MODELING GRAZING IN THE SEMI-ARID RANGELANDS OF LEBANON USING GRASIM

F. A. El-Awar, T. Zhai, R. H. Mohtar, W. Jabre

ABSTRACT. *Sustainable pasture management is critical for the economic viability of animal agriculture and particularly so in dryland areas. Simulation models serve as tools to evaluate management scenarios in order to find sustainable dryland grazing systems which account for the dynamic interplay of the components of a pasture grazing system. These management scenarios would be costly in both time and labor to test through field experiments. The GRAzing Simulation Model (GRASIM) was developed for the Midwest region of the United States. This study evaluated GRASIM's ability to simulate grazing in a semi-arid environment. Local weather, soil water, nitrogen, and growth data from a two-year experiment conducted in the Beqaa Valley, a semi-arid region in eastern Lebanon were used. The model performed well in predicting plant growth ($R^2 = 0.98$), soil water contents, and soil nitrate leaching. Case studies were conducted using the GRASIM model to simulate grazing systems under semi-arid Bekaa area conditions to assess the impacts of key system factors including soil type, and stocking rate, grazing management regimes/grazing pressure, and water availability in terms of biomass production and water and nitrate leaching losses. Simulations showed significant negative impact of high grazing pressure (high stocking rate and/or continuous grazing) on biomass production, as well as positive impact of higher soil water availability on forage growth. Simulations also resulted in low nitrate leaching for all simulated scenarios due to vigorous plant uptake and high evapotranspiration relative to rainfall.*

In conclusion, the GRASIM model showed sufficient robustness to use in a decision-aid framework, around which better grazing management practices can be designed while accounting for key factors (weather, soil, plant, and animal). The current version of the model can be used via the internet at http://pasture.ecn.purdue.edu/~grasim/.

Keywords. *Semi-arid grazing system, Pasture management, GRASIM, Beqaa valley of Lebanon, Nitrate leaching, Decision support system, Pasture modeling.*

With permanent pasture estimated to cover 16,000 ha (around 15% of the total area of the country), sustainable pasture management is critical to the sheep, goat, and dairy industries in Lebanon which constitute a major part of the country's Gross Domestic Product (GDP) (FAO, 2003). Over a 25-year period (1976-2001) the overall size of the cattle herd in Lebanon has more than doubled. Beginning in the mid-1990s, the dairy and beef cattle sector witnessed a major shift. Intensive large-scale production systems gradually replaced the traditional extensive small-scale farms. During the last 10 years, private investments of more than $500 million have led to unprecedented growth in the sector, which has been pivotal in the economic development of the country. Dairy and beef livestock are estimated at around 85,000 heads (of which 55,000 are dairy cattle) and small ruminants (sheep and goats) at around 825,000 heads (FAO, 2003). Nevertheless, the dairy sector meets only 30% of the local demand. Therefore, significant potential for further development in this sector still exists in Lebanon.

As in other dry-land areas, scarce rainfall and its sporadic spatial and temporal distribution severely limits forage productivity. Feed shortages have been one of the major obstacles to ruminant production in the region (Nordblom and Shomo, 1995). Economic, environmental, and conservation concerns have long been associated with overgrazing on arid rangeland (Homewood et al., 2001; Oba et al., 2001). Overgrazing affects more than just productivity in achieving sustainability of these grazing systems. Research on arid rangeland has mainly dealt with forage productivity and quality (Hiernaux, 1998; Hegazy and El-Khatib, 2001), animal ecophysiology (Grenot, 1992; Illius and O'Connor, 2000), and vegetation response to grazing pressure (Weber et al., 2000; Pringle and Landsberg, 2004) and rainfall (Fynn and O'Connor, 2000). More inclusive efforts aimed at more than one interacting factor and/or utilizing computer modeling tools either are based on too large a scale so that remotely sensed data by satellite are needed (Mouat et al., 1997; Pickup and Bastin, 1997; Sparrow et al., 1997) or have not been applied/tested in the Middle East region (Hatch et al., 1996; Wu et al., 1996; Connolly et al., 1997; Dunkerley, 1997).

