A Grazing Simulation Model: *GRASIM* A: Model Development

R. H. Mohtar, D. R. Buckmaster, S. L. Fales

Abstract. *A comprehensive grazing simulation model, GRASIM, that links components of the pasture system was developed. The grass component of the model contains two main carbon compartments: storage and structure. It accounts for root growth and maintenance, shoot growth, shoot respiration, senescence, and recycling. Shoot growth is partitioned into leaf and stem. The soil profile is partitioned into two zones. The top zone is where water and nitrogen additions and uptake, water evaporation, and nitrogen transformations take place. Nitrogen transformations include nitrification, mineralization, uptake, volatilization, denitrification, and leaching. The lower zone activities include plant uptake of water and nitrogen. Soil water is budgeted using a simplified water balance that considers runoff after a heavy rainfall, evapotranspiration, water movement between layers, and leaching. Effects of nitrogen and water stresses on growth are included. GRASIM predicts daily growth rate, biomass accumulation, protein and fiber content, water and nutrient levels. The simulation model can be used to obtain a better understanding of the pasture system and determine management strategies which yield more efficient use of pastures both economically and environmentally. It generates information suitable for estimating the financial and environmental consequences of alternative dairy management strategies including partial mechanical harvest in the context of the year round feeding needs of the dairy herd. GRASIM can be used to evaluate stocking rate effect on supplementation and amount of harvested feed, and storage/harvest needs, and year to year variability.* **Keywords.** *Production agriculture, Pasture, GRASIM, Dairy farms, Grazing, Modeling, Crop simulation models.*

With an increased interest among dairy farmers in using pastures for dairy cows, there is a need to better understand intensive rotational grazing. A recent survey of 1,200 Pennsylvania dairy farm operators indicated that over 29% of these farmers use pasture as a primary source of forage during part of the year (Gripp et al., 1993) primarily because of economic pressure. Recent decreases in profit margins for dairy farms have forced farmers to examine alternative production systems. Use of intensively managed pasture can significantly reduce total feed costs and other costs during the pasture season. Several whole-farm budgeting studies have indicated that the use of pasture can increase returns between $85 to $168 per cow (Gripp et al., 1993). The use of intensively grazed pasture for dairy cows offers significant opportunities to increase profits on Pennsylvania dairy farms because of reduced feed costs (Gripp et al. 1993; Parker et al., 1992, 1993). Since feed costs account for approximately 50% of milk producing costs, the best strategy for increasing profit is to reduce feed costs.

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The authors are **Rabi H. Mohtar**, ***ASAE Member Engineer,*** Assistant Professor, Department of Agricultural and Biological Engineering, Purdue University, West Lafayette, Ind.; **Dennis R. Buckmaster**, ***ASAE Member Engineer,*** Associate Professor, Department of Agricultural and Biological Engineering, and **Steven L. Fales**, Professor and Head, Agronomy Department, Penn State University, University Park, Pa. **Corresponding author:** R. H. Mohtar, Dept. of Agric. and Biological Engineering, Purdue University, West Lafayette, IN 47907; tel.: (317) 494-1791; fax: (317) 496-1115; e-mail: <mohtar@ecn.purdue.edu>.

In addition to economics, dairy farming systems are under increasing environmental pressure. Meeting environmental constraints increases the variable costs of managing agricultural chemicals, nutrients, and water; all natural parts of the agroecosystem. To optimize the potential environmental and economic benefits of pastures in dairy farms, pasture utilization must be understood.

Knowledge about the effects of grazing on plant growth and quality, spatial distribution, and animal intake exists in other parts of the world, but information associated with the high producing cows used in the U.S. is limited. For example, scientists in Europe and New Zealand have extensively studied pasture systems and developed grass growth models to understand pasture dynamics (Mohtar et al., 1994). In the United States crop modeling, particularly grass growth models, has received much attention in the last 10 years. Unfortunately, many of these studies and models have several drawbacks with respect to grazing.

Parsch and Loewer (1995) developed GRAZE, a model for daily performance and interaction associated with beef forage grazing systems. GRAZE has its roots in the Kentucky BEEF model developed at the University of Kentucky in the late 1970s. The plant component of the model is based on quadratic polynomial logic function that reflects the relationships between plant growth and climate. The animal component of GRAZE uses a division of energy flow to describe animal growth, intake and response to environment. GRAZE is specific to beef cattle and does not include any nutrient flow and soil components to study the environmental impact of grazing.

While crop growth models can appraise various protocols of pasture management, they sometimes fail to incorporate quality and environmental factors, which are essential to evaluate animal responses. The comprehensive dairy forage system model, DAFOSYM (Rotz et al., 1989), links forage quantity and quality from in-field production through harvest, storage, and feeding, and simulates animal performance based on the resulting feed supply. This analysis approach is ideal for maximizing efficiency of pasture-based systems, but DAFOSYM currently does not include grazing as a "harvest" method, nor does it include crops other than alfalfa and corn. A recently developed simplified grazing system model (Yanez, 1992) uses much of the DAFOSYM animal model, but does not evaluate grazing in the context of whole-farm management.

Another drawback of studies and models on pasture system is the lack of information on the nutrient cycle and grazing effect on that cycle. The nutrient cycle on dairy farms has received much study, and recommendations on managing nutrients have been made (Morse et al., 1993; Bacon et al., 1990). Russelle (1992), in tracing the cycle of nutrients, found that decomposed livestock manure may either contribute to soil fertility reserves and plant production or may be lost to surface and ground water. Nitrate losses from pastures have been studied (Jarvis et al., 1989; Kerensky et al., 1993), and nitrate leaching to ground water is understood well enough to be modeled (Bergstrom and Jarvis, 1991; Hutson and Wagenet, 1991). However, the overall role of pastures in the nutrient cycle of whole farms is poorly understood and data are needed from grazed systems for model refinement and validation. Flows to surface waters have also been measured and modeled, but they are not well defined for pasture systems in the U.S. (Cooper et al., 1992).

Pasture growth rates under grazing must be characterized for different plants, soils, nutrient levels, and weather patterns before pasture systems can be refined and tested for U.S. conditions using simulation models. Because pasture exists on such a wide range of land types, there is also a need to identify grazing management plans that are environmentally and economically appropriate on a variety of resource bases. The increasing interest in intensive grazing has created a demand for basic and practical information to optimize grazing systems (Parker et al., 1993).

