Mathematical Model of Seasonal Growth of Halophytic Plant Community with Account of Environmental Factors

T.I. Pisman, N.A. Slyusar
Institute of Biophysics SB RAS, Akademgorodok, Krasnoyarsk 660036
E-mail:pech@ibp.ru

ABSTRACT
Field investigations of yields of halophytic meadow plant communities were performed near of Lake Kurinka in the central part of the Republic of Khakasia in 2004 - 2006. A mathematical model has been constructed to describe the growth dynamics of different plant communities of halophytic meadows as dependent upon the temperature factor and the salinity level of the soil. Results of field investigations and model studies show that there is a correlation between plant growth and the temperature of the air for plant communities growing on soils containing the lowest (0.1%) and medium (1.84%) salinity levels. It has been proven in model studies that for plant communities growing on high-salinity (3.58%) soils, not only the temperature of the air but also the salinity level of the soil should be taken into account.

Keywords: halophytes, plant communities, temperature, salinity level of the soil.

INTRODUCTION

Mathematical methods are widely used to study plant growth and production (Apchevskii, 1990; Kul K.and Kul O., 1989). Construction of dynamic models of biological production is currently considered to be the most efficient method in mathematical modeling. These models take into account as many basic processes and parameters influencing plant growth as possible.

Models showing the influence of climate and climate change on plant growth, which would also involve soil site parameters, could be of both practical and theoretical interest.

A computer simulation model of regional vegetation dynamics was applied to the terrestrial ecosystems of China to study the responses of vegetation to elevated CO_2 and global climatic change. The primary production processes were coupled with vegetation structure in the model. Simulation results were obtained for each of the climatic scenarios with the model running toward equilibrium solutions at a time step of 1 month. Preliminary validation indicated that the model wascapable of simulating the net primary productivity of most vegetation classes and the potential vegetation structure in China under present climatic conditions. (Gao et al., 2000).

A mathematical model of the processes involved in carbon metabolism is described that predicts the influence of temperature on the growth of plants (Gent Martin and Enoch Herbert, 1983). The model assumes that the rate of production of dry matter depends both on the temperature and the level of nonstructural carbohydrate. The level of nonstructural carbohydrate is determined by the rates of photosynthesis, growth, and maintenance respiration. The model describes the rate of growth and dark respiration, and the levels of carbohydrate seen in vegetative growth of carnation and tomato.

Lopatin and his co-authors (Lopatin et al., 2006) performed mathematical analysis of the effect of solar radiation on the structure and productivity of plants. The author of another study determined the main properties of saline soils that are responsible for the level of the crop yield and developed models of their fertility (Kursakova, 2005). Models could be used to describe natural processes and to make a quantitative prediction of their development. An aim of crop modelers is to develop a dynamic model of plant growth that takes account of the varying environmental conditions imposed upon the crop, and of the competition occurring between plants within the crop (Aikman and Scafe, 1993).

Halophytic plants are capable to exist on soil with high salt concentration. Different researchers observed beneficial effects of moderate salinization on life processes of halophytic plants. Particularly, increasing of ferments strength, responsible for a salt exchange, maximal growth, etc was observed. However, high concentrations of soluble salts in the soils had negatively impact on plants. In addition, toxic salts action depends on chemical compound of salts and depends on salt tolerance of plant (Prokop'ev, 2001).

Influence of the temperature and a soil salinity degree on growth of halophyties also is insufficiently studied now. The purpose of this work was to construct and study a mathematical model describing the dynamics of seasonal growth of different plant communities in halophytic meadows, depending upon the air temperature and soil salinity level, which could be further used to predict yields of these plant communities.

