essential to secure a stable supply of livestock products since such products are very important sources of dietary protein for human beings. A grassland or pasture forms an ecosystem in which materials circulate and energy flows through the various components including the atmosphere, plants and animals day by day. The amounts of energy and materials passing through or accumulating within these components are affected by the interactions between several factors such as topography, climate, vegetation, grassland management and grazing animals. The complexity of this system could be effectively resolved by a system approach.

Introduction of the system concept, use of high speed computers and ecosystem ecology studies in the latter half of the 1960s have paved the way for the future orientation of research in grasslands. Goodall, in 1967 and 1969, proposed an analysis of grazing pastures in Australia using system dynamics and Van Dyne (1969) introduced a similar concept into Prairie studies. The application of methods based on system dynamics in grassland science has been widely accepted worldwide. A research team at Kentucky University studied an intensive livestock production system under non-grazing conditions with hay and silage being offered to cattle (Loewer *et al.*, 1977).

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In Japan, studies on native grasslands have been conducted by the International Biological (JIBP) Team (Iwaki and Hirosaki, 1975), while system approach methods applied to *Zoysia* grassland were evaluated by a group of researchers of the National Grassland Research Institute (Okubo *et al*., 1977) and studies on nutrient circulation were carried out in a grassland ecosystem in eastern Hokkaido (Hakamata and Hirashima, 1978) in the 1970s. A system approach for arable grassland has been designed by Shiyomi *et al*. (1982, 1983) since 1980, and the blueprint of the system model has been established.

System approaches to grassland ecosystems have been proposed for the following purposes: 1) To analyse various factors and their interactions which affect grassland productivity; 2) To forecast short-term grassland productivity for a year or one season, and make decisions for short-term grassland management, including grazing intensity and amount of fertilizers to apply; 3) To analyse the conditions under which high and stable grassland productivity can be maintained on a long-term basis, i.e., 10 years or more, since grassland plants are perennial and since, theoretically, land should be utilized for many years continuously; 4) To seek optimal grassland conditions and to evaluate the conversion efficiencies of solar energy, including both solar radiation and fossi fuel, to plant and animal biomass; 5) To compare efficiencies among various livestock production systems from the viewpoints of energy and economics, and to decide which system or which combination of systems should be adopted. For solving these problems, a system model of grassland ecosystem, with emphasis placed on energy flow and nitrogen cycle, will be proposed and several results of system simulation will be reported in this paper.

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Grassland for modelling approach

In a grassland, part of the solar energy is fixed by plants, some parts of these plants are fed on by grazing animals, while other parts of the plants fed on are stored in animal bodies as energy. Energy excluded from these fixations is accumulated as soil organic matter *via* feces, or diffuses into the atmosphere from animals as heat. Residual plant matter changes into standing dead plant materials and then into soil surface litter, and finally accumulates in the soil. Matters such as nitrogen and phosphorus circulate through other elements in the grassland, and affect plant and animal growth.

In order to record these energy and matter flows, field surveys were carried out in an experimental grassland at the National Grassland Research Institute for 11 years from 1974 onward. The site parameters and grazing conditions are summarized in Table 1. Observations in this grassland will be discussed as compared with results of system simulation.

System model of energy flow

A compartment model of energy flow in a grassland system from the sun to animal or soil is shown in Figure 1. In this figure, the amounts of energy accumulated in the system are depicted by rectangles; direction of energy flow is indicated by arrow-headed solid lines; and external effects including environmental and artificial effects on the energy flow are shown by ellipses, and these effects impinge upon the points indicated by arrow-headed broken lines. Bows pointed at by arrow-headed broken lines indicate valves for regulating energy flow; for example, leaf area per unit ground area, LAI, affects the amount of energy from the sun to plants. If the valve is loosened, LAI becomes larger and the amount of energy fixed in plants increases.

The amounts of energy accumulated in eight different compartments of a grassland, that is, eight variables are as follows: (1) aboveground live plant portion available to grazing

Table 1 Site parameters and experimental pasture conditions for the modelling approach

Item	Explanation
Latitude	36°55′N
Longitude	136°58′E
Altitude	330 m above sea level
Mean monthly air-temperature	Minimum 1.1°C (Jan.), Maximum 24.2°C (Aug.), Annual average 12.3°C
Mean monthly precipitation	Minimum 40.9 mm (Jan.), Maximum 255.9 mm (Aug.), Annual total 1,631.9 mm
Daily global solar radiation	Minimum 1,735.5 kcal/m^2/day, Maximum 3,844.9 kcal/m^2/day, Annual average 2,681.4 kcal/m^2/day
Pasture plants	Mixture of *Dactylis glomerata, Lolium perenne, Festuca arundinacea, Agrostis alba, Poa pratensis* and *Trifolium repens*
Yearly fertilizer application	N : 100 kg/ha, P_2O_5 : 180 kg/ha, K_2O : 100 kg/ha
Grazing conditions	Paddock size : 0.5 ha ; Number of paddocks : 4 ; Number of cattle : 8 ; Breed : young Japanese black ; Total initial body weight at the beginning of each grazing season (April) : 1,600 kg ; Stocking rate in mid-April : 800 kg/ha ; Rotated between 4 paddocks in a set sequence each week from April to November