Objective

The objective of this study is to develop a comprehensive grazing system model which enables us to study the effect of climatic factors and pasture management on biomass accumulation, nutrient flows, and animal intake. This article will describe the grazing model and will present simulation results for few grazing scenarios. Model calibration and field testing are presented in a companion article.

Model Description

Overview

GRASIM is designed as a tool to simulate intensive rotational grazing management where grazing is a primary forage source during the grass growing season. It accounts for carbon, nitrogen, and water budgets, and their dynamic interaction in the pasture environment.

GRASIM data requirements include minimum and maximum daily temperatures, daily rainfall, average daily solar radiation, soil physical properties, grass growth parameters, soil nitrogen transformation rate constants, and initial crop mass, water, and nitrogen levels. A complete listing of these parameters is included in the appendix. The model output includes daily biomass production, and water and nitrogen levels in different pools. GRASIM state variables are the above ground grass biomass, grass growth rate, leaf area index, soil moisture content, soil nitrogen content, plant residues, and organic matter content.

GRASIM contains four different modules: grass growth, water budget, nitrogen budget, and harvest manager. The grass growth module simulates the photosynthesis process where light energy is converted to carbohydrate. The carbohydrate is then partitioned into various compartments in the plant system. External inputs that affect the carbon budget include climate and pasture management. Feedback to the plant carbon budget includes water and nitrogen stresses and updated carbon levels in each of the pools after a grazing or harvest event.

The soil nutrient module accounts for nitrogen transformations in the plant, soil, and water systems. The module interacts dynamically with the growth module to compute and update plant nutrient uptake and nutrient cycling. A nitrogen stress factor is included as a feedback control to the growth module. The nutrient loss through deep percolation is driven by the water flux. Therefore, a link to the water budget is made to compute the amount of nutrient lost in leaching. External inputs to the module are nutrient applications and site specific transformation rate coefficients.

The water budget computes the amount of water runoff from daily precipitation, water loss to evapotranspiration and leaching. Soil evaporation is a soil-specific computation. Plant transpiration changes with plant growing stage and foliage. It also accounts for changes in soil water content and determines any water deficit in the plant growth module through a water stress factor.

The harvest module controls grazing based on simple management rules. The rules include minimum and maximum allowable biomass, grazing cycle, and resting period. The user can decide on using a fixed time rotation with a fixed resting period or a dynamic cycle based on available biomass. The module updates state variables after each grazing or harvest event. This module assumes uniform harvest rate by grazing over the entire field.

GRASIM operates on a daily time step. Multiple paddocks within the pasture system are budgeted separately. The paddocks share the same weather information but can have different soil and plant species. A block diagram of the grazing system showing the four modules and their interactions, external inputs, and output is shown in figure 1.

GRASIM's flow algorithm starts by initializing time and space independent parameters and time variable parameters. The model then steps through time with daily increments, reads weather data, computes the sward daily growth and updates water and nutrient levels in each paddock. It then sorts the paddocks according to accumulated forage and decides which paddock is to be grazed and/or mechanically harvested. All state variables are updated daily. Currently, GRASIM assumes a fixed intake based on a typical animal. A simplistic flow chart of the model is shown in figure 2.

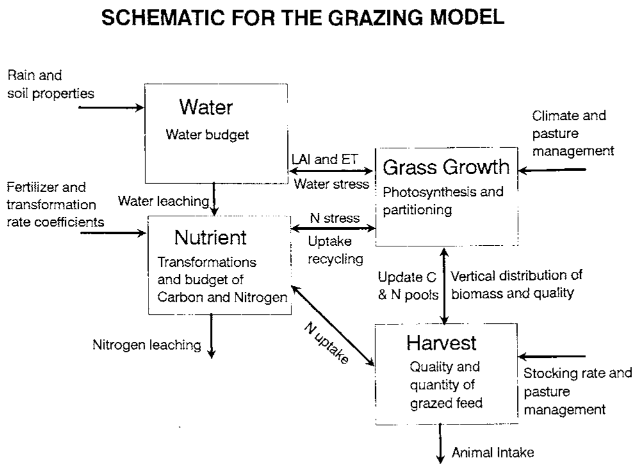

Figure 1–Schematic representation of the grazing model, GRASIM.

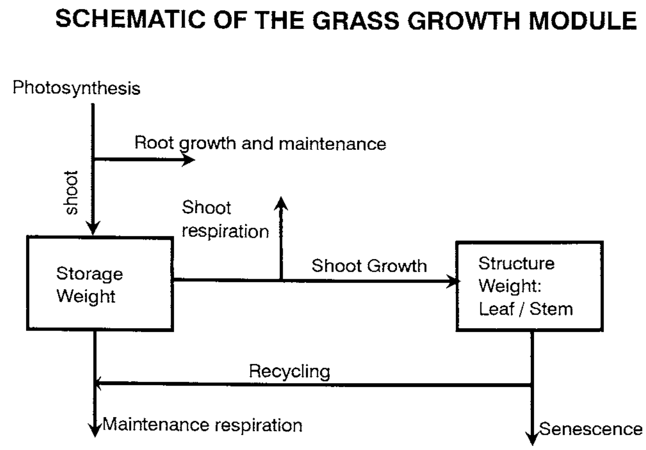

Figure 3–Grass module schematic showing components and processes.

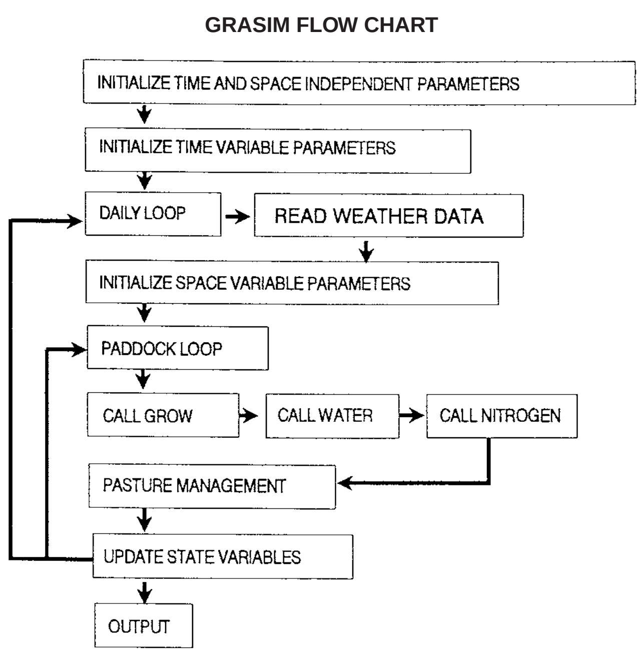

Figure 2–Flow chart of the grazing model, GRASIM.