Currently, common grazing practices in Lebanon involve a mixture of settled and nomadic styles (Hamadeh et al., 2001). In their survey of the economic sustainability of these grazing practices, Hamadeh et al (2001) found that only the

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Submitted for review in March 2005 as manuscript number IET 5807; approved for publication by the Information & Electrical Technologies Division of ASABE in July 2007.

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Applied Engineering in Agriculture

Vol. 23(6): 803-810

ISSN 0883-8542

settled systems that have moderate to low use of rangelands and are integrated with barley production were profitable. Yau et al. (2003) also stated the need for incorporating forage (legume) into the traditional barley crop rotation for sustainable crop production in the semi-arid areas of Lebanon. A comprehensive computer model was evaluated for estimating grain crop (barley in particular) and forage production and grazing management under the arid conditions in Lebanon.

In this study, the GRAzing SIMulation (GRASIM) model was used because of it mechanistically-based representation of the processes in the four main components of a pasture system, i.e. plant growth, soil water budget, nitrogen cycling, and harvest/grazing management. The model's plant growth parameters that represent the major physiological processes of photosynthesis, senescence, resource partitioning and recycling were calibrated to the region. These parameters have been traditionally measured in field experiments using methods that were often impractical because of the time and labor required. It should be noted the model has been previously applied to intensively managed pasture/grassland (Mohtar et al., 1997b; Zhai et al., 2004b) that resembles the aforementioned settled grazing systems in Lebanon.

The overall goal of this article was to develop a modeling framework to evaluate strategies for sustainable pasture management under semi-arid weather conditions of Lebanon. The modeling framework/tool was used to evaluate scenarios where soil, topography, water and nutrient availability, forage species, grazing animal and weather conditions differ across the landscape, as an aid in the design of integrated management practices.

METHODOLOGY

THE MODEL

The GRASIM model is a mechanistically based pasture and grassland production simulation model developed by Mohtar et al. (1997a). The model consists of four major components: plant growth, soil water budget, nitrogen cycling, and harvest/grazing management. The model operates on daily time step at the whole farm level, where multiple paddocks can be simulated simultaneously (Zhai et al., 1999). Zhai et al. (2004b) developed a multi-species version of GRASIM that can simulate mixed pastures where multiple species can grow in competition for light, water, and nutrients. Both the model development (Mohtar et al., 1997ab) and extension (Zhai et al., 2004b) included full sensitivity analyses which evaluated the impact of input parameters on each of the model components.

The plant growth module in GRASIM simulates the conversion of light energy into carbohydrates based on leaf and canopy photosynthetic characteristics (Johnson et al., 1983). It accounts for growth, senescence, and recycling processes among plant structural and storage pools. Potential daily growth is further controlled by the species competition, prevailing weather, level of water and nitrogen stress, and grazing or harvesting practices.

The water budget component calculates surface runoff, as well as water content within soil layers. It accounts for precipitation, evaporation, transpiration, infiltration, and leaching or drainage. The water stress factor is then computed and used by the plant growth component.

The nitrogen cycling component is based on the NLEAP model (Follett et al., 1991). This module simulates nitrogen transformations that occur in several soil pools through processes of nitrification, denitrification, mineralization, and volatilization. It also accounts for nitrogen addition from fertilization, as well as nitrogen reduction from leaching and plant uptake. The module also calculates a nitrogen stress factor which is used to control plant daily potential growth.

Grazing and mechanical harvesting are modeled based on certain management rules that include minimum and maximum allowable grazing biomass levels, a grazing cycle, and a resting period. Animals are allowed to graze if the dry matter in the field is greater than a minimum and less than a maximum level. Machine harvesting occurs if the dry matter is greater than the maximum allowable level and in accordance with grazing cycle rules. Animal execretion is incorporated back into soil nutrient cycling. Figure 1 shows the relational structure of the model components. A complete guide and full access for GRASIM execution is available at http://pasture.ecn.purdue.edu/~grasim/ (Mohtar et al., 2000).