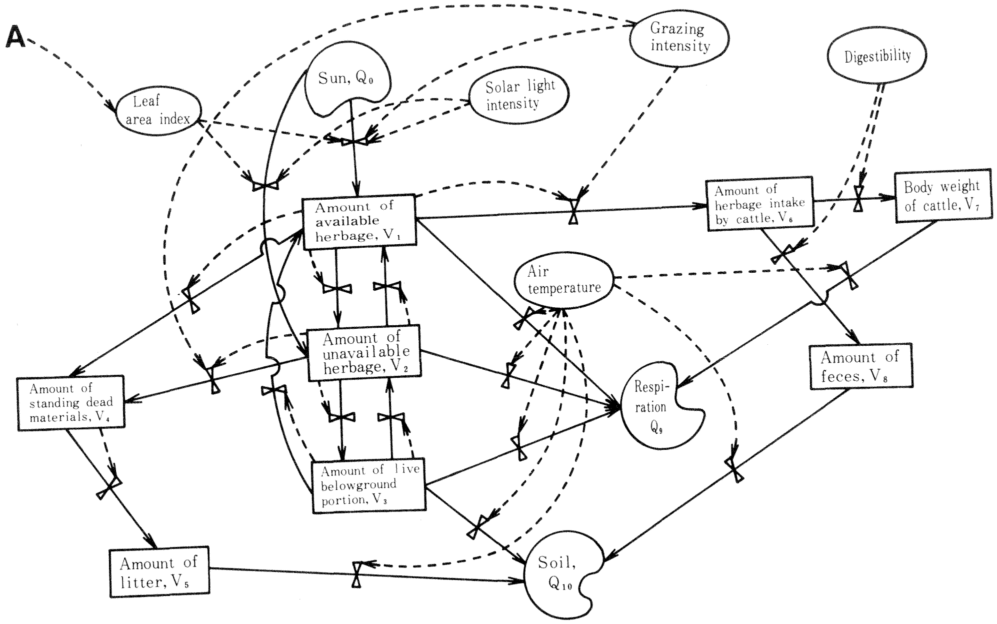

Fig. 1 Compartment model of energy flow in a grassland. See text for details.

animals, V_1, (2) unavailable aboveground live plant portion, V_2, (3) belowground live portion including roots, V_3, (4) standing dead plant materials, V_4, (5) soil surface litter, V_5, (6) plants consumed by grazing animals, V_6, (7) cattle body weight (cattle biomass), V_7, and (8) feces on the soil surface, V_8. All these variables are measured in relation to their calorific value, and changes with time t.

Changes in these variables can be formulated by a set of differential equations as follows:

$$
\begin{aligned}
\dot{V}_1 &= f_{01}Q_0 + f_{21}V_2 + f_{31}V_3 - (f_{12} + f_{14} + f_{19})V_1 - F_{16} \\
\dot{V}_2 &= f_{02}Q_0 + f_{12}V_1 + f_{32}V_3 - (f_{21} + f_{23} + f_{24} + f_{29})V_2 \\
\dot{V}_3 &= f_{23}V_2 - (f_{31} + f_{23} + f_{39} + f_{310})V_3 \\
\dot{V}_4 &= f_{14}V_1 + f_{24}V_2 - f_{45}V_5 \\
\dot{V}_5 &= f_{45}V_4 - f_{510}V_5 \\
\dot{V}_6 &= F_{16} \\
\dot{V}_7 &= f_{67}F_{16}h_1 - F_{79}h_2 \\
\dot{V}_8 &= f_{68}F_{16} - f_{810}V_8, \text{ if there are cattle in the given pasture,} \\
&= -f_{810}V_8, \text{ if there are no cattle in the pasture,}
\end{aligned}
\qquad (1)
$$

where $\dot{V}$ denotes dV/dt. In equation (1), the unit adopted for these variables, except cattle biomass, is kcal/m^2 and the unit for cattle biomass is kcal/ha. Parameters in equation (1), f_{ij}' s, represent the energy flow rate or velocity from variables i to j, and generally they are also functions of time t. They vary with the season, environmental changes and agricultural activities. Main parameters in equation (1) are expressed by the following functions:

(1) Global solar radiation on grassland is expressed by

$$Q_0 = 3100 + 1100\sin[2\{(t-10)/365\}], \text{ (kcal/m}_2\text{/day)} \qquad (2)$$

where t denotes the number of days counted from March 1. The maximum and minimum values of Q_0 per day are 4,200 kcal/m^2 and 2,000 kcal/m^2, respectively.

(2) f_{01} is the energy conversion efficiency of global solar radiation into plant material (plant portion available to cattle), and it is expressed as

$$f_{01} = 97\left\{1 - \frac{1}{1.2L+1}\right\}\frac{A}{AQ_0+1}, \text{ (dimensionless)} \qquad (3)$$

where L is the leaf area index and A is a constant whose value ranges between 0 and 0.7.

(3) f_{i9}'s are coefficients of energy loss from the i-th compartment, *i.e.*, aboveground plant portion, belowground portion, etc., by respiration of plants, and they are expressed as linear functions of air-temperature (unit: dimensionless).

(4) f_{i10}'s are coefficients of energy flow from the i-th compartment, *i.e.*, soil surface litter or feces, to the soil, and they are functions of air-temperature (unit: dimensionless).

(5) F_{16} is the amount of plant materials consumed by animals:

$$
\begin{aligned}
F_{16} &= 8.33 \times 10^{-7} V_7, \text{ if available amount of plant is sufficient for cattle,} \\
&= 0.75\,V_1, \text{ if not sufficient (kcal/m}^2\text{/day).}
\end{aligned}
\qquad (4)
$$

(6) F_{79} is the energy loss from animals by respiration and is also a function of air-temperature (unit: kcal/m^2/day).

(7) f_{67} is the energy accumulated in animal bodies and

$$f_{67} = 0.65 \times 0.414, \text{ (dimensionless)} \qquad (5)$$

where 0.65 is the proportion of the digestible energy in plants, and 0.414 is the proportion of digested energy utilized by animals.

Coefficients h_1 and h_2 are constants denoting the area of grassland or paddock and the number of cattle in the paddock having a given area.

System simulation of grassland productivity

Several results of system simulation calculated on the basis of equation (1) will be presented below.