Grass Growth

The simplified grass growth simulation model of Johnson et al. (1983) was used, but some modifications were made to fit the grazing environment. The model includes photosynthetic transformations and general growth functions. Light energy is transformed into carbohydrate that is partitioned into root and shoot growth and maintenance using partitioning coefficients. The photosynthate allocation to the above ground part is composed of two compartments, storage and structure. The sum of the two pools is the total weight of the above-ground biomass. Partitioning of the shoot growth into leaf and stem takes place at a later stage within the structure pool. Maintenance respiration is taken from the storage pool unless the plant is under stress. When stressed, recycled material from the plant structural pool contributes to maintenance. Senescence of plant material is taken from the structure pool. The schematic of the grass module is shown in figure 3. A complete mathematical description of the grass growth algorithm is presented in the appendix.

The accumulated total sward weight is represented by the sum of the storage and structure dry weight. The storage weight rate of change is computed as the photosynthetic input less the storage utilization into structure added to the recycling of structure:

$$\frac{dW_s}{dt} = \phi\,\theta\,P - \frac{\mu\,W_g}{Y} + \gamma\,W_g \qquad (1)$$

where P is leaf gross photosynthetic rate integrated over day length and canopy (eq. 15, appendix).

The structure weight rate change is computed as the shoot growth less the sum of recycling of structure and the senescence.

$$\frac{dW_g}{dt} = \mu\,\frac{W_g\,W_s}{W} - \gamma\,W_g - \beta W_g \qquad (2)$$

The above equations are solved numerically using the Euler's method:

$$W_s^{t+1} = W_s^t + \Delta t \times WSF \times NSF \times GDNG$$

$$W_g^{t+1} = W_s^t + \Delta t \times WSF \times NSF \times RDNG \qquad (3)$$

where Δt is the time step in days, WSF (range 0-1) is the water stress factor, NSF (range 0-1) is the nitrogen stress factor, GDNG is the storage daily net growth: shoot growth – storage utilization + recycling, and RDNG is the structural daily net growth: growth – recycling – senescence. A detailed description of the derivation of equations 1 and 2 is presented in the appendix.

Temperature is considered to affect senescence rate (β) maximum specific growth rate (μm), and recycling coefficient (γ). The model corrects for the temperature effects using a linear, a Q-type or a Bell-type function. The Q-type function is described as:

$$X(T) = X(T_0)Q_n^{(T - T_0)/n} \quad (4)$$

where X is the temperature dependent parameter, T is the actual temperature in [°C], T_0 is the reference temperature in [°C], n is an increment or the base for the distribution, and Q_n is the factor by which the rate constant increases for a temperature increment of n. The bell function is described as:

$$\text{Bell}(T) = \left[\left(\frac{T_{max} - T}{T_{max} - T_{opt}}\right)\left(\frac{T - T_{min}}{T_{opt} - T_{min}}\right)^{\left(\frac{T_{opt} - T_{min}}{T_{max} - T_{opt}}\right)}\right]^z \quad (5)$$

where T_{max} is the maximum temperature, T_{min} is the minimum temperature, T_{opt} is the optimum temperature, z is a shape parameter. T_{max}, T_{min}, and T_{opt} are species-dependent parameters. The temperature adjustment factors using different correction methods are shown in figure 4. The model allows the user the choice to use any of these correction equations.

Nitrogen Cycling

GRASIM uses a simple soil nitrogen transformation scheme. It accounts for two nitrogen forms, nitrate and ammonia. The source and sink pools include plant and soil storage, soil organic matter, and crop residues. The transformation processes include leaching, nitrification, mineralization, plant uptake, volatilization, and denitrification. The nitrogen transformation equations were adopted after the Nitrate Leaching and Economic Analysis Package, NLEAP (Follett et al., 1991). The general block diagram for the transformation relations is shown in figure 5.

Nitrogen available for leaching is computed as:

$$NAL = N_f + N_p + N_{rsd} + N_n - N_{plt} - N_{det} - N_{oth} \quad (6)$$

where NAL is the nitrate nitrogen available for leaching [kg/ha], N_f is the nitrate nitrogen added to the soil from fertilizers [kg/(ha × (t)], N_p is the nitrate nitrogen added from precipitation and irrigation water [kg/(ha × Δt)], N_{rsd} is the nitrate nitrogen added from residual material [kg/ha], N_n is the nitrate nitrogen added to the soil from nitrification of ammonium [kg/(ha × Δt)], N_{det} is the nitrate nitrogen lost from the soil to denitrification [kg/(ha × Δt)], and N_{oth} is the nitrate nitrogen lost from the soil to runoff and erosion [kg/(ha × Δt)].

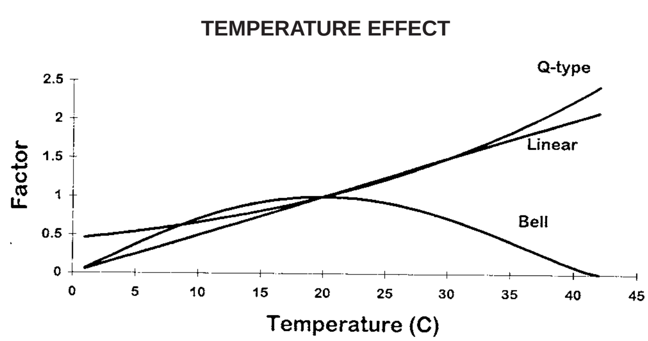

Figure 4–Temperature adjustment factors for maximum specific growth, recycling and senescence. z = 1.33 for bell function, n = 10, Q_{10} = 1.5, for Q-type distribution, and minimum, optimum, and maximum temperatures were 0, 20, and 42, respectively.

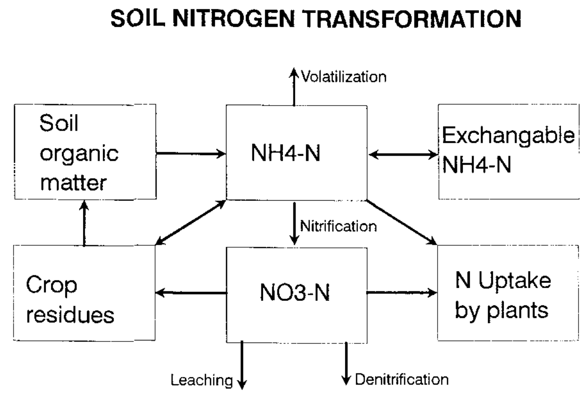

Figure 5–Nitrogen pools and transformations schematics.