MODEL EVALUATION

GRASIM has been evaluated in field conditions on pastures under temperate North American conditions (Mohtar et al., 1997b; Chen, 2000; Zhai et al., 2004b). Zhai et al. (2004a) developed a procedure for estimating plant growth parameters for species with limited growth data under

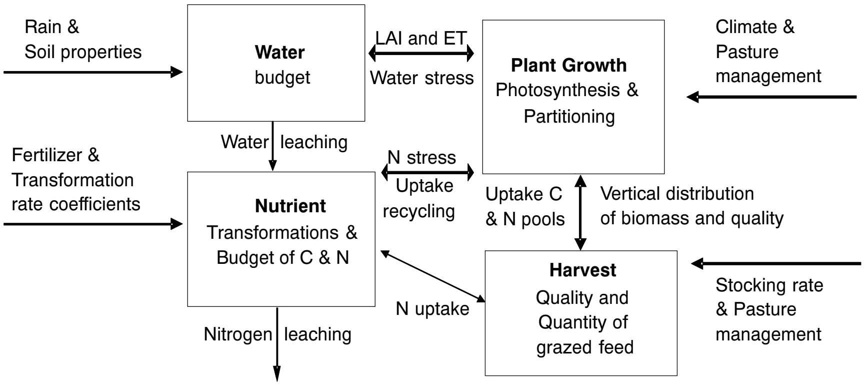

Figure 1. Structure of the GRASIM model (Mohtar et al., 1997a).

the semi-arid conditions of Lebanon. The methodology uses a non-linear iterative numerical optimization procedure to estimate the ten major crop growth parameters of GRASIM (table 1) by minimizing the difference between model-predicted and field observed biomass data. Physiological ranges of the parameters were also derived from literature and used as upper and lower bounds in the numerical procedure to ensure their feasibility. In the current study, this procedure was used in the calibration of the GRASIM model against data from field experiments for barley. Crop biomass, soil moisture contents, soil nitrate leaching, and local weather data from the two-year (1999-2000) field experiment were used in the model evaluation. Model parameters were calibrated using the first-year data and further validated using the second-year data.

FIELD EXPERIMENT

The field experiment was conducted as a part of an on-going effort to collect field observations on cropping, soil, and weather conditions for developing decision support tools for the semi-arid weather conditions of Lebanon. The experiment site is at the Agricultural Research and Education Center (AREC, 33° 55' 33.07" N 36° 04' 37.52" E elevation 3260 ft), the experiment station of the Department of Agricultural and Food Sciences at the American University of Beirut (FAFS-AUB). AREC is located in Hawsh Sneid in the central Bekaa valley close to the eastern Lebanese-Syrian borders. Similar to most of the Bekaa valley, the area is characterized by a semi-arid climate with dry hot summers and cold winters. Located between two ranges of relatively high mountains, the area receives an average of 500 mm of rainfall annually, which mostly occurs during the fall and winter seasons (September to April), and is characterized by high annual variability with maximum annual rainfall depth of more than 800 mm and a minimum of less than 250 mm.

In the two growing seasons (mid-November to mid-June) of 1999-2000, barley crop of local variety Rayhan was planted on a 0.5-ha plot using a seed drill at the rate of 120 kg/ha. The plot was divided into subplots each of around 100 m^2 planted with barley. The experimental design consisted of an RCBD (Randomized Complete Block Design) which accounted for the spatial variability of measured data. In both years, stands in all subplots were generally in healthy condition and showed no sign of diseases. The biomass was measured at 2- to 3-week interval till inflorescence emergence. Plants were clipped to ground level in 0.25-m^2 quadrants within the plots. The samples were then dried and weighed to record standing biomass.

Soil moisture was measured biweekly in the shallow (0 to 30 cm) and deep (30 to 100 cm) soil layers using time domain reflectometer and gravimetric methods. Soil nitrate leaching data were collected with ceramic cup lysimeter positioned at 1-m depth. Weather data, including daily temperatures, precipitation, and solar radiation, were measured with automatic weather station across the two growing seasons.

CASE STUDIES

Upon its calibration under local semi-arid conditions, GRASIM was used to simulate and analyze a number of case studies in order to evaluate the effects of soil type, water availability, and grazing management on forage growth, as well as water and nitrate losses due to leaching. The case studies or scenarios presented here (soil types, stocking rates, grazing methods, and rainfall pattern) strive to replicate typical local soil and grazing conditions to quantify their impact. They are introduced as follows:

Soil Types

Crop growth in three soil types (clay soil, sandy-loam soil, and sandy soil) was simulated in order to investigate soil type's effect on pasture productivity. The simulations were done using different soil physical parameters used by GRASIM such as bulk density, field capacity, and permanent wilting point, while keeping all other conditions constant. No grazing was assumed in this set of simulations.