MATERIAL and METHODS

The study was performed on plants of halophytic meadows in the coastal area of Lake Kurinka in the Altaiskii District of the Republic of Khakasia. The common mineralization is changing from 72 to 108 g/l (Krivosheev, 1991). Field investigations were conducted during 2004–2006. The mathematical model was analyzed using field data of 2004 and 2006, the years of contrasting air temperatures. Harvest was gathered during the time period of May to September, on the same days of every month. Three plant communities were studied: meadow fescue-couch grass (*Festuca pratensis* Huds., *Elytrigia repens* (L.) Nevski) – PC.1, sagebrush-puccinellia (*Artemisia nitrosa* Web., *Puccinellia tenuissima* Litv. ex V. Krecz.) – PC.2, and seablite (*Suaeda linifolia* Pall.) – PC.3. Every plant community grew on the soil of a different level of salinity – the amount of the solid residue of the saline soil aqueous extract (Table 1). The type of salinity is sulfate-sodic. Theoretical results are compared with the field data of the first three months of active growth of plant communities (May, June, and July). The field data were processed statistically (Dospekhov, 1973).

Table 1. Structure of plant communities and soil salinity level

Plant community	Plant community structure	Soil salinity, %
PC.1	*Elytrigia repens* (L.) Nevski *Elymus junceus* Fish	0.1
PC.2	*Puccinellia tenuissima* Litv. ex V. Krecz. *Artemisia nitrosa* Web.	1.84
PC.3	*Puccinellia tenuissima* Litv. ex V. Krecz. *Suaeda linifolia* Pall.	3.58

Plant productivity was determined in the growth period in 2004-2006 year. Three permanent study plots (10×10 m^2) were located on soil with different degree of salinity. The occurrence of each vascular species, its coverage, density and mean height was recorded in each plot. Plant productivity calculations were based on alive aboveground biomass from samples that were harvest from a 1 × 1m area in four replications in the center of each plot. Raw material was separated into five botanical-functional groups: gramineous plants, sedges, beans, sagebrush, herbs. All reproductive shoots were weighed, dried from air-dry state (at 80°C) and weighed again (Voronov, 1973).

For determination of the solid residue of the saline soil aqueous extract was measured 30 g of soil samples and scooped of soil into a 300-ml conic flasks. Then, in conical vessel was added 150 ml of distilled water. The soil samples and water was stirred in during 3 min and was leave the solution to settle for at least 5 min. After that an extract filter, using double folded filters, and place in porcelain cup. Previously, porcelain cup was dried up and weighed with a margin error no more 0,001g. After that porcelain cup was put up on a water-bath for evaporation of a filtrate. Then a cup was weighed again (with a margin error no more than 0,001g). The mass fraction of solid residue of the saline soil aqueous extract (total dissolved solid (TDS)) was calculated under the formula:

$$TDS = (A - B)*1000 / V$$

where:

A = weight of dried residue + dish, mg, and

B = weight of dish, mg.

V= sample volume, ml (Schukin, 1985).

The mathematical model was studied using Mathcad software.

RESULTS

Temperature is one of the main ecological factors determining whether a plant species can grow in a certain climate zone and perform its primary biological production.

Variations in the mean daily air temperature in 2004 and 2006 are shown in Figure 1 (based on the data obtained from Meteorological Station "Khakasskaya").