The manure input to the system is handled by adding the amount of manure to the organic matter pool. The transformation relations of the nitrogen cycling are described in the appendix.

The feedback from the nitrogen module to the growth module indicating the soil nitrogen level is carried through the nitrogen stress factor. The nitrogen uptake in this analysis is assumed to be linear. Optimum nitrogen uptake under pastures was determined from field data and a linear relation between uptake and stress factor was established as follows:

$$NSF = 0.16 \times DNU + 0.37 \quad (7)$$

where DNU is the linear daily nitrogen uptake [kg/ha], 0.16 and 0.37 are slope and intercept of the nitrogen stress-uptake linear regression.

Water Budget

GRASIM divides the soil strata into two layers. The top layer (30 cm) is where most nitrogen additions, uptake and transformations, and water evapotranspiration take place. The lower layer (30 cm to the bottom of the rooting depth) activities include water and nitrogen uptake. Leaching of water and nitrogen from the top layer is captured by the lower layer. Leaching from the lower layer is lost from the system. The water balance is updated daily for every paddock. It computes surface runoff from daily rainfall data, accounts for daily water consumption from plant and soil surface, and updates the soil water content. Runoff computation is done based on the Soil Conservation Service "Soil Cover Complex Method" (SCS, 1972). A simple schematic of the water budget is shown in figure 6.

Water available for leaching in the top layer, WAL1 [cm], is calculated as:

$$WAL1 = P_e - ET1 - (AWHC1 - S_{t1}) \quad (8)$$

where P_e is the effective precipitation (cm), ET1 is the evapotranspiration in the top layer (cm), S_{t1} is the available water in the top layer, and AWHC1 is the available water holding capacity in the top layer.

Water available for leaching through the soil profile, WAL, is:

$$WAL = WAL1 - ET2 - (AWHC2 - S_{t2}) \quad (9)$$

where ET2 is the evapotranspiration in the lower layer (cm), S_{t2} is the available water in the lower layer, and AWHC2 is the available water holding capacity in lower layer.

The effective rain is computed using Dastane (1974):

$$P_e = E\,R_g + A \quad (10)$$

where, R_g is the growing season rainfall [cm], A is the average irrigation application [cm], and E is the ratio of consumptive use of water to rainfall during the growing season.

The evapotranspiration component in GRASIM is based on work by Ritchie (1972). Actual soil evaporation is computed in two stages based on the moisture status in the top layer of the soil matrix. In stage one, soil evaporation is energy controlled and therefore equal to the potential evaporation. In stage two, the accumulated soil evaporation exceeds the first stage upper limit. The main relations involved in these computations are described in the appendix.

The water stress factor is computed as the ratio of available water (SW) and the water holding capacity (WHC).

$$WSF = \frac{SW}{WHC} \quad (11)$$

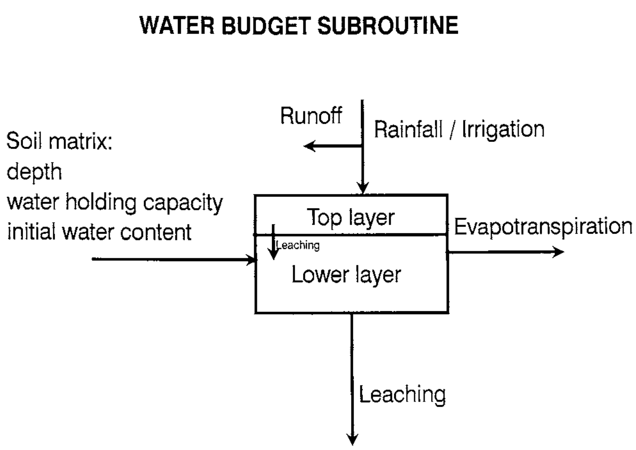

Figure 6–Water budget schematics showing outputs and inputs to the soil matrix.

Harvest

GRASIM uses either grazing or mechanical harvesting for defoliation. The harvest module sorts the paddocks daily according to the total biomass. A threshold value is selected to commence grazing at the beginning of the grazing season. When a paddock is selected for defoliation it will stay under grazing until its mass reaches a user selected minimum. At that time the paddock with the highest biomass is chosen for rotation unless its biomass exceeds a user selected maximum then mechanical harvesting is performed. All state variables affected by defoliation are updated daily following a harvest. These include grass biomass, leaf area, protein and fiber content, soil water and nutrient pool levels. Alternatively, the user can choose to use a fixed preset cycle of grazing/rest period management. In addition to dry matter computation this module traces total nitrogen uptake to estimate feed nutritional quality. Nutritional quality indicators include, protein and fiber content.

Model Numerical Assumptions

The model simulation included the following assumptions:

- The biomass, grazing/harvest is uniformly distributed in space.
- Growth, recycling, and senescence processes all use the same minimum, maximum, and optimum temperatures during the bell distribution temperature correction (can be easily changed if needed).
- Soil evaporation only affects soil water in the top layer.
- Water loss to plant transpiration is assumed to come in equal proportions from the top and the bottom profiles (can be easily changed if needed).
- Seventy percent of plant nitrogen uptake comes from the top layer, the other 30% comes from the lower layer.
- Daily intake per animal is assumed to be fixed across the season.
- Pasture utilization rate is assumed to be 70%, i.e., only 70% of biomass will be available for animal intake (can be easily changed).
- The two components of biomass storage and structure are uniformly distributed through the canopy.
- Forage quality does not vary with season or through the vertical canopy distribution.
- Twenty percent of the total water is considered gravitational and not available to evapotranspiration.
- Soil evaporation is a two stages process as described by Ritchie (1972). The first is a linear stage, where the second is induced after a threshold value of the sum of evaporation less rainfall is reached.
- Water flow follows a piston flow pattern with no fingering effects.
- In all nitrogen transformation equations, air temperature is used instead of soil temperature.

Most of the above assumptions can be easily adjusted using a different parameter than the one used, or by choosing a dynamic parameter if local data sets become available.