Stocking Rates

Five paddocks (1000 m^2 per paddock) with local clayey soil under continuous grazing method were simulated with increasing stocking rates, i.e., 0, 1, 2, 3, and 4 heads of sheep/ha. All other conditions were kept constant throughout the simulation of stocking rate scenarios.

Grazing Methods

The following grazing practices were simulated in order to test the impact of different grazing rotation regimes on forage growth. The following grazing rotation schemes were simulated:

- gsch 0: continuous grazing with stocking rate of 4 head/ha
- gsch 1: flash grazing (restricted to one paddock) of 7 days grazing and 14 day's rest with 4 head/ha
- gsch 2: rotational grazing based on minimum and maximum biomass thresholds in the pasture: minimum biomass threshold for grazing is 100 kg/paddock; maximum biomass threshold for machine harvest is 280 kg/paddock; stocking rate is 4 head/ha
- gsch 3: rotational grazing (moving from one paddock to another) based on user defined maximum grazing period and minimum resting period for each paddock: maximum grazing period on each paddock is 7 days; minimum rest period of each paddock is 14 days; stocking rate is 4 head/ha

Rainfall Pattern

The combined effect of rainfall and irrigation was modeled by uniformly adding 20 mm to the available soil water every 7 days throughout the simulation period. This simulates the effect of augmenting rainfall depth received through sporadic events by irrigation to a total of 20 mm every 7 days. The grazing schedule used is the continuous grazing, with stocking rate of 4 head/ha.

RESULTS

MODEL EVALUATION

The input data sets used to run GRASIM simulations are presented in tables 1 and 2. The set of optimized growth parameters is listed in table 1, and initial conditions used in both calibration and validation runs are listed in table 2. Simulation results of barley growth in the calibration and validation runs are shown in figures 2 and 3, respectively.

Table 1. Default and optimized plant growth parameters.

Parameter	Unit	Default Value	Optimized Value
Specific leaf area	$m^2 (kg C)^{-1}$	40.0	35.8
Leaf extinction coefficient	unitless	0.5	0.20
Leaf transmission coefficient	unitless	0.12	0.19
Leaf photosynthetic efficiency	$kg CO_2 J^{-1}$	1.2E-8	1.88E-8
Light-saturated leaf photosynthetic rate constant	$kg CO_2 m^{-2} s^{-1}$	4.0E-7	4.01E-7
Light-saturated leaf photosynthetic rate coefficient	$kg CO_2 m^{-2} s^{-1} c^{-1}$	5.0E-7	2.88E-6
Maximum structural specific growth rate	day^{-1}	0.4	0.24
Recycling rate constant	day^{-1}	0.1	0.021
Senescence rate constant	day^{-1}	0.008	0.01
Photosynthate fraction partitioned to shoot	fraction	0.9	0.89

Table 2. Initial conditions used for 1999 and 2000 simulations.

Initial Variables	Unit	Default Value	Value Used for 1999 and 2000 Simulation
Top and bottom soil layer field capacity	mm/mm		0.44
Top and bottom soil layer plant available water	mm/mm		0.13
Top and bottom soil layer permanent wilting point	mm/mm		0.3
Top soil layer bulk density	mg/m^3		1.16
Bottom soil layer bulk density	mg/m^3		1.24
Top soil layer depth	mm	300	220
Bottom soil layer depth	mm	700	570

GRASIM closely simulated biomass production for both years (1999 and 2000), despite the significant difference in the weather conditions between the two years (2000 was significantly cooler and wetter than 1999).