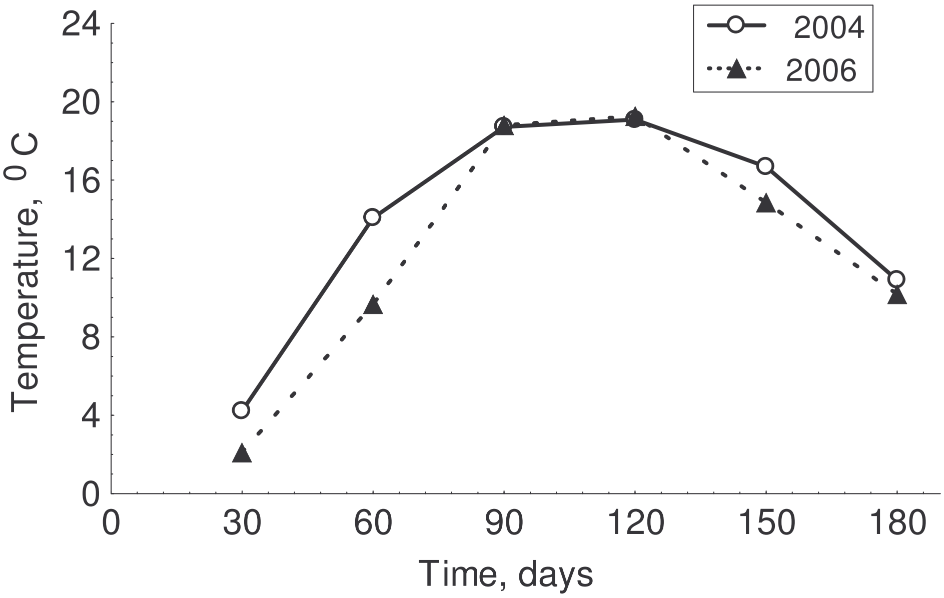

Fig. 1. Daily mean air temperature

In 2004, plant growth conditions (temperature and moisture) were optimal – it was warm and humid; 2006 was cold and humid. The mean daily air temperature of the first three months of active plant growth was higher in 2004 than in 2006

Results of Field Investigations. The graphs of Figures 2 and 3show the crop yields of PC.1and PC.3 in 2004 and 2006 (field data) (Pisman and Slyusar, 2007). For PC.1 there is a correlation between the crop yield and air temperature. The crop yield of PC.1 on the soil with the lowest salinity level (0.1%) was 12-14% higher during the first three months of active plant growth in 2004 than in 2006 (Fig. 2). The temperature-dependent crop yield dynamics of PC.2 growing on the medium-salinity soil (1.84%) was similar to the crop yield dynamics of PC.1. The only parameter in which they differed was the maximum crop yield.

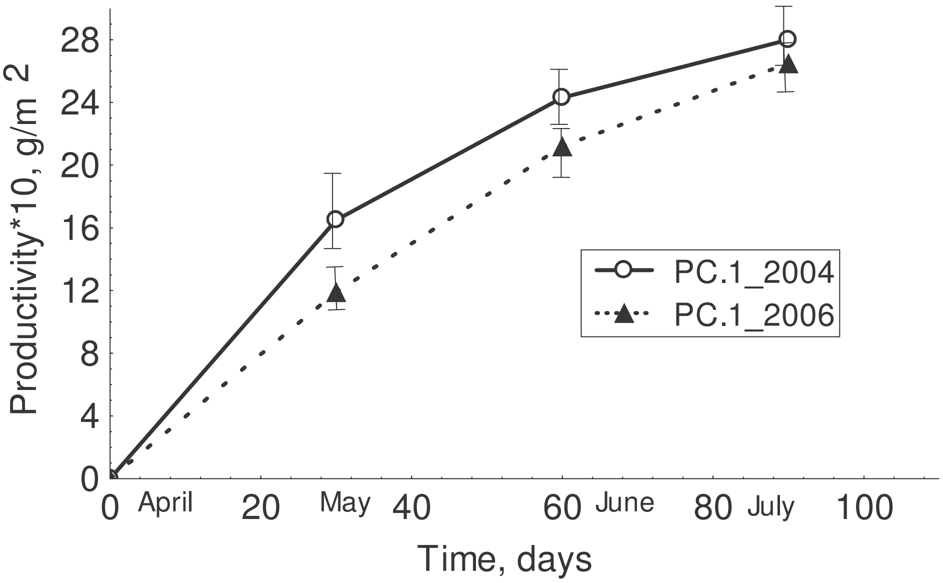

Fig. 2. Seasonal crop yield of PC.1 in 2004 and 2006 (field data).

However, no correlation was found between the crop yield of PC.3, growing on the high-salinity soil (3.58%), and the air temperature (Fig. 3). Moreover, the crop yield of PC.3 during the active plant growth was much lower than the crop yields of PC.1 and PC.3, reaching just 140 g/m^2 in 2004 and 2006.