Selected Model Output

This section presents GRASIM's simulation results for several possible grazing scenarios. These scenarios describe some of the potential uses of the model in real life situations. Model field testing results are presented in a companion article. GRASIM generates daily output of the following: the two growth pools: storage and structure (kg C/m^2), the growth rate kg C/m^2/day), the soil moisture (mm), the soil nitrate level (kg/ha), and amount of nitrogen leached below the root zone (kg/ha). Results are tested for orchardgrass pastures at Penn State campus research farms in State College, Pennsylvania. Work is underway to establish a set of matrix parameters for other grasses. Each paddock is assumed a monocrop and same soil type, however, the model is capable of allowing different grass, soil type and condition.

Figures 7 and 8 show the growth components: storage and structure, and potential growth rate; and soil water and nitrate levels, respectively. The scenario represents a grazing situation with a stocking density of two cows per hectare under continuous grazing, 300 mm initial water content, 100 kg/ha NO_3, and actual 1991 State College , Pa., weather data. The potential growth rate in figure 7 is not limited by the water and nitrogen stresses and grazing intensity. It is a potential rate based on the climatic conditions. The total growth, structure and storage components, however, are affected by the weather, soil water and nitrogen contents and grazing intensity. Due to all of these factors, all curves in figure 7 except potential growth rate, shows a decline in the standing biomass after the third week from the beginning of the growing season. The water and nitrogen levels are shown in figure 8. The biomass production was not sufficient to keep up with the demand of feeding animals. Additionally, 1991 seasonal rainfall may not be sufficient to keep up with the evapotranspiration demand and leaching of water and nitrate were zero.

Effect of Initial Nitrate Application

The effect of initial nitrate application on biomass production was studied by varying the rate of nitrate applied at the beginning of the season. This effect on biomass production is shown in figure 9. The scenario represents a grazing situation with a stocking density of 2 cows/ha under continuous grazing, 300 mm initial water content, and actual 1991 State College, Pennsylvania, weather data. The nitrate non-limiting case shows a higher biomass production compared to the other nitrate levels. Grazing intensity and water deficit, however, were still limiting for maximum growth. This is captured by a plateau after 70 days from the beginning of the growing season. Nitrogen is a limiting factor for the two application rates on the figure 9.

Effect of Initial Water Level

The initial water level was studied by varying the initial soil water content. Results of the initial water level effect on biomass production are shown in figure 10. The scenario represents a grazing situation with a stocking density of 2 cows/ha under continuous grazing, 100 kg/ha NO_3 of single application at the beginning of the season and actual 1991 State College weather data. The water non-limiting case shows a higher biomass production compared to the other initial water levels. Grazing intensity and nitrate level, however, were limiting for optimal production for all initial water levels.

Weather Effect

Figure 11 shows the temperature and solar radiation effect on biomass production. The scenario represents a

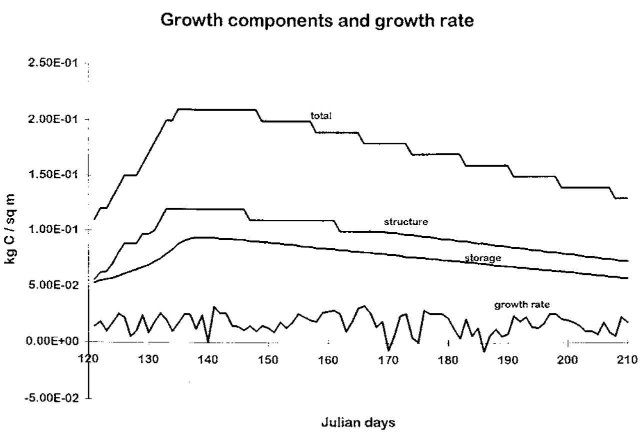

Figure 7–Graphical output showing structural and storage components of total growth and potential growth rate.

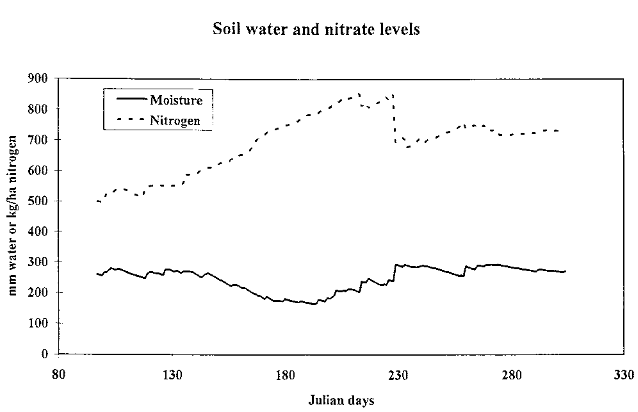

Figure 8–Graphical output showing soil water and nitrate levels.

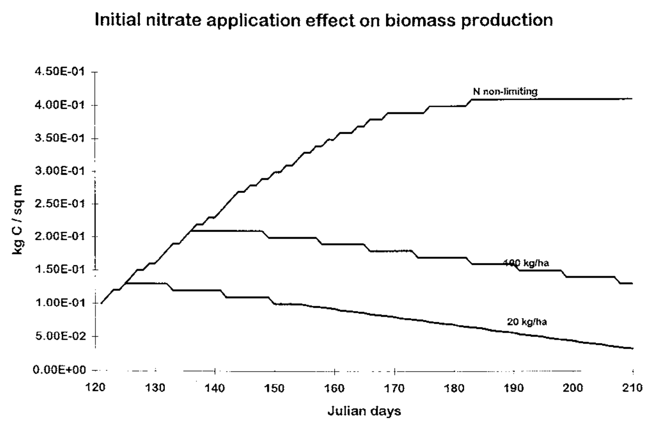

Figure 9–Biomass production as a function of initial nitrate application.