Most of these calculations are expressed in relation to calorific values, and values for dry plant matter and live animal matter in kcal per g dry or liveweight are as follows: available and belowground plant portions 3.5; standing dead plant materials, surface litter and feces 3.0; and live cattle body 3.0. Calculations of differential equations were performed using the general program designed by Hirosaki *et al.* (1979).

1 Short-term prediction

A prediction of grassland productivity for 1982 is shown in Figure 2. This calculation was performed by giving the conditions of the grassland on March 1, 1982 and the total body weight of the cattle on the grassland at the beginning of the grazing season in that year. Data on the meteorological conditions of a "normal year", which were obtained by computing average values over a period of 30 years, were used in the calculations. These simulated data fitted very well with those observed in the experimental grassland.

The same grassland ecosystem was used in 1984 and the variables predicted on the basis of equation (1)are shown in Figure 3.For this calculation, actual meteorological data were used from March to May and the meteorological data for a "normal year" were used after May. In the calculations, periodical changes in the biomass of aboveground portion of the plants were related to the rotation grazing schedule, as shown in Table 1.

2 Long-term prediction

Any grassland has to be maintained for a long period of time, for example, 10 years or more. For this reason, unless changes in the grassland ecosystem caused by various agricultural activities are adequately predicted, ineffective or excessive investments may be

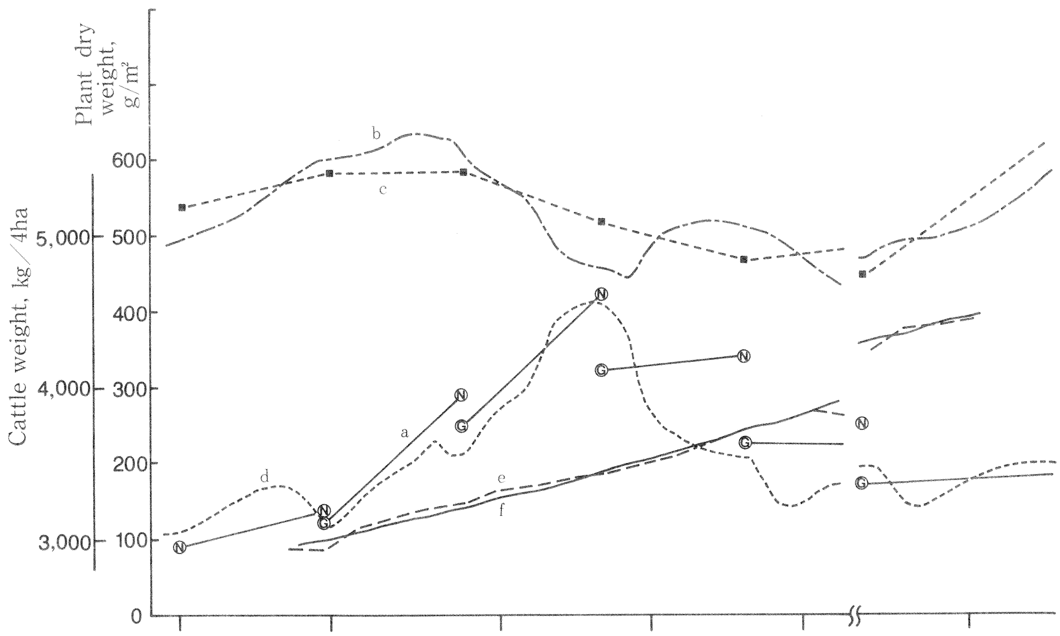

Fig. 2 Experimental grassland in 1982 and simulation on equation (1).
G : aboveground plant part biomass exposed to grazing, N : aboveground plant part biomass protected from grazing. The difference between these two values indicates the amount ingested by cattle. a : observed belowground portion, b :calculated below-ground portion, c : observed aboveground portion, d : calculated aboveground portion, e: observed total cattle body weight, f : calculated total cattle weight.

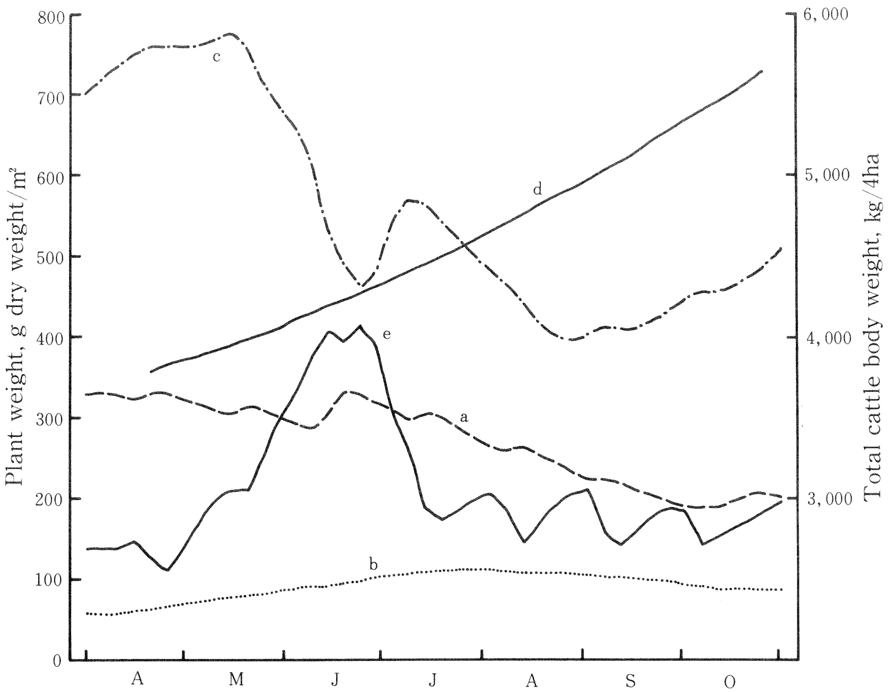

Fig. 3 Prediction of experimental grassland conditions in 1984 by equation (1).
a : standing dead material, b : surface litter, c : belowground plant portion, d : total cattle body weight.

made, grassland may be wasted, resulting in environmental disturbances.