Results of GRASIM simulated soil moisture contents for the two soil layers (top 30-cm layer and bottom 70-cm layer) and 1999 and 2000 field data are shown in figures 4 and 5, respectively. The simulated soil moisture contents reasonably followed the time series of the observed data for both growing seasons. In 1999, there were more abrupt fluctuations in the measured soil moisture contents in both top 30-cm and lower 70-cm soil layers that the model's prediction did not closely follow. In the 2000 simulations, the model over-predicted both the top and bottom soil layers' water contents in what appears to be the cooler and wetter year of the 2-year experiment based on measured daily temperature and rainfall data, albeit the observed low water contents in both soil layers. The GRASIM model closely predicted nitrate leaching following the two major precipitation events that caused leaching in the 1999 (11 Feb.) and 2000 (4 March) growing seasons (fig. 6).

CASE STUDIES

Effect of Soil Types

Results of the case study of soil type effects on biomass production, as well as water and nitrate leaching from the upper soil layers are shown in figure 7. The clayey soil yields the highest amount of biomass, while the sandy soil yields the lowest amount. This is expected due to the higher level of retained water in clayey soils that would be available to support plant water requirements. However, significant differences occur in water and nitrate leaching patterns in terms of both quantity and timing of leaching events. This indicates that soil types and moisture conditions are very important factors in pasture management.

Effect of Stocking Rates

Figure 8 shows that biomass production decrease as stocking rates increase from 0 to 4 sheep/ha. The stocking rates showed no appreciable impact on water drainage and nitrate leaching in the simulation.

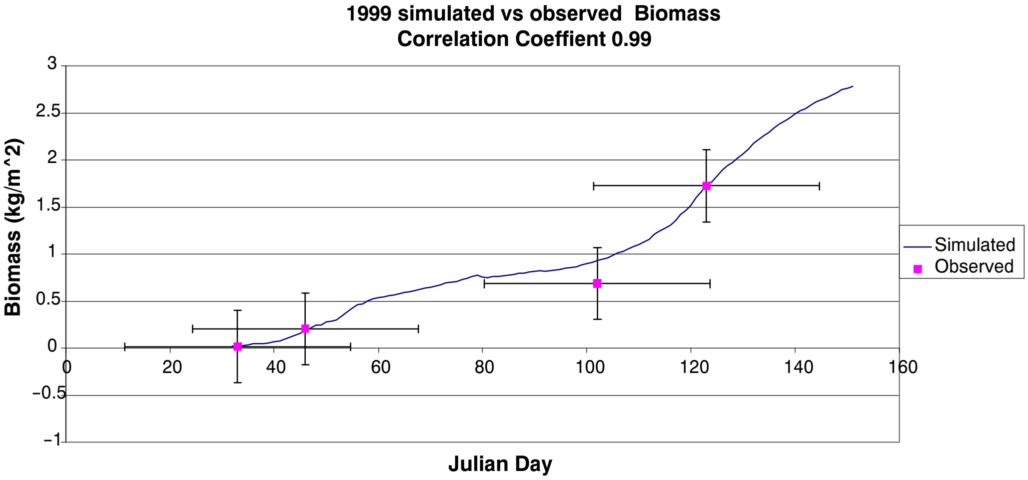

Figure 2. Observed and predicted barley crop biomass for 1999, Lebanon ($R^2 = 0.9884$).

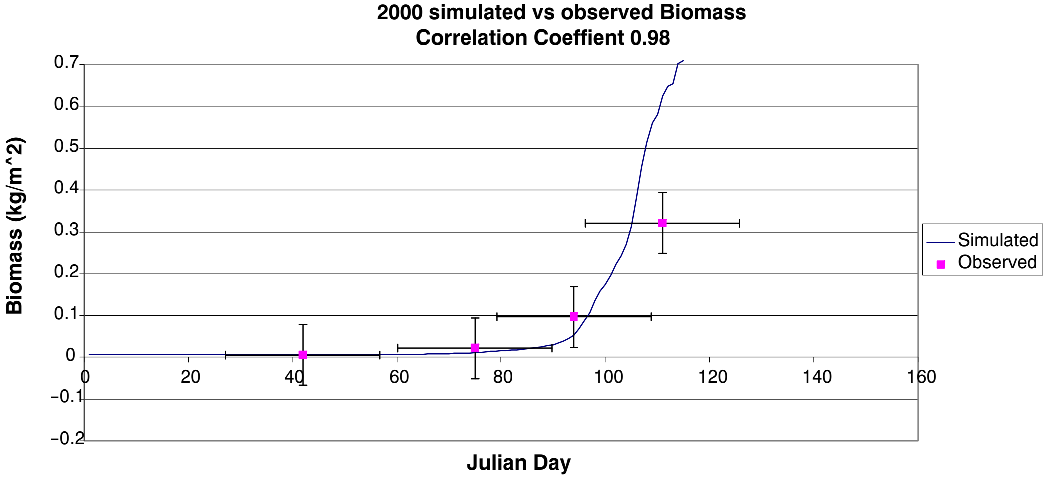

Figure 3. Observed and predicted barley biomass using 2000 Lebanon data (R^2 = 0.9898).