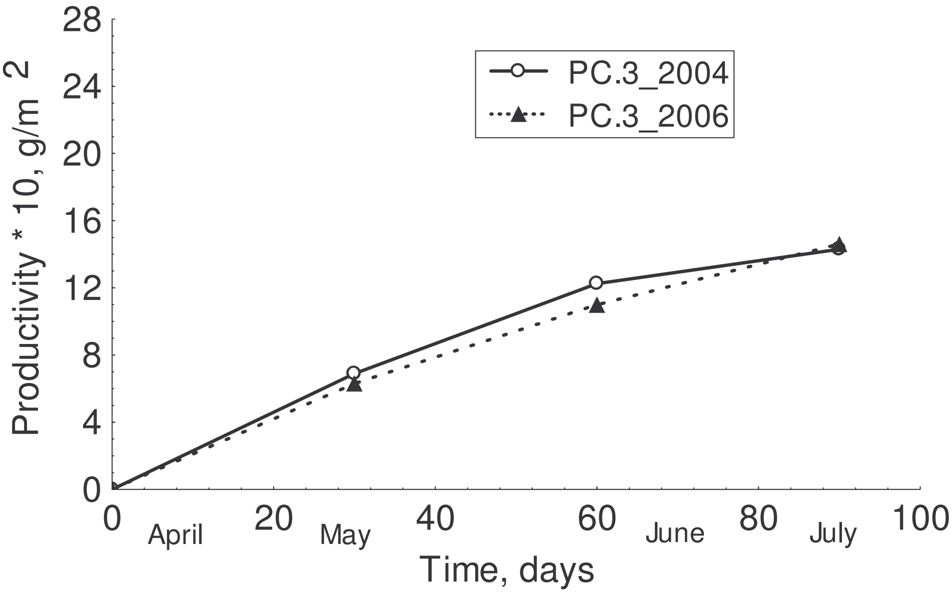

Fig. 3. Seasonal crop yield of PC.3 in 2004 and 2006 (field data).

Theoretical Results. A mathematical model of temperature-dependent seasonal dynamics of the yield produced by plant communities of halophytic meadows was constructed to account for the abovementioned differences in the functioning of the plant communities (PC.1and PC.3) of halophytic meadows and the relationship of their yields to climate factors (temperature) and ecological factors of their environments (soil salinity level). The model is represented by a system of two differential equations (1), using the coefficients preliminarily obtained from field experiments.

$$dP/dt = \mu(T)P - \mu(T)P^2/ P_{max}$$

$$dT/dt = \alpha T - \alpha T^2/T_{max} \quad (1)$$

$$\mu(T) = \mu_{max}[(T_{max} - T)/(T_{max} - T_{opt})] [(T - T_{min})/(T_{opt} - T_{min})]$$

where P is crop yield, g/m^2; T – temperature, °C; $\mu(T)$ – specific growth rate of a plant community, d^{-1}; P_{max} = 280 g/m^2 – maximum crop yield of a plant community; μ_{max} = 0.07 d^{-1} – maximum specific growth rate of plants; T_{min} = 5°C – minimum air temperature at which plants begin growing; T_{opt} = 25°C – optimum air temperature; T_{max} = 40°C – maximum air temperature;

α = 0.01– rate of temperature change, d^{-1}.

The equation for the specific growth rate of a plant community – $\mu(T)$ – contains 4 parameters: 3 basic parameters for the temperature (T_{opt}, T_{max} and T_{min}) and μ_{max} – the maximum specific growth rate of plants at T_{opt}. Specific growth rate will be equal to 0 ($\mu = 0$) if $T = T_{min}$ or if $T = T_{max}$, and it will be maximal ($\mu = \mu_{max}$) if $T = T_{opt}$.

Figure 4 show results of theoretical calculations of the dynamics of PC.1 crop yields in 2004 and 2006. Investigation of the model showed a qualitative agreement between the field data and the theoretical results: the crop yields of PC.1 and PC.2 are temperature dependent on soils with low (0.1%) and medium salinity levels (1.84%). The crop yield of these plant communities is higher in 2004, at the optimal air temperature, than in 2006, at a low temperature.