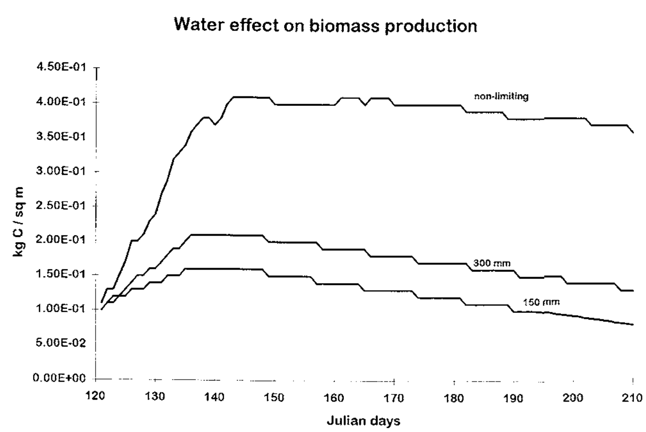

Figure 10–Biomass production as a function of initial soil water level.

grazing situation with a stocking density of 2 cows/ha under continuous grazing, 300 mm initial water content, 100 kg/ha NO_3 applied at the beginning of the growing season and actual 1991 State College weather data. The weather file was modified in this scenario by fixing the appropriate factor (temperature or solar radiation), while keeping all other factors the same. The biomass production seems to be more sensitive to solar radiation than to temperature. Selecting a different temperature correction factor and different minimum, maximum, and optimum temperatures during the temperature adjustment process make the temperature effect more prominent. The biomass deficit shown in the graph in all cases is also due to the grazing effect and water and nitrogen stresses. The units on the solar radiation numbers are j/m^2/day. The larger number (16e6) represents a bright day, while the smaller number (8e6) represents a cloudy day.

Herd Effect

Figure 12 shows the effect of the stocking density on biomass accumulation. The scenario represents a grazing situation with a variable stocking density 0-5 cows/ha under continuous grazing, 300 mm initial water content, 100 kg/ha NO_3 applied at the beginning of the growing season and actual 1991 State College weather data. The line representing zero stocking density on figure 12 levels off after three weeks from the beginning of the growing season. This matches with the reduction of the nitrate level in the soil to zero. The growth curve for zero stocking rate would probably increase continuously if the water and nitrate levels could support growth until temperature become the limiting factor later in the season.

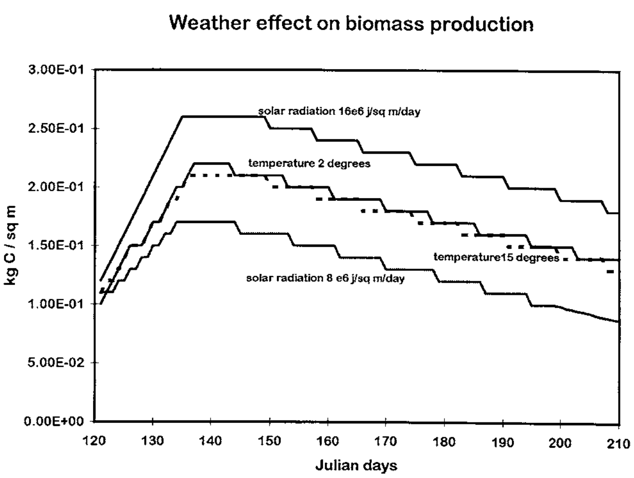

Figure 11–Biomass production as a function of temperature and solar radiation.

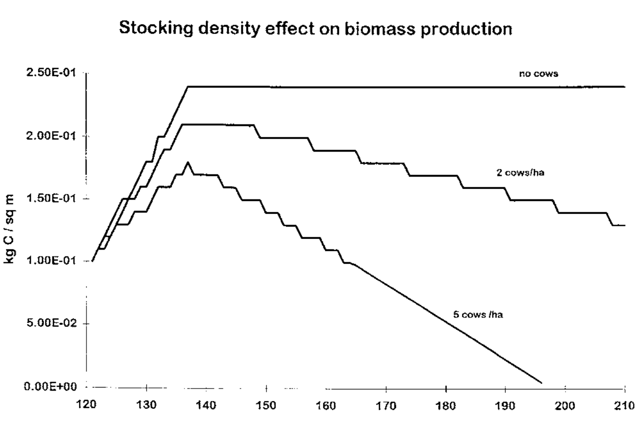

Figure 12–Biomass production as a function of stocking density.

Summary and Conclusions

A model for grass growth in a pasture-based system was developed for the northeastern United States. The model uses local experimental data for parameter estimation. It predicts growth rate, grass nutritional quality, and grass weight/leaf area index correlation. Effects of nitrogen and water on grass growth rate and quality are included. The model will be used to obtain a better understanding of the pasture system and determine management strategies which yield more efficient utilization of pastures.

GRASIM is designed as a tool to simulate intensive rotational grazing management. It accounts for carbon, nitrogen, and water budgets in the pasture environment. Its data requirement include minimum and maximum daily temperatures, daily rainfall, average daily solar radiation, soil physical properties, grass growth parameters, soil nitrogen transformation coefficients, and initial water and nitrogen levels. The model output includes daily biomass production, and water and nitrogen levels in different pools. GRASIM state variables are the grass biomass, grass growth rate, leaf area index, soil moisture content, soil nitrogen content, plant residues, and organic matter content. GRASIM is used to determine the best management strategy to improve economical and environmental sustainability of a dairy farm. It provides a better understanding of the pasture system and determines management strategies which yield more efficient use of pastures. The model can be used to determine optimum stocking rate, grazing residuals height, grazing cycle. It can be used in an analysis mode to evaluate farm performance and in a predictive mode to aide in farm management decision making.

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APPENDIX

The following is a brief description of the relations used in the model. Details on the grass component, nitrogen component, and water component can be found in Johnson et al. (1983), Follett et al. (1991), Ritchie (1972), and SCS (1972), respectively.

MODEL EQUATIONS

GRASS GROWTH

The accumulated total sward weight is represented by the sum:

$$W = W_s + W_g \qquad \text{(A1)}$$

The photosynthetic input of carbon allocated to the shoots is:

$$\phi\, \theta\, P \qquad \text{(A2)}$$

The gross specific growth rate for the structural component [day^{-1}] is defined as:

$$\mu = \frac{1}{W_g}\frac{dW_g}{dt} \qquad \text{(A3)}$$

and is estimated using the relation:

$$\mu = \mu_m \frac{W_s}{W} \qquad \text{(A4)}$$

The rate of utilization of storage into structure is:

$$\frac{1}{Y}\,\mu W_g \qquad \text{(A5)}$$

The recycling of structure to storage is:

$$\gamma W_g \qquad \text{(A6)}$$

The respiration rate is defined as:

$$R = \frac{1 - Y}{Y}\,\mu W_g \qquad \text{(A7)}$$

The senescence is calculated using the following:

$$S = \beta W_g \qquad \text{(A8)}$$

The daily photosynthetic rate over the plant canopy for a day length is expressed as:

