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Competition Between Crop and Weeds in Agroecosystems Studied Using Satellite Data and a Mathematical Model

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In this study, the data obtained by satellite remote sensing and by studying a mathematical model are combined to investigate seasonal dynamics of wheat and oat agroecosystems with different levels of weed infestation. The study was performed in the south of the Krasnoyarskii Krai. NDVI was used to show the possibility of identifying weed-free and weed-infested crop fields. The model study was based on variations in the initial percentages of the crop and weed biomasses, with plant growth limited by mineral element deficiency. Model prediction of productivity of agroecosystems with different levels of weed infestation showed that the initial weed biomass higher than 30% is critical for crop productivity and may result in considerable crop yield loss.

Keywords: agroecosystems, weed infestation, satellite remote sensing, mathematical modeling.

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Конкуренция культурных и сорных растений в агроценозах на основе спутниковой информации и математической модели

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В работе использовано комплексное применение данных спутникового зондирования Земли и результатов исследований математической модели сезонной динамики агроценозов пшеницы и овса с различной степенью засорения. Исследования проводились на территории

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Юга Красноярского края. На основе NDVI показана возможность идентификации чистых и засоренных полей с посевами зерновых культур. Исследование модели проводилось в зависимости от начального соотношения биомассы культурных и сорных растений при лимитировании роста минеральными элементами. В результате оценена возможность прогноза урожайности агроценозов с разной степенью засорения. Показано, что превышение начальной доли сорной растительности свыше 30 % может стать критическим и привести к значительному уменьшению урожайности культурных растений.

Ключевые слова: агроценозы, засорение, спутниковое зондирование, математическое моделирование.

Introduction

Weeds are always present in agroecosystems. The weed species that are ecologically similar to the crops are strong competitors. Many weed species are sources of pests and diseases of crops [1].

However, at low densities, weeds may have a beneficial effect. They accumulate nutrients that have not been assimilated by the crop and retain them, and, then, decaying weeds fertilize the soil. Some weeds are melliferous and medicinal plants.

Remote detection of high densities of weeds and the ability to predict their effects on crop yield are prerequisites for successful reduction in the agricultural application of herbicides. Arkhipova et al. [2] reported results of decoding medium resolution space images from Landsat satellites. They were used to identify high densities of common ragweed in agroecosystems in South Russia based on NDVI.

A number of empirical models have been developed to describe the response of the crop yield to weed infestation. The most important parameters are weed density and the time of emergence of the weeds relative to the time of emergence of the crop [3]. A model has been constructed to describe the interaction between crop yield loss and weed leaf area index [4]. These models, however, need evaluations of many parameters for both the crop and weeds.

The purpose of the present study was to estimate the level of infestation and predict crop yields in agroecosystems by using satellite remote sensing and a mathematical model. The model was verified with results of field studies of wheat and oat agroecosystems [5].

Material and methods

Monitoring of crop development in the south of the Krasnoyarskii Krai was conducted by using the data of the MODIS/Terra spectroradiometer. Evaluation of photosynthetically active biomass was based on Normalized Difference Vegetation Index (NDVI). NDVI was determined from the satellite data obtained in the red (620–670 nm) and near-infrared (841–876 nm) channels, at a spatial resolution of 250 m.

Interpretation of satellite images was based on ground-truth data gathered by monitoring the crops: wheat (*Triticum acstivum* L.) and oats (*Ovena sativa* L.) fields in the south of the Krasnoyarskii Krai [5]. The major weed in the oats agroecosystem was the field milk thistle (*Sonchusarvensis*). The wheat agroecosystem was infested by the fall panicum (*Panicum dichotomiflorum*). During the growing season, field investigations of wheat and oat ecosystems were performed on the estimated dates of the passage of the Modis/Terra satellite over the

area. The coordinates of the sample plots were recorded with a GPS navigator. Five samples of fresh aboveground biomass were collected from each of $1 \times 1 \text{ m}^2$ plots and weighed [5]. Before weighing, the plants cut from the sample plots were separated into three groups: reproductive organs of crops (grains), vegetative organs of crops (stems and leaves), and weeds. The mass of each group was determined separately.

The mathematical model of seasonal dynamics of crop and weed productivities was studied using the Mathcad software. Coefficients used in the model study were computed from results of land-based investigations of wheat and oat agroecosystems [5].