The model expressed by equation (1) is a faithful image of the experimental grassland previously mentioned. A grassland of 2 ha was divided into 4 paddocks of equal dimensions; a herd, consisting of 9 heifers with a total body weight of 1,540 kg on April 15, was released to graze on one of the paddocks, and the herd was rotated on these 4 paddocks according to a previously determined schedule from April to November, for 10 years, during which the "normal year" mean air-temperature was used. The annual and seasonal changes that occurred over the 10-year period, *i.e.*, 3,650 days, are shown in Figure 4, indicating that trends among years were very similar. These simulated results roughly approximated the results observed for eight years and described by Takahashi *et al.* (1984) as follows: the aboveground plant biomass showed a peak from May to June reaching the value of 300 g dry weight/m^2, while the belowground plant biomass showed a peak with a value of 600 g dry weight/m^2 in winter. Daily per head weight increase (or daily weight gain, DG) was 0.32 kg in liveweight, yearly total weight increase (TG) was 586 kg/herd/2ha in liveweight, and the total grazing days measured in animal unit day (AUD) per herd at the conversion rate of 500 kg, were 374 days/ha/yr.

3 Optimum stocking rate

In the next step, the total body weight or stocking rate was changed.

The increase in daily body weight and total body weight with various stocking rates was calculated, and indicators of changes in the body weight increase are plotted in Figure 5. It is obvious from this series of simulations, that an optimal stocking rate could be identified.

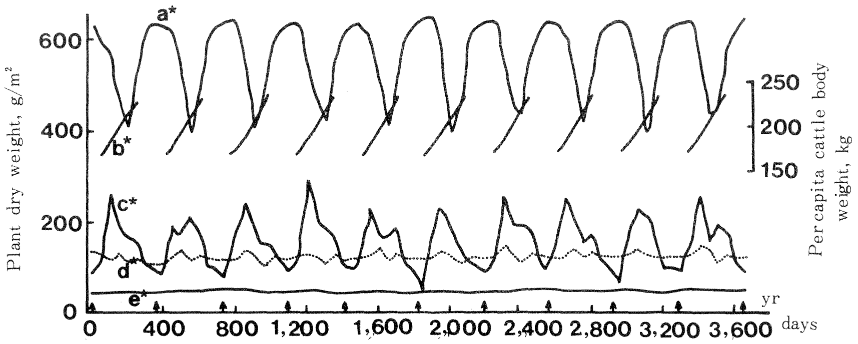

Fig. 4 Simulation of pasture productivity over a 10-year period, where the total body weight of cattle at the beginning of the grazing season is 1,540 kg/2ha and meteorological conditions correspond to those of a "normal year".
a* : underground biomass, b* : body weight of cattle per head, c* : aboveground biomass, d* : standing dead material, e* : surface litter.

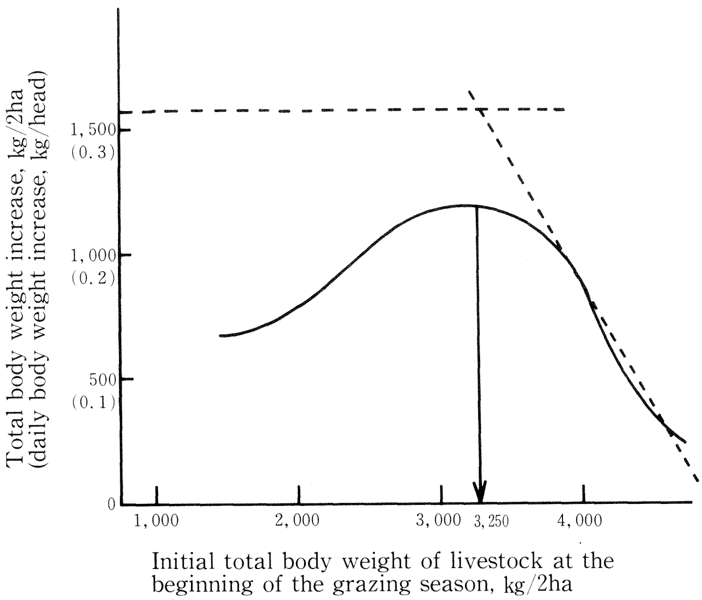

Fig. 5 Determination of optimal stocking rate under meteorological conditions corresponding to those of a "normal year", assuming that cattle with the total body weight indicated in this figure graze for 203 days from April 15.
Solid line : changes in total body weight increase (TG) for various stocking rates, dotted line : changes in daily per head weight increase (DG) under various stocking rates.

The maximum increase of daily body weight was attained for an initial (April 15) stocking rate of about 3,250 kg/2ha and the yearly increase of total body weight was attained for the same stocking rate under the meteorological conditions of a "normal year". Seventy to eighty percent of this estimated optimum stocking rate may be recommended since the meteorological conditions prevailing may cause a level of plant production lower than that in a "normal year".