$$P = \int_0^L \int_0^h P_g\, dL\, d\tau \qquad \text{(A9)}$$

The leaf area index, L, is determined from the structure component weight using the following relation:

$$L = aW_g \qquad \text{(A10)}$$

The leaf gross photosynthetic rate is determined as:

$$P_g = \frac{\alpha\ I_1\ P_m}{\alpha\ I_1\ P_m} \qquad \text{(A11)}$$

The light intensity over a leaf is determined from the irradiance using the following:

$$I_1 = \frac{k}{1 - m}\, I_0\, e^{-kL} \qquad \text{(A12)}$$

The maximum gross photosynthetic rate of a leaf P_m is a temperature dependent parameter and also varies according to the relation:

$$P_m = P_0 + P_1 T \qquad \text{(A13)}$$

The irradiance throughout the day is assumed to follow the relation:

$$I_0 = \frac{2J}{h}\sin^2\left(\frac{\pi\,\tau}{h}\right) \qquad \text{(A14)}$$

Then analytical integration of P_g over day length and canopy is possible and yield:

$$P = \frac{P_m h}{k} \times \ln \times \left\{ \frac{\frac{\alpha k J}{h} + (1-m)P_m + \left\{\frac{2\alpha k J}{h}(1-m)P_m + (1-m)^2 P_m^2\right\}^{1/2}}{\frac{\alpha k J}{h}e^{-kL} + (1-m)P_m + \left\{\frac{2\alpha k J}{h}(1-m)P_m e^{-kL} + (1-m)^2 P_m^2\right\}^{1/2}} \right\} \qquad \text{(A15)}$$

where P has the units of [kg CO_2 m^{-2} day^{-1}].

NITROGEN CYCLING

The ammonium-nitrogen nitrification is determined as:

$$N_n = K_n \cdot TFAC \cdot WFAC \cdot ITIME \qquad \text{(A16)}$$

Subject to the constraint $N_n \le NAF$.

The ammonia nitrogen content is computed using the relation:

$$NAF = NAF_f + NAF_p + NAF_{rsd} + NOMR + NRESR + NMANR - NPLTA - N_{NH3} - NAF_{oth} \qquad \text{(A17)}$$

The temperature stress factor used above is computed using the Arrhenius equation:

$$TFAC = 1.68E9e^{-\left\{\frac{13.0}{(1.99E-3)(TMOD+273)}\right\}} \qquad \text{(A18)}$$

where

$$TMOD = \frac{T-32}{1.8}, \; T \le 86°F$$

$$TMOD = 60 - \frac{T-32}{1.8}, \; T > 86°F \qquad \text{(A19)}$$

The water stress factor are computed as:

Aerobic process

$$WFAC = 0.0075\ WFP,\ WFP \le 20$$

$$WFAC = -0.253 + 0.0203\ WFP,\ WFP \ge 20,\ \textit{and} < 59$$

$$WFAC = 41.1\ e^{\{-0.0625 \times WFP\}},\ WFP \ge 59 \qquad \text{(A20)}$$

Anaerobic process

$$WFAC = 0.000304\ e^{\{0.0815 \times WFP\}}$$

Soil organic matter mineralization is calculated using:

$$NOMR = k_{omr}\ OMR\ TFAC\ WFAC\ ITIME \qquad \text{(A21)}$$

Crop residues and other organic matter mineralization is computed using:

$$CRES = P_c\ RES \qquad \text{(A22)}$$

$$CRESR = k_{resr}\ CRES\ TFAC\ WFAC\ ITIME \qquad \text{(A23)}$$

The carbon residue is updated after each time step as:

$$CRES = CRES - CRESR \qquad \text{(A24)}$$

constrained by CRESR ≤ CRES.

The net mineralization-immobilization is determined using:

$$NRESR = \frac{CRESR}{\frac{1}{CN} - 0.042} \qquad \text{(A25)}$$

constrained by NRESR ≤ NAF + N1T1, when NRESR < 0,

The N content of the decaying residues is updated after each time step using:

$$NRES = NRES - NRESR \qquad \text{(A26)}$$

constrained by NRESR ≤ NRES. A new CN value is computed as:

$$CN = \frac{CRES}{NRES} \qquad \text{(A27)}$$

Crop N uptake is calculated based on a minimum of crop demand and N available. The crop N demand is computed assuming an uptake of sigmoidal shape:

$$N_{dmd} = YG\ TNU\ fNU\ ITIME \qquad \text{(A28)}$$

The nitrogen available in the top horizon N_{avail_1} is computed as:

$$N_{avail_1} = NAF + N1T1 \qquad \text{(A29)}$$

While the nitrogen available in the lower horizon N_{avail_2} is:

$$N_{avail_2} = N1T2 \qquad \text{(A30)}$$

Nitrogen loss to ammonia volatilization is

$$N_{NH3} = k_{af}\ NAF_s\ TFAC\ ITIME \qquad \text{(A31)}$$

with constraint, $N_{NH3} \le NAF_s$.

Nitrogen loss to denitrification is computed as:

$$N_{det} = k_{det}\ N1T1\ TFAC\ [NWET + WFAC(ITIME - NWET)] \qquad \text{(A32)}$$

with constraint, $N_{det} \le N1T1$.

Nitrate leached from the top layer, NL1, is computed as:

$$NL1 = NAL1 \left(1 - e^{-\frac{K\,WAL1}{POR1}}\right) \qquad (A33)$$

Nitrate available for leaching, NAL, is determined as:

$$NAL = NAL2 + NL1 \qquad (A34)$$

Nitrate leached below root zone, NL [kg/ha], is determined as:

$$NL = NAL \left(1 - e^{-\frac{K\,WAL1}{POR2}}\right) \qquad (A35)$$

Water Budget

The potential evaporation is computed with the equation:

$$E_o = \frac{1.28\ H_o\ \Delta}{\gamma\ + \Delta} \qquad (A36)$$

Potential soil evaporation, E_o [cm], is computed using:

$$E_{so} = \min \begin{cases} E_o e^{-0.4\,LAI} \\ E_o C \end{cases} \qquad (A37)$$

The soil evaporation for day t [cm] is then computed as:

$$E_s = 25.4\ \alpha\ [t^{0.5} - (t-1)^{0.5}] \qquad (A38)$$

The first stage upper limit, U [cm], is determined using:

$$U = 25.4 \times 1.38\ (\alpha - 0.118)^{0.42} \qquad (A39)$$

Potential transpiration, E_{po} [cm], is determined as:

$$E_{po} = \frac{E_o\ LAI}{3}, \qquad 0 \le LAI \le 3$$

$$E_{po} = E_o - E_s \qquad LAI > 3 \qquad (A40)$$

Plant evaporation is then computed as:

$$E_p = \frac{E_{po}\ SW}{0.25FC}, \qquad SW \le 0.25FC$$

$$E_p = E_{po}, \qquad SW > 0.25FC \qquad (A41)$$

If $(E_p + E_s)$ exceeds soil water, then the sum is set equal to available water.