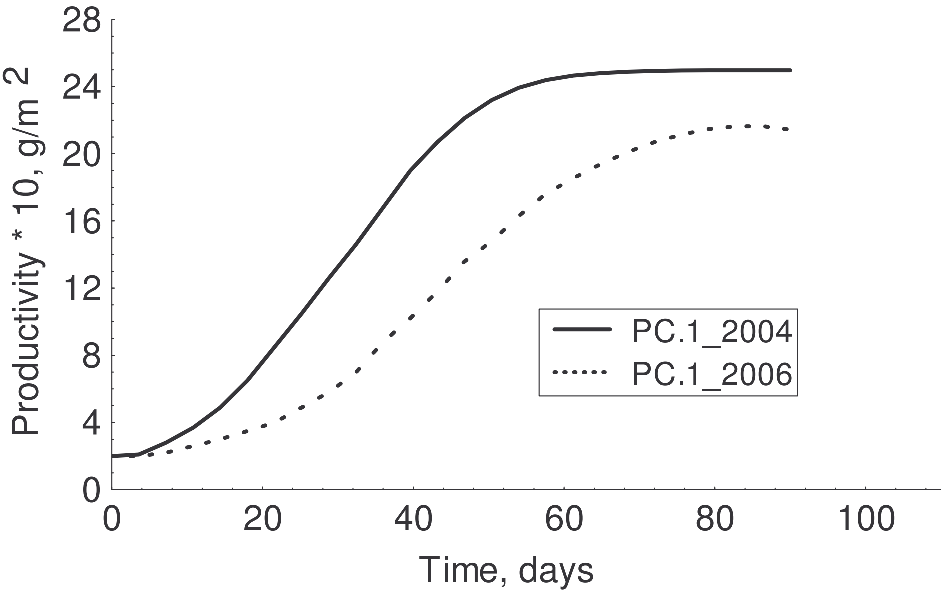

Fig. 4. Crop yield of PC.1 in 2004 and 2006 (theoretical results).

However, no qualitative agreement between experimental and theoretical results for the temperature dependence of the crop yield of the plant community was obtained for PC.3, the plant community growing on the high-salinity (3.58%) soil. It was assumed that the crop yield of PC.3 is affected not only by the temperature but also by soil salinity.

To check this assumption, we used our field results to calculate soil salinity dependence of the maximum specific growth rate of the puccinellia, the plant representing most of the plant communities. It had a shape of a classical curve showing inhibitor dependence of specific growth rate (Fig. 5).

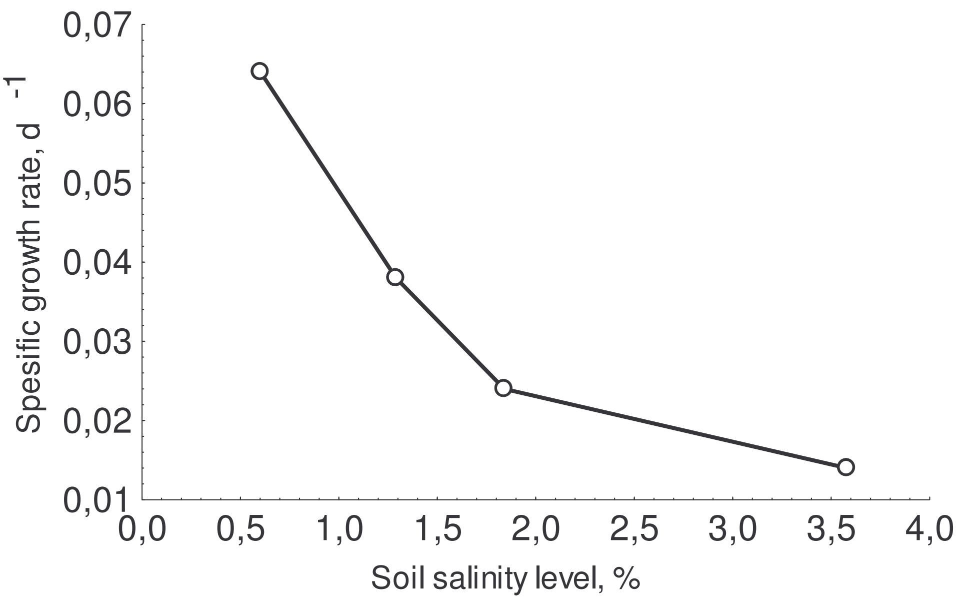

Fig. 5. Puccinellia growth depending upon soil salinity level.