Nitrogen cycle model

1 Preliminary model

Nitrogen application is one of the most important factors that control grassland productivity. To evaluate the nitrogen effects on grazing in a grassland, another system model or a submodel of the previous model was constructed. Nitrogen flows in a grassland can be conceptually represented as indicated in Figure 6. The amount of nitrogen contained

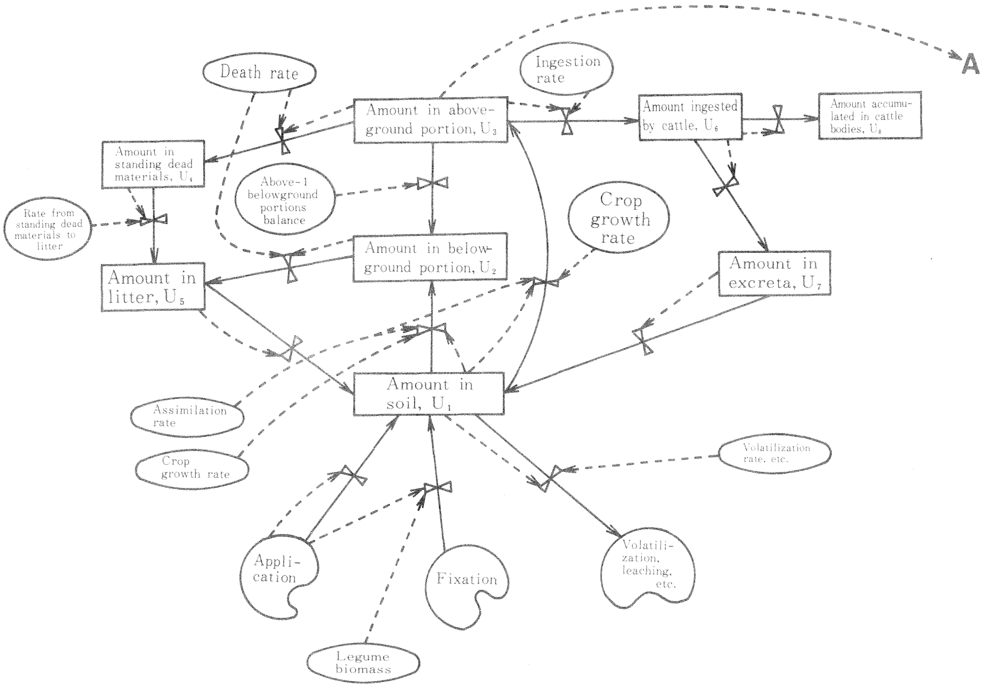

Fig. 6 Compartment model of nitrogen flow in a grassland ecosystem. See text for details.

in the aboveground plant part is linked with the leaf area index in the energy flow compartment model (see Figure 1); that is, a high nitrogen content in the aboveground parts of the plant promotes leaf area growth. The nitrogen cycle system in the grassland has eight compartments or variables with regard to the amount of nitrogen, as follows: (1) amount in soil, U_1, (2) amount in belowground plant parts, U_2, (3) amount in aboveground plant parts, U_3, (4) amount in standing dead materials, U_4, (5) amount in surface litter, U_5, (6) amount in herbage ingested by cattle, U_6, (7) amount in excreta, U_7, and (8) amount accumulated in animal bodies, U_8. These amounts naturally vary with time t in response to environmental and artificial changes. These changes can be described by the set of the following differential equations:

$$\begin{aligned}
\dot{U}_1 &= g_{15} f_{510} V_5 + g_{71} f_{810} V_8 + G_{61} + G_{101} + g_{25} f_{310} V_3 - (g_{10} + g_{12}) U_1 \\
\dot{U}_2 &= g_{12} g_{(3)} U_1 + g_{32} U_3 - g_{25} f_{310} V_2 \\
\dot{U}_3 &= g_{12} (1 - g_{(3)}) U_1 - g_{34} (f_{14} V_1 + f_{24} V_2) - g_{36} F_{16} / h_1 - g_{32} U_3 \\
\dot{U}_4 &= g_{34} (f_{14} V_1 + f_{24} V_2) - g_{45} f_{45} U_4 \\
\dot{U}_5 &= g_{45} f_{45} V_4 - g_{51} f_{510} V_5 \\
\dot{U}_6 &= g_{36} F_{16} / h_1 - g_{67} V_7 / h_{10} - g_{68} \dot{V}_8 / h_{10} / h_7 - G_{61} \\
\dot{U}_7 &= g_{68} \dot{V}_8 / h_7
\end{aligned} \qquad (6)$$

$\dot{U}_8 = g_{67}V_7/h_{10} - g_{71}f_{810}V_8$, if there are cattle in the given pasture,

$= -g_{71}f_{810}V_8$, if there are no cattle in the pasture,

where $\dot{U}$ denotes dU/dt. The unit for these U's is g nitrogen/m^2. Parameters, g_{ij}'s denote nitrogen flow rates or velocities from compartment i to j, and they usually vary with seasonal and environmental changes. Main parameters in equation (6) are expressed by the following functions:

(1) $g_{10}+g_{12}$ is the proportion of the total nitrogen amount lost from the soil, and it is expressed as:

$$\begin{aligned} g_{10}+g_{12} &= 0.01,\ t \leqq 10 \text{or}\ t>270, \\ &= 0.0079t-0.0768, 10<t\leqq 30, \\ &= 0.1602, 30<t\leqq 120,\ \text{(dimensionless)} \\ &= 0.352-0.0016t, 120<t\leqq 170, \\ &= 0.199-0.0007t, 170<t\leqq 270, \end{aligned} \quad (7)$$

where t is the number of days counted from March 1.Parameter g_{10} is the portion lost by volatilization, leaching, and so on from the soil, and g_{12} is the portion absorbed by plants. Parameters $g_{(3)}$ and $1-g_{(3)}$ are the ratios of nitrogen absorbed by plants to the nitrogen absorbed by aboveground plant parts and to that absorbed by the belowground plant parts, respectively, on the assumption that $g_{(3)}=0.22$ for$1\leqq t<61$ and $154<t\leqq 245$, $g_{(3)}=0.25$ for $62\leqq t<154$ and $g_{(3)}=0.3$ for $t>245$.

(2) g_{68} is tentatively fixed at 0.0315, which indicates that the 3.15% of cattle body weight increase is the nitrogen amount accumulated in the cattle body.