Results and discussion

Satellite remote sensing

Figure 1 shows seasonal dynamics of NDVI of oats and wheat crops. NDVI is known as a “greenness” index. Therefore, the dynamics of NDVI during the plant growing season (June – August) rather accurately corresponds to the dynamics of the seasonal production of total fresh aboveground phytomass of the agroecosystem (the crop and weed biomass). In August, crops lose moisture and turn yellow earlier than weeds, and, thus, weeds growing among cultivated plants can be discerned in high-resolution satellite images.

The initial NDVI value of the oat agroecosystem is higher than that of the wheat agroecosystem (Fig. 1) because of the greater amount of total photosynthesizing vegetation in the oat agroecosystem. Field investigations revealed high weed densities in that agroecosystem [5].

To achieve higher accuracy in detecting weeds among crop plants, we investigated oat agroecosystems located in different plots, with different levels of weed infestation (Fig. 2). During the plant growing season (between June 12 and September), we measured the main biometric parameter – biomass. Measurements showed high correlation between plant biomass and the NDVI values averaged for each field, which were obtained for each plot from the Modis/Terra scanner during the growing season.

The angles of inclination of the relationships between total fresh biomass of the oat crop and NDVI values are clearly different for agroecosystems with different levels of weed infestation. The initial

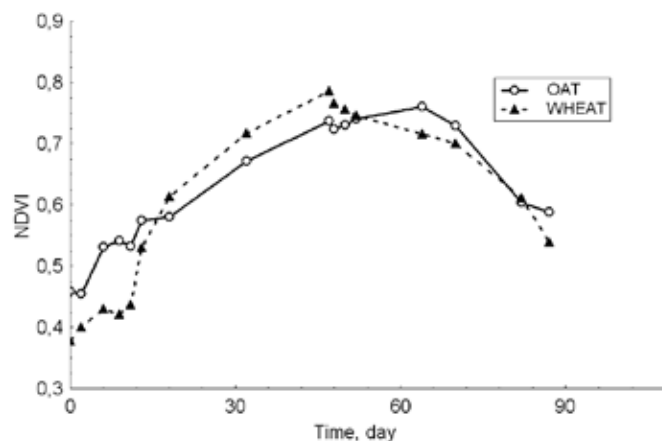


Fig. 1. Seasonal dynamics of NDVI of wheat and oat crops. Time zero is June 1

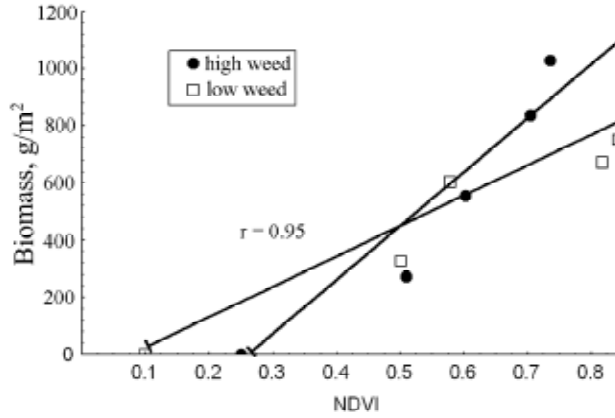


Fig. 2. The relationship between NDVI and total fresh biomass of oats agroecosystems with different levels of weed infestation

NDVI value for the plot with a low level of weed infestation is about 0.1, corresponding to an open (plant-free) land plot. The initial NDVI value for the plot with a high level of weed infestation is 0.2 or higher, probably suggesting the presence of some initial quantity of photosynthesizing vegetation. Later, field studies proved the presence of weeds there [5].