Nomenclature

Grass Module

W Total simulated weight [kg carbon m^{-2}]
W_s Storage dry weight [kg carbon m^{-2}]
W_g Structure dry weight [kg carbon m^{-2}]
θ Conversion from carbon dioxide to carbon [kg C / kg CO_2] 0.273
ϕ Fraction available for shoot growth 0.9
Y Yield factor, the units of structure that result from the use for synthesis of one unit of storage material, the rest being respired 0.75
μ Gross structural specific growth rate [day^{-1}]
μ_m Upper bound of as W_s gets large compared to W_g [day^{-1}] 0.5
γ Recycling coefficient [day^{-1}] 0.1
β Senescence rate [day^{-1}] 0.05
P_g Leaf gross photosynthetic rate
L Leaf area index
h Day length
a Structural specific leaf area [m^2 leaf area (kg C in $W_g)^{-1}$] 40.0
I_1 Light intensity over a leaf [W m^{-2}]
P_m Limit of P_g as I_1 gets large [kg CO_2 m^{-2} s^{-1}]
α Leaf photosynthetic efficiency [kg CO_2 J^{-1}] 2e-9
k Extinction coefficient of the canopy 0.5
m Leaf transmission coefficient 0.1
I_0 Irradiance [W m^{-2}]
P_0 & P_1 Constants [kg CO_2 m^{-2} s^{-1}] 0.5e-5 & 0.05e-5
J Day light integral [J m^{-2} day^{-1}]
Proportion of C fixed by photosynthesis available for shoot growth: 0.9
Fractional C content in carbohydrate: [kg C / kg DM] 0.4
Fraction of photosynthetic material partitioned into leaf: 0.5
Yield goal: [Kg DW / hac] 2500
Total N uptake: [Kg N/Kg Harvest DM] 0.02
Length of growing season: [days] 90

Nutrient Module

N_n Nitrogen nitrified [kg/(ha time step)]
k_n Zero order rate coefficient for nitrification [kg/ha/day] 33.6
TFAC Temperature stress factor (0-1)
WFAC Water stress factor (0-1)
ITIME Time step [days]
NAF Ammonia nitrogen content of the top foot at the end of the time step [kg/ha]
NAF_f Ammonia nitrogen added from fertilizer [kg/(ha time step)]
NAFp Ammonia nitrogen added from precipitation and irrigation [kg/(ha time step)]
NAF_{rsd} The residual soil ammonia from the previous time step [kg/ha]
NOMR The ammonia mineralized from soil organic matter [kg/(ha time step)]
NRESR The net mineralization of ammonia from crop residues [kg/(ha time step)]
NMANR The net mineralization of ammonia from manure plus other organic wastes crop residues [kg/(ha time step)]
NPLTA Plant uptake of ammonia [kg/(ha time step)]
N_{NH_3} Ammonia volatilization [kg/(ha time step)]
NAF_{oth} Ammonia lost to runoff and erosion [kg/(ha time step)]
T Soil temperature [°*F*]
WFP Water filled pores in percent
NOMR Ammonia mineralized [kg/(ha time step)]
k_{omr} Rate coefficient 0.00072
CRESR Residue C metabolized [kg/(ha time step)]
k_{resr} First order rate coefficient [1/day] 0.03
OMR Soil organic matter [kg/ha]
NRESR Net residue-N mineralized [kg/(ha time step)]
CN Carbon Nitrogen ratio of the residues
N1T1 Nitrate content of the top layer [kg/(ha time step)]
N_{dmd} N uptake demand [kg/(ha time step)]
YG Yield goal [kg dw/ha] 800
TNU Total N uptake [kg/(ha time step)]
fNU Fractional nitrogen uptake based on a sigmoidal uptake distribution
N1T2 Nitrate content of the lower layer [kg/(ha time step)]
k_{af} Rate constant for nitrate volatilization, percent of total per day 10
NAF_s Ammonia content of the surface [kg/ha]
k_{det} Rate constant for denitrification, percent of total per day 10

NWET Number of days with precipitation during the time step.
NAL1 Nitrogen available for leaching from the top layer [kg/ha]
K Leaching coefficient [unitless]
POR1 Porosity for top layer [unitless] 0.4
WAL1 Water available for leaching in to layer [cm]
NAL2 Nitrogen available for leaching in lower layer
NAL Nitrogen available for leaching [kg/ha]
K Leaching coefficient [unitless] 1.2
POR2 Porosity for lower layer [unitless] 0.4
WAL Water available for leaching [cm]

WATER MODULE

Eo Potential evaporation [cm]
γ A psychometric constant 0.68
Δ Slope of the saturation-vapor- pressure curve at the mean air temperature:

$$\frac{5304}{T_k^2} e^{\left(21.255 - \frac{5304}{T_k}\right)}$$

H_o Net solar radiation [langley]: $\frac{(1-\lambda)R}{58.3}$
R Daily solar radiation [langleys]
λ Albedo 0.23(crop),2(soil)
C Cover factor 0.5(plant),1(soil)

α Soil evaporation parameter [in./day0.5] 0.15
t Time since stage two began [days]
SW Soil water in the root zone [cm]
FC Field capacity, soil moisture at 3 bar of suction
S_r Residual saturation [%] 0.2
ρ_b Bulk density [gm/cc] 1.4
ρ_p Particle density [gm/cc] 2.65
Effective rainfall coefficient: 0.9
Leaching coefficient: 1.2
7.6-64*soil water at 15 bar if the later parameter is less than 0.1.
Root depth: [mm] 1000
Top layer [mm] 300
Lower layer [mm] 700

GRAZING MANAGEMENT

Stocking density: [cow / hectare]
Intake / cow: [Kg DM / day] 15
Mass at which grazing animals are removed from the pasture: [Kg / ha] 1000
Mass at which animals are brought to the pasture: [Kg / ha] 2800