(3) g_{67} is experimentally estimated at 0.158 g, which is the nitrogen amount contained in dung that a 1 kg heifer excretes a day.

(4) G_{61} is experimentally estimated as

$$G_{61} = 0.286^{g} \times (\text{grazing cattle body weight})^{kg}. \quad (8)$$

(5) Parameters g_{51} and g_{71} are tentatively fixed at 0.015 and 0.022, respectively. g_{34}, g_{45}, g_{25} and g_{36} are assumed to be proportional to the energy flow between the components (unit: dimensionless).

G_{91} and G_{101} are the amounts of nitrogen applied and nitrogen fixed by soil microorganisms, and coefficients h's are constants relating to the grassland area and the number of grazing cattle per unit ground area.

2 System simulations

Calculated results of dry matter weight and nitrogen content are shown in Figure 7. This simulation was performed by adopting the grazing schedule designed previously. The nitrogen amount in the aboveground parts of plant varies cyclically due to the rotation of grazing. Similar trends were observed in the amount of nitrogen contained in dung and soil. The soil nitrogen curve showed two distinct peaks caused by nitrogen applications performed in April and August. These seasonal trends are appropriate but further improvements for the model are needed. This model can be effectively utilized for further fertilizer application plans.

Discussion

The objectives of this report are as follows: 1) To propose a basic model of grassland ecosystem for predicting the productivity and 2) To present several examples of system simulations. These primary objectives have probably been attained, although the model needs to be further improved.

For model building and improvement, data on energy flow and circulation of materials between compartments, which vary with the season, year, management practices, biotic and abiotic factors and their interactions, should be collected in the field (rather than in the

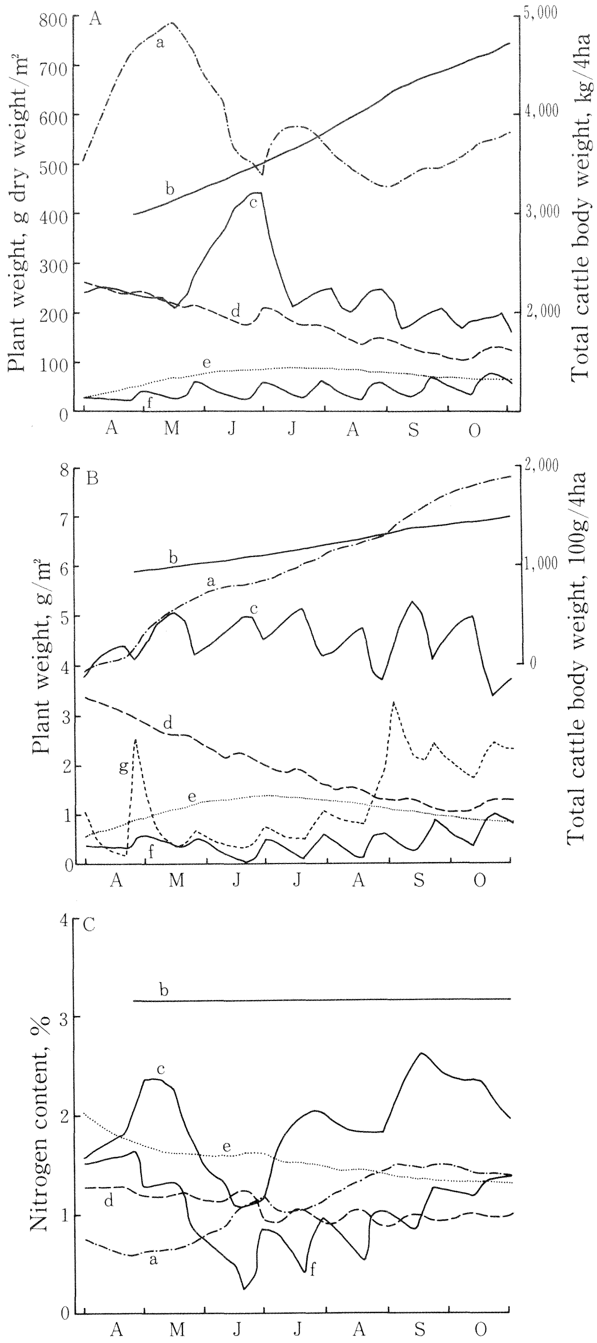

Fig. 7 Simulation of seasonal changes in nitrogen storage of various plant parts (dry matter), cattle body (live matter) and soil (dry matter).

A : seasonal changes in plant dry weight and total cattle body weight, B : seasonal changes in nitrogen storage, C : seasonal changes in nitrogen content. a : belowground portion, b : total cattle body, c : aboveground portion, d : standing dead material, e : surface litter, f : dung, g : soil (shown by values of which 280 g/m² for soil nitrogen are subtracted).

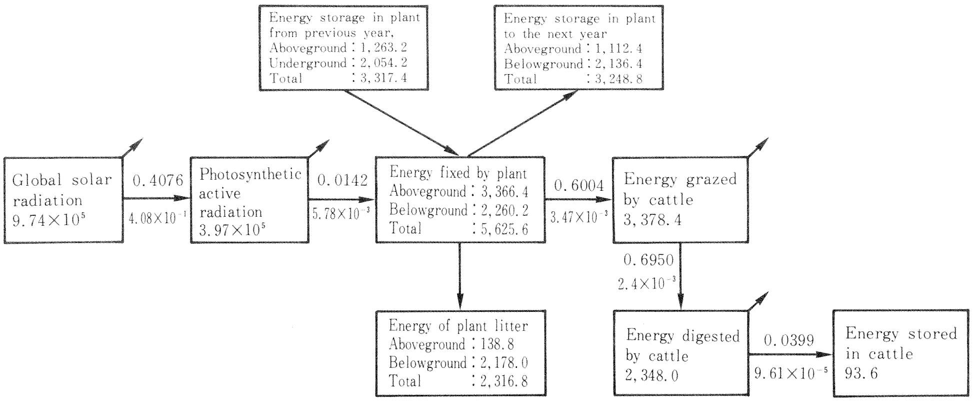

Fig. 8 Energy storage and heat conversion efficiencies observed in the experimental grassland. (Akiyama *et al.*, 1981).