To confirm the assumption that soil salinity affects the crop yield of PC.3, we modified the equation for the specific growth rate (2), taking into account inhibitor (soil salinity) dependence of PC.3 development:

$$\mu(T, I) = \mu_{max} [(T_{max} - T)/(T_{max} - T_{opt})] [(T - T_{min})/(T_{opt} - T_{min})][k_I/(k_I + I)], \quad (2)$$

where I is soil salinity level, %;

$k_I = 1.5\%$ – inhibition constant numerically equal to the soil salinity level at which specific growth rate of the plant community is equal to half maximum specific growth rate.

With the modified model we obtained a qualitative agreement between the experimental and the theoretical results (Figs. 3 and 6): the crop yields of PC.3 (soil salinity 3.58%) during the period of active plant growth (May – July) are the same in 2004 and 2006, i.e. they are temperature independent, reaching 150 g/m^2, which is much lower than the crop yields of PC.1 (soil salinity 0.1%) and PC.2 (soil salinity 1.84%).

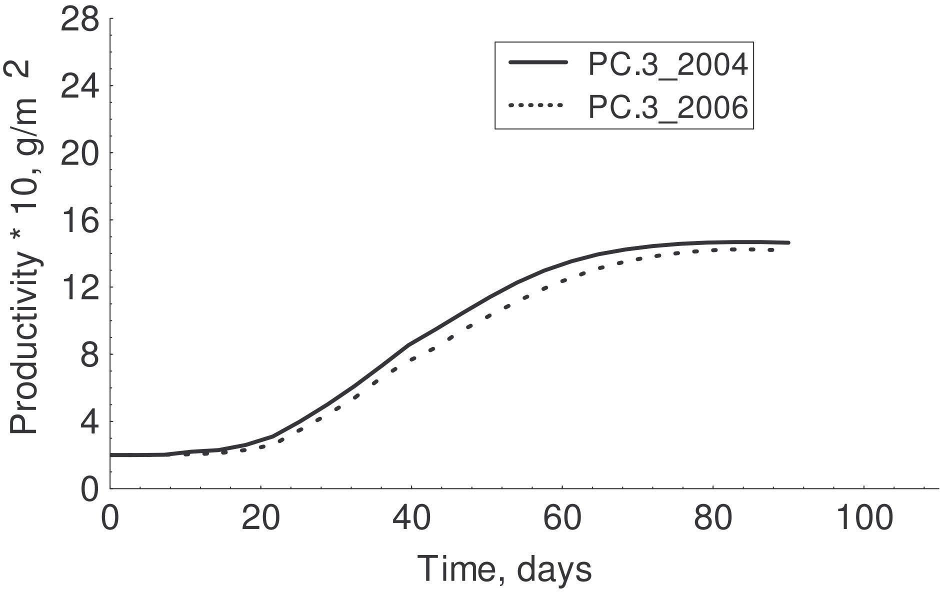

Fig. 6. Crop yield of PC.3 in 2004 and 2006 (theoretical results).

Thus, results of our study, in which we used a mathematical model describing the development of plant communities of halophytic meadows and field measurements, suggest that both climate conditions (temperature) and ecological factors of the plants' habitat (soil salinity level) should be taken into account when constructing models for predicting crop yields.

DISCUSSION

It is difficult to predict growth rates of plants because there are no accurate methods of making relatively long-term weather forecasts. So, one has to model seasonal trends in some meteorological parameters, which are clearly of periodic nature. This is true for air temperature, which is the main factor controlling plant growth rates. Therefore, attempts are made to find the way to predict the value of this factor first. Although temperature has a pronounced yearly trend, there are significant fluctuations in temperature conditions from year to year. Thus, variations in temperature conditions (and, of course, all other weather parameters) cause interseasonal variations in plant growth rates.

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