Effect of Grazing Schedules

Different grazing regimes show significant impact on forage biomass production, water, and nitrate leaching (fig. 9). The two grazing regimes with mandatory resting period (gsch1 and gsch3) allow more biomass production than the other two methods. The four grazing schedules did not cause any appreciable difference in water loss. Continuous grazing lead to more nitrate loss due to reduced vegetation uptake and increased animal waste in a field.

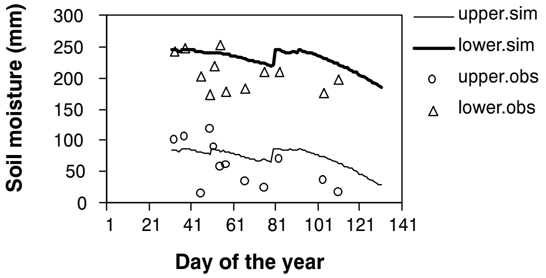

Figure 4. GRASIM simulated soil moisture content vs. calibration data set from 1999 growing season.

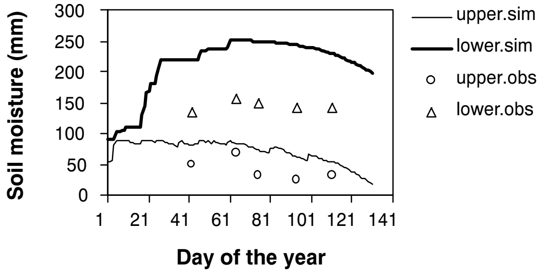

Figure 5. GRASIM simulated soil moisture content vs. validation data set from 2000 growing season.

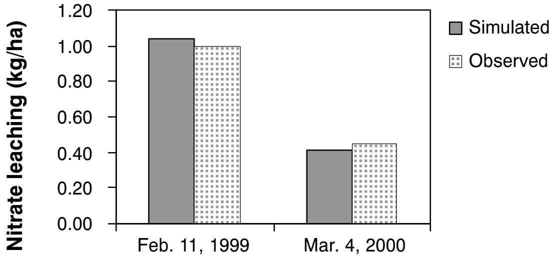

Figure 6. GRASIM simulated vs. observed nitrate leaching following two rainfall events in 1999 (11 Feb.) and 2000 (4 March) growing seasons.

Effect of Rainfall Pattern/Irrigation Depth

Figure 10 shows that the additional water from simulated irrigation significantly improves biomass production, and leads to increased water drainage compared to rainfed conditions. However, no difference is shown in nitrate leaching between the two water regimes.

DISCUSSION

MODEL EVALUATION

Numerical algorithms were used to systematically search for the ’right’ combination, of the 10 growth parameter values, that produces model predictions that are closest to their observed values. Feasibility of the optimized parameter

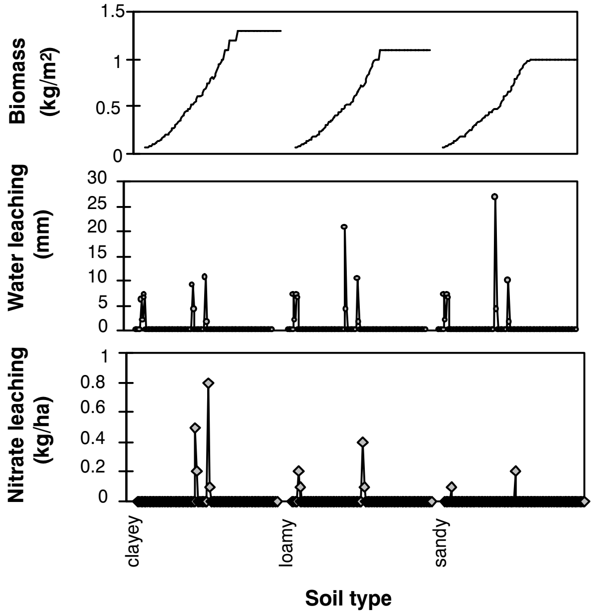

Figure 7. Case study simulation results for the soil type effects on crop biomass production, soil water leaching, and nitrate leaching from the upper soil.