The number inside each frame indicates energy storage in kcal/m²/yr. The number above the arrows indicates the conversion efficiencies from the previous to the next items, and the number below the arrows indicates overall efficiencies derived from global solar radiation.

laboratory). To achieve this objective, a long-term experiment has been carried out in the experimental grassland site shown in Table 1. Several examples concerning energy and matter budgets obtained in the experiment are as follows.

1) Energy flow: Akiyama *et al.* (1981) presented data on annual energy flow (Fig. 8) indicating that about 0.5% of the global solar radiation (9.74×10^9kcal/ha/yr) is fixed by plant as net primary production, and 0.01% of the global solar radiation is accumulated in animal bodies. These solar energy conversion efficiencies naturally vary with agricultural activities. Shiyomi *et al.* (in press), for example, showed by system simulation that the net

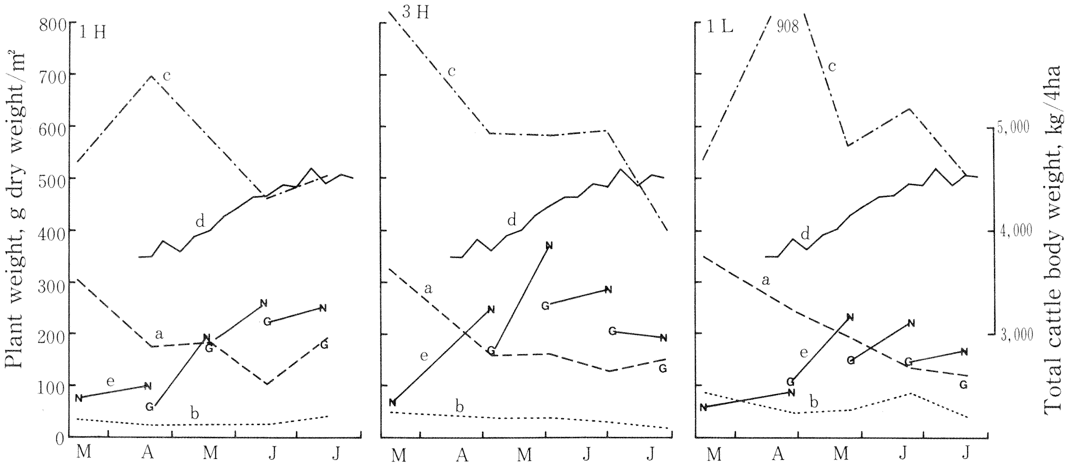

Fig. 9 Actual data in the experimental grassland in 1984 (till July). These figures indicate the values observed at 3 out of 4 paddocks in the rotation schedule.

G : aboveground biomass exposed to grazing, N : aboveground biomass protected from grazing. The difference between these two values indicates the amount ingested by cattle. a : standing dead material, b : surface litter, c : belowground biomass, d : total cattle body weight.

primary and secondary production in a grassland can be enhanced 2 or 3 fold by the optimization of the animal stocking rate.

Changes in plant and animal biomass measured in the experimental grassland from March to November, 1982 and from March to August, 1984 are shown in Figures 2 and 9, respectively.

2) Nitrogen flow: in the same grassland as that indicated previously seasonal changes in nitrogen content for each plant species and the nitrogen mass were measured from 1982

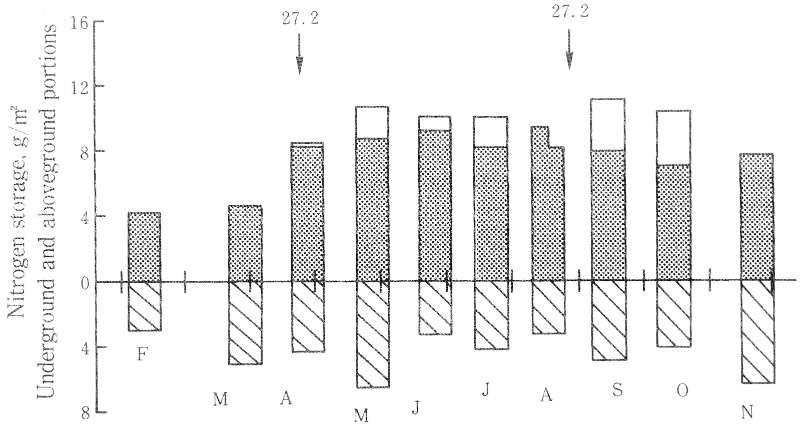

Fig. 10 Observations of seasonal changes in nitrogen storage for aboveground and belowground portions on a unit ground area (g/m²). (Akiyama *et al.*, 1985).
Grazed aboveground parts, Non-grazed aboveground parts, Belowground parts. Numbers at the top show the amount of nitrogen applied. Arrows indicate the dates of fertilizer applications.