Mathematical model

Seasonal dynamics of the crop and weed yields under nitrogen deficiency can be described by the following model:

$$\begin{aligned}
 dX_c / dt &= \mu_c(N)X_c - \mu_c(N)(X_c^2 / X_c \max) \\
 dX_w / dt &= \mu_w(N)X_w - \mu_w(N)(X_w^2 / X_w \max) \\
 dN / dt &= N_0 - \mu_c(N)X_c / Y_c - \mu_w(N)X_w / Y_w \\
 \mu_c(N) &= \mu_c \max N / (k_{cN} + N) \\
 \mu_w(N) &= \mu_w \max N / (k_{wN} + N)
 \end{aligned} \tag{1}$$

where X_c and X_w are biomasses of crop and weeds in the agroecosystem, respectively, g/m^2 ; $\mu_c(N)$ and $\mu_w(N)$ are specific rates of increase in the crop and weed biomass, d^{-1} ; $X_c \max$ and $X_w \max$ are maximal biomasses of crop and weeds; $N_0 = 10 g/m^2$ and N are the initial and current nitrogen concentrations in the soil; $\mu_c \max$ and $\mu_w \max$ are maximal specific rates of increase in the crop and weed biomass, d^{-1} ; $Y_c = Y_w = 30 g \text{ biomass} / g \text{ nitrogen}$ – yield coefficients of crop and weeds on nitrogen; $k_{cN} = k_{wN} = 3 g/m^2$ – half-saturation constants of nitrogen for crop and weeds, which are numerically equal to nitrogen concentration at which specific rates of increase in the crop or weed biomass amount to half of the maximal rate.

Different initial crop to weed ratios were used to study the model of seasonal dynamics of crop and weed productivities. Figure 3 shows results of studying the model of dynamics of the wheat agroecosystem with a low weed density. Initially, the crop constituted about 96% and the weeds about

4%. By the middle of the plant growing season, the crop had decreased to 64%, the weeds increasing to 36%. Then, a stationary state was reached, and throughout the remaining season, crop productivity was higher than weed productivity.

To verify the model, we used field data for the wheat agroecosystem with a low level of weed infestation [5]. The initial biomass of the crop was 40 g/m² and the initial biomass of the weeds was 2 g/m². At the end of the growing season, the crop productivity (800 g/m²) was considerably higher than the weed productivity. Thus, for the scenario with a low weed infestation, we obtained qualitative agreement between the field data on the seasonal growth of the wheat agroecosystem and results of studying the model.

Figure 4 shows results of studying the model describing dynamics of the oats agroecosystem with a high weed density. Initially, the crop constituted 67% and the weeds 33%. By mid-June, the crop had decreased to 40%, the weeds increasing to 60%. Then, a stationary state was reached, and throughout the remaining season, weed productivity was higher than crop productivity. Thus, model

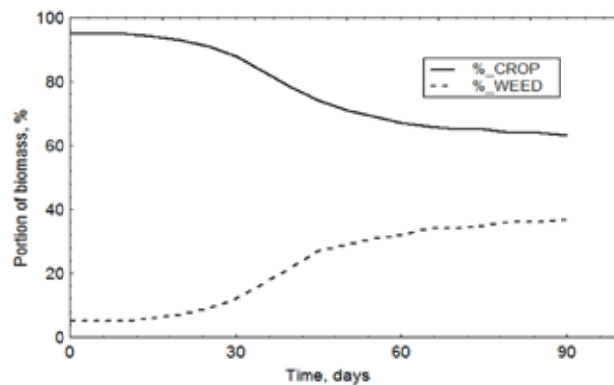


Fig. 3. Seasonal dynamics of the crop and weeds in the wheat agroecosystem with allow initial level of weed infestation (theoretical results). Time zero is June 14

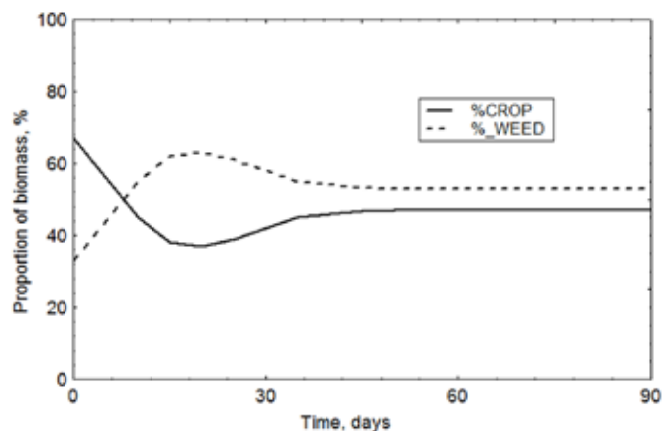


Fig. 4. Seasonal dynamics of the crop and weeds in the oats agroecosystem with a high initial level of weed infestation (theoretical results). Time zero is June 14

studies suggest that the initial weed biomass higher than 30% is critical for crop productivity and may cause considerable reduction in crop biomass and, hence, crop yield loss at the end of the growing season.