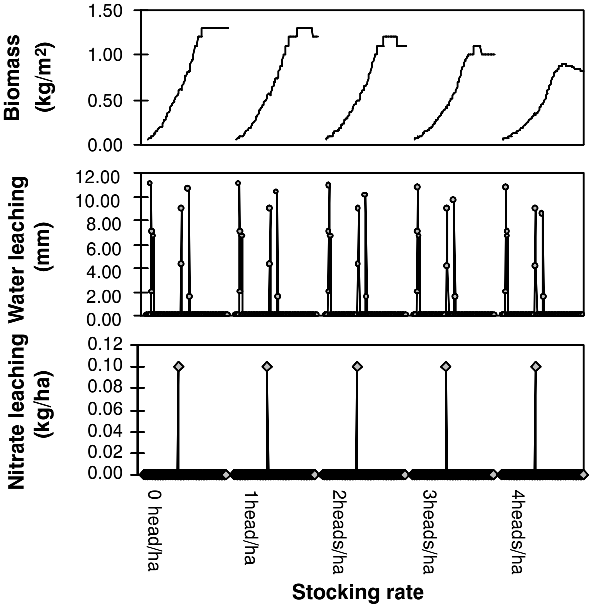

Figure 8. Case study simulation results for the stocking rate effects on crop biomass production, soil water leaching and nitrate leaching from the upper soil at 0, 1, 2, 3, and 4 sheep/ha.

values was ensured by imposing physiologically sensible ranges as upper and lower bounds for the parameters in the optimization procedure. There have been attempts in the past to use numerical optimization techniques to estimate the large number of parameters used in many process-based models (Bayram and Bunyamin, 1999; Calmon et al., 1999; Schmied et al., 2000). Some of these attempts were quite successful (Yin et al., 1997a, 1997b).

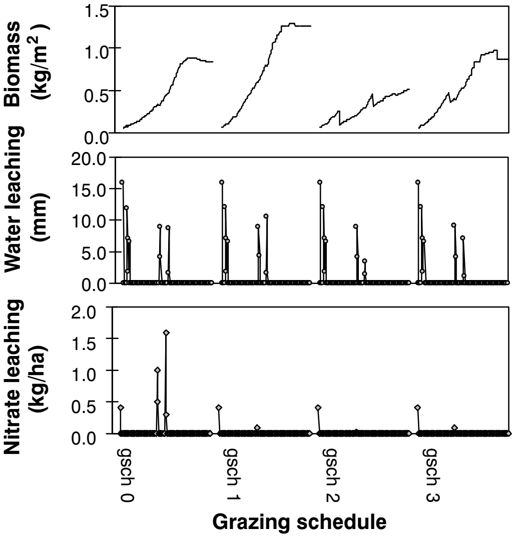

Figure 9. Case study simulation results of the grazing regime effects on biomass production, water and nitrate leaching from the upper soil layer. gsch0: continuous grazing with stocking rate of 4 head/ha; gsch1: flash grazing of 7 days grazing and 14 days rest with 4 head/ha; gsch2: rotational grazing based on minimum and maximum biomass thresholds in the pasture at stocking rate 4 head/ha; gsch3: rotational grazing based on user defined maximum grazing period and minimum resting period for each paddock at stocking rate 4 head/ha.