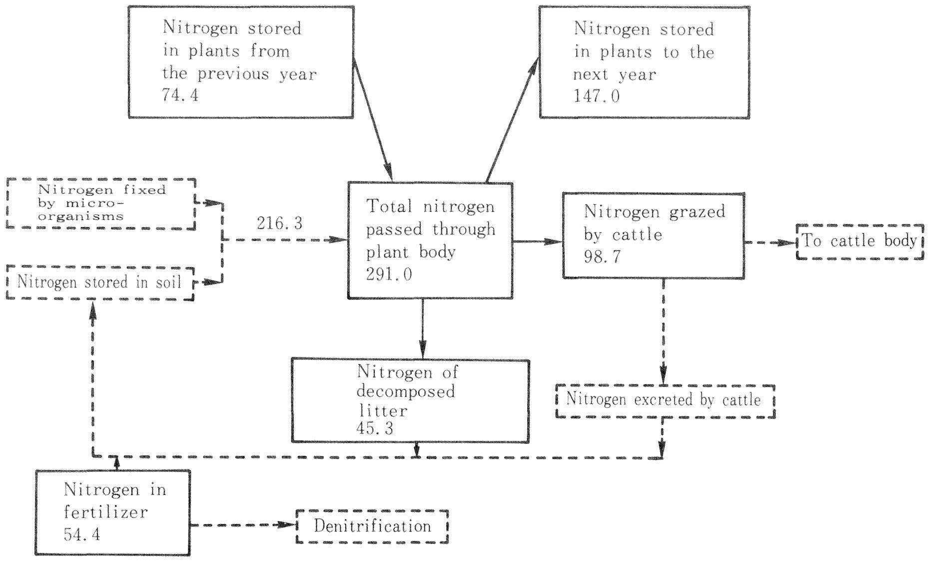

Fig. 11 Nitrogen budget in a grassland. (Akiyama *et al.*, 1985).
Numbers in the boxes indicate the amount of nitrogen (kg/m²/yr). Dotted lines and boxes indicate factors which were not determined in this experiment.

onward, and presented by Akiyama *et al.* (1985) and Koyama *et al.* (1984). Seasonal changes in nitrogen storage for the above-and belowground plant parts are shown in Figure 10 (cited from Akiyama *et al.*). The seasonal trends between the observed and the simulated results shown in Figures 7 and 9, respectively, are almost identical, and the nitrogen budget on a year basis is summarized in Figure 11.

A system model of nitrogen cycle in a grassland in eastern Hokkaido was proposed by Hakamata and Hirashima (1978), and a dynamic simulation model of nitrogen flow in a grassland in the Pawnee site of US-IBP is also presented by Reuss and Innis (1978).

3) Phosphorus budget: Kondo *et al.* (in press) determined the phosphorus cycle in the same field as that indicated in Table 1 in 1981 and 1982. The phosphorus flow in the grassland is shown in Figure 12. A simulation model of phosphorus cycling in the Prairie is presented by Cole *et al.* (1978), but Kondo *et al.* have not completed their model yet.

4) Conclusion: the most important but difficult problem to solve is to construct a model

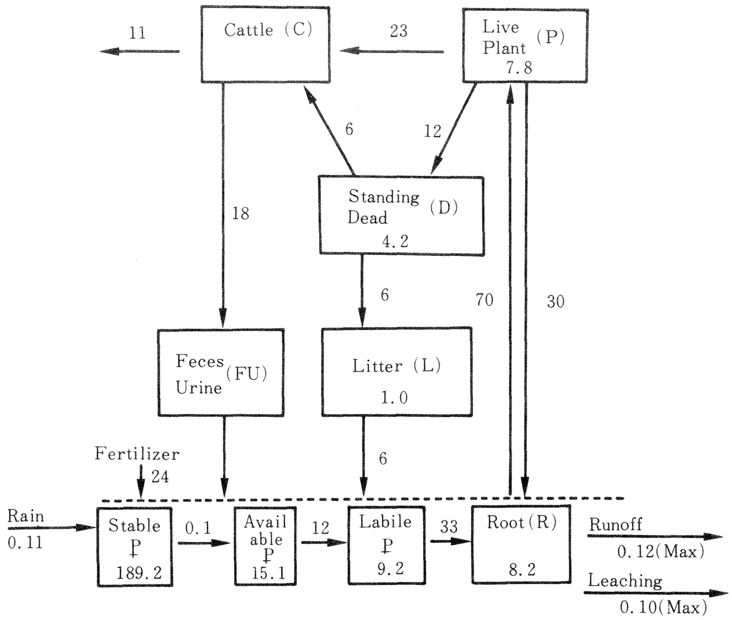

Fig. 12 Phosphorus budget in grassland (kg/ha/yr). (Kondo *et al.*, in press).
Figures in boxes indicate 2-year averages of phosphorus amount and figures out of boxes indicate 2-year average annual net translation rates.

including the *interactions* between the flows of materials for evaluating the impact of agricultural activities. The accumulation and integration of the knowledge acquired experimentally from separate precise studies into a system model is a new area of research, and productivity prediction as well as evaluation of the effect of fossil-fuel investments on grassland management and effect of grasslands on the environment should be made possible through models developed in such system studies.

Summary

A grassland ecosystem is a field where energy flows and various materials such as nitrogen and phosphorus, circulate from component to component. This ecosystem usually

depends on a large number of environmental, biological and, often, agricultural factors, which affect the productivity in the ecosystem. Moreover, studies of a grassland ecosystem require such a large area of land, even in an experiment, that it is difficult, in most cases, to replicate the experiment. For these reasons, this problem should be best solved by a system approach instead of series of field experiments.

In this paper, a system model of grassland ecosystem, which includes energy and nitrogen flows in the ecosystem, was described by a set of differential equations, and long-term and short-term productivity of the grassland was predicted with the system model. It was also shown that such a model is useful for determining the optimum stocking rate of animals. It is expected that the use of system model in grassland agriculture will contribute to the enhancement of grassland productivity in future.

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Discussion

Cocks, P.S. (ICARDA), **Comment:** With regard to your method of measuring herbage intake, the difference between open and closed quadrats is not a very good method of prediction of herbage intake due to the interaction of leaf area index with growth rate. This aspect should be taken into account if accurate results are to be obtained.