To verify the model, we used field data for the oat agroecosystem with a high level of weed infestation, about 20 g/m² [5]. At the end of the season, the percent of weeds was higher than the percent of crop (oats).

Thus, having studied the model of seasonal dynamics of crop and weeds with different initial percentages of the components, we showed qualitative agreement between the model data and results of the field studies of wheat and oat agroecosystem productivities. The initial weed biomass of about 4% does not significantly affect crop yield at the end of the growing season. However, the initial weed biomass higher than 30% is critical for crop productivity and may result in considerable crop yield loss at the end of the growing season. Coefficients and initial crop to weed ratios of the model can be varied to predict productivities of agroecosystems with different levels of weed infestation.

Conclusion

The reasons underlying interest in the damage done by weeds are numerous, but here are the most important ones [6]. First, the common use of herbicides has failed to solve the weed issue, making it even more controversial. The floristic composition of the weeds has changed, and the abundance of resistant species has increased, decreasing the economic efficiency of the herbicides. Second, in practical and theoretical agriculture, weed populations are usually treated as impurities contaminating crops. In fact, however, all components of agroecosystems interact with each other, and weeds may be considered as a necessary ingredient of the agroecosystem structure. The strategy of weed control should be changed and directed towards prevention of severe weed infestations.

Remote sensing and theoretical studies of interactions between crops and weeds in agroecosystems are useful tools for tackling these issues. The major goal of mathematical modeling is to find a unified mathematical model that will enable statistically reliable predictions of crop yield dynamics over the entire range of variations in weed density and qualitative estimations of potential weed damage and possible crop losses [6].

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References

[1] Торопова Е.Ю., Глазунова Е.Б. Влияние состава агроценоза на развитие корневой гнили яровой пшеницы в лесостепи Западной Сибири, *Вестник Алтайского государственного аграрного университета*, 2014, 4 (114), 38–42 [Торопова Е.Ю., Glazunova E.B. The effect of the agroecosystem composition on the development of root rot of spring wheat in forest steppe of West Siberia. *Bulletin of the Altai State Agrarian University*, 2014, 4 (114), 38–42 (in Russian)]

[2] Архипова О.Е., Качалина Н.А., Тютюнов Ю.В., Ковалев О.В. Оценка засоренности антропогенных фитоценозов на основе данных дистанционного зондирования земли (на примере амброзии полыннолистной), *Исследование Земли из космоса*, 2014, 6, 15-26 [Arkhipova O.E.,

Kachalina N.A., Tyutyunov Yu.V., Kovalev O.V. Estimating weed infestation of anthropogenic plant ecosystems based on the data of Earth remote sensing (using common ragweed). *Issledovanie zemli iz kosmosa (Earth research from space)*, 2014, 6, 15–26 (in Russian)]

[3] Damgaard C., Weiner J., Nagashima H. Modelling individual growth and competition in plant populations: growth curves of *Chenopodium album* at two densities. *Journal of Ecology*, 2002, 90, 666–671.

[4] Kropff M.J., Spitters C.J.A simple model of crop loss by weed competition from early observations on relative leaf area of the weeds. *Weed Research*, 1991, 31, 97–105.

[5] Жукова Е.Ю., Шевырнов А.П., Жукова В.М., Зоркина Т.М., Пугачева И.Ю. Сезонная динамика продуктивности агроценозов юга Минусинской котловины, *Вестник Томского университета*, 2009, 323, 354–358 [Zhukova E.Yu., Shevyrnogov A.P., Zhukova V.M., Zorkina T.M., Pugacheva I.Iu. Seasonal dynamics of the productivity of agroecosystems in the south of the Minusinsk Hollow. *Bulletin of Tomsk University*, 2009, 323, 354–358 (in Russian)]

[6] Туликов А. М. Вредоносность сорных растений в посевах полевых культур, *Известия ТСХА*, 2002, 1, 92-107 [Tulikov A.M. Damage done by weeds to field crops. *Proceedings of МТАА*, 2002, 1, 92–107 (in Russian)]