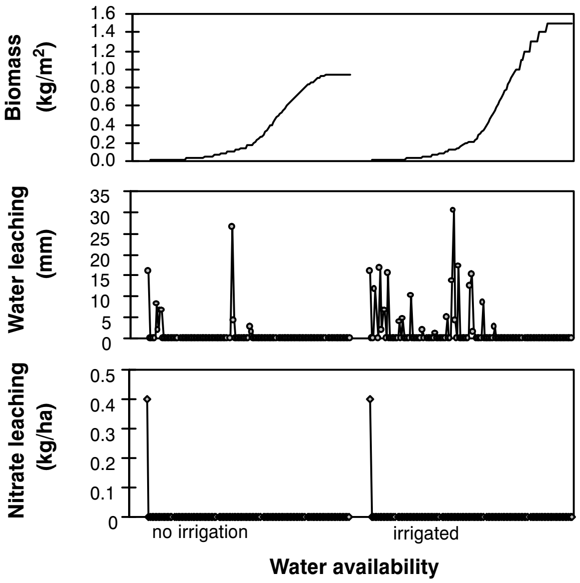

Figure 10. Case study simulation results for water availability effects on biomass and water and nitrate leaching from upper soil layer under rain-fed (no irrigation) and irrigated conditions. Stocking rate is at 4 head/ha.

The optimized parameters (table 1) allowed GRASIM to reasonably simulate the barley growth, soil water dynamics, and nitrate leaching during the two growing seasons, while the parameters remained within the physiological defined ranges. This indicates a general applicability of GRASIM under the semi-arid conditions in Lebanon, considering the great natural variability of the local weather conditions as manifested in the two-year weather data. However, soil water content measurements showed some perhaps unique features of soil of arid land that allow water content to fluctuate quickly (fig. 4) or stay at extremely low level for extended periods of time (fig. 5), which could be better modeled.

CASE STUDIES

The four case studies with GRASIM simulation generally confirmed common observations for grazing systems under arid conditions. These include soil type's strong influence on biomass production and soil water and nutrient budget (fig. 7); the negative relationship between grazing pressure and forage biomass production (figs. 8 and 9); and the positive relationship between water availability and biomass production, water leaching, and nitrate leaching (fig. 10). Additionally, the grazing schedule simulation strongly indicated the necessity of a dormant period for maintaining productivity and protecting against heavy nitrate loss (fig. 9). This is consistent with findings in other reported work on grazing systems in arid or semi-arid lands regarding the need for some form of resting and exclusion period to improve the sustainability of rangeland production (Allen et al., 1995; Wiegand and Milton, 1996; Bertiller and Bisigato, 1998). In all four case studies, it was shown that nitrate leaching was not correlated to increased soil water leaching and that nitrate leaching is generally low. Observations made in other published work (Delgado et al., 2001; Darwish et al., 2003) indicate that under arid conditions, vegetation could uptake substantial amount of soil nitrate leading to reduced leaching.

SUMMARY AND CONCLUSIONS

As managed animal production agriculture has been on the rise in Lebanon, utilizing its rangeland in combination with traditional agronomic crop rotation, the GRASIM model was evaluated as a decision aid tool for analyzing the combined effects of key factors in the grazing systems of semi-arid Lebanese areas. The model's usefulness in the region was tested with local crop, soil water, and nitrate leaching data collected from a two-year (1999 and 2000) field experiment. GRASIM adequately simulated crop growth, soil water dynamics, and nitrate leaching in both growing seasons under the conditions prevailing in the Bekaa region of Lebanon.

Case studies were conducted using GRASIM to simulate the performance of grazing systems under different soil types, grazing pressure, grazing management regimes, and soil water availability in terms of biomass production and soil-water and nitrate leaching potential. Results showed strong negative impact from higher grazing pressure on forage biomass production and water and nutrient availability. A mandatory resting period imposed on grazing regimes was shown to be necessary to maintain pasture productivity and limit nutrient loss. Added soil water by irrigation was shown to increase production significantly.

The simulations indicate that nitrate leaching losses are generally low under common local soil conditions and rotational grazing regimes in the semi-arid Bekaa valley region in Lebanon; albeit the validity of the phenomenon requires further in-depth soil water movement and nutrient transport studies. Overall, the GRASIM model was shown to have good potential to be part of a comprehensive decision-making system for integrated management of grazing systems under the semi-arid areas of Lebanon.

ACKNOWLEDGEMENT

This work was partially funded by a Purdue University Global Initiative grant. Authors would like to thank Dr. Mohammad Farran, AREC director for his assistance in conducting the field trial.

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