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Produkcia biomasy a sezónna transpirácia

Biomass production and its relation to transpiration

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Abstrakt

Práca opisuje metódu určenia produkcie biomasy v závislosti na úhrne sezónnej transpirácie, ktorá bola vypočítaná retrospektívnym modelovaním pomocou programu HYDRUS-ET. Tento nástroj, umožňuje určenie produkcie biomasy (úrody) v závislosti na sezónnom úhrne transpirácie. Postup je zdôvodnený tiež teoretickou analýzou. Kumulatívna čiara prekročenia úhrnov sezónnej transpirácie ako základná charakteristika vodného režimu pôdy, bola využitá na výpočet kumulatívnych čiar prekročenia potenciálnych a skutočných úrod. Z rozdielov medzi nimi je možné určiť zvýšenie úrod dosiahnuteľné optimalizáciou vodného režimu pôdy a tak posúdiť efektívnosť investícií do technického vybavenia ako aj nákladov na prevádzku závlah alebo odvodnenia a porovnať ich s prínosmi očakávaného zvýšenia úrody.

Kľúčové slová: vodný režim pôdy, transpirácia, úroda, matematické modelovanie

Abstract

This paper presents a method for estimating plant production as a function of the seasonal transpiration total calculated retrospectively with the HYDRUS-ET software package. This approach is based on empirical relationships between seasonal transpiration totals of particular canopy and biomass production (yield). Novelty of this approach is the development of the tool to evaluate the biomass production as related to the seasonal transpiration. The cumulative frequency distribution of seasonal transpiration was chosen as the basic characteristic of the soil water regime. This approach allows one to estimate cumulative frequency curves of actual and potential yields. The difference between these two curves is the cumulative frequency distribution of yield to be optimized by the irrigation system. The method permits a better cost-benefit analysis by comparing expected yield increases with the investment and operational expenses of the newly designed irrigation system, or of newly invoked water management practices.

Key words: soil water regime, transpiration, biomass production, mathematical modeling

Introduction

Soil water is only the one of many preconditions to influence biomass production. It is known, that irrigation as one of the methods of soil water regime optimization is contributing to the biomass production significantly. About 20 percent of irrigated soils of the world is producing more than 40 percent of plant production. Those soils are located mainly in arid or semiarid zones. A key step in design and implementation of irrigation or drainage system is to diagnose the existing (natural) soil water regime and possible influence of its optimization on biomass production increase.

Is not easy to relate directly the soil water content to biomass production, therefore it is necessary to look for another ways of expression the relation between biomass production and soil water influence on it. Plant production can be evaluated by use of so called "crop growth models", calculating assimilation rate as a complex function of environmental parameters, which is difficult to estimate; those models are usually canopy oriented: WOFOST (van Diepen etal., 1989), MACROS (Penning de Vries et al., 1989), DAISY (Hansen et al., 1990). The soil water influence on plant production is expressed roughly there and they are not suitable to evaluate soil water regime influence on yields. Because direct and unambiguous relationships soil water content (soil water potential) – growth rate (biomass production) were not found, researchers tried to find another ways of expressing quantitatively the role of soil water in biomass production. One of proposals was to characterize the influence of soil water on plant production using transpiration as an integral part of production process. This approach is used in MACROS model too.

Results of numerous measurement in vitro conditions demonstrated the low variability of assimilation and transpiration intensity ratio under given conditions (Hsiao, 1993). From it follows linear relation between photosynthesis and biomass production rate. In reality, results of field measurements has shown linear relationship between plant production and transpiration total during vegetation period of particular plant.

A quantitative assesment of the influence of soil water in the soil root zone on biomass production can be made using well-known and widely accepted empirical relationships between biomass production (yield) and transpiration total during the growing season of a given crop (Hanks and Hill, 1980, Vidovič and Novák, 1987, Feddes et al., 1999, Kirkham, 2005). These relationships, generally thought to be approximately linear, are valid for a particular plant (canopy) at a particular site subject to standard tillage and nutrition conditions. The only transient characteristic is the transpiration rate as influenced by local meteorological conditions and soil water. The relationship between biomass production (yield) and the seasonal transpiration rate can be expressed by the linear equation.

The aim of this paper is to evaluate the long standing seasonal transpiration totals and corresponding yields of three important crops – maize, winter wheat and spring barley grown in conditions of South Slovakia for. Then to design the curves of their exceedance and evaluate the variability of yields and their possible increase by optimizing of soil water regime.

Theory

Rate of photosynthesis, expressed by the rate of carbon dioxide consumption by plant can be expressed by the equation (Bierhuizen, Slayter, 1964)

$$P = \frac{\Delta c_{ou}}{r_{ac} + r_{sc} + r_m} \qquad (1)$$

Transpiration rate can be expressed by the equation (van Honert, 1948)

$$E_t = \frac{\Delta c_v}{r_a + r_s} \qquad (2)$$

P – photosynthesis rate [kg m^{-2} s^{-1}]

E_t – transpiration rate [kg m^{-2} s^{-1}]

r_{ac} , r_{sc}, r_m - resistance (aerodynamic) of an air boundary layer adjacent to the leaf surface, stomata resistance and mesophyll resistance to carbon dioxide transport from leaf to atmosphere [s m^{-1}]

r_a , r_s - resistance (aerodynamic) of an air boundary layer adjacent to the leaf surface, stomata resistance to transport of water vapour from leaf to atmosphere [s m^{-1}]

Δc_{ou} – mass concentration difference of carbon dioxide between leaf (after carboxylation) and atmosphere [kg m^{-3}]

Δc_v – mass concentration difference of water vapour between leaf and an atmosphere [kg m^{-3}]

By combination of equations (1) and (2) we can get

$$\frac{E_t}{P} = \frac{r_{ac} + r_{sc} + r_m}{r_a + r_s} \frac{\Delta c_v}{\Delta c_{ou}} \quad (3)$$

All the resistances in the Eq. (3) are complex functions of plant properties and are changing in time. For particular plant, environment and time interval as an approximation can be assumed constant ratio of both types of resistances, as it is expressed by the first part of the right side of the equation (3) and it can be expressed as A´. Then, photosynthesis rate can be expressed as

$$P = \frac{E_t}{A'} \frac{\Delta c_{ou}}{\Delta c_v} \quad (4)$$

The difference of carbon dioxide concentration between atmosphere and mesophyl is not changing significantly during the vegetation period, it can be expressed as a constant too

$$A = \frac{\Delta c_{ou}}{A'} \quad (5)$$

then we can get

$$P = A \frac{E_t}{\Delta c_v} \quad (6)$$

term B is the ratio

$$B = A / \Delta c_v \quad (7)$$

Finally, it can be written equation for photosynthesis rate P as proportional to plant transpiration rate E_t

$$P = B.E_t \quad (8)$$

Where term B is in physiological literature usually expressed as transpiration efficiency, its value depends on photosynthesis type (for C3 type B = 0.002 – 0003, for C4 type B = 0.004 mol CO_2 / mol H_2O).

This equation (8) is an expression of linear relation between photosynthesis rate and rate of plant transpiration. Approximative approach to the development of this equation lead to the robust but simplified relationship, neglecting a lot of important properties of an environment. Nevertheless, this approach is extraordinary feasible for practical purposes. Nowadays, there are relative reliably methods of transpiration estimation, mostly based on Penman – Monteith approach (Budagovskij, 1981, Novák, 1995, Allen, et al., 1998). So, the above mentioned „growth“ models, are allowing biomass production modeling using photosynthesis evaluation, need many not easy acquired inputs and they are usually single type canopy oriented (Hansen et al., 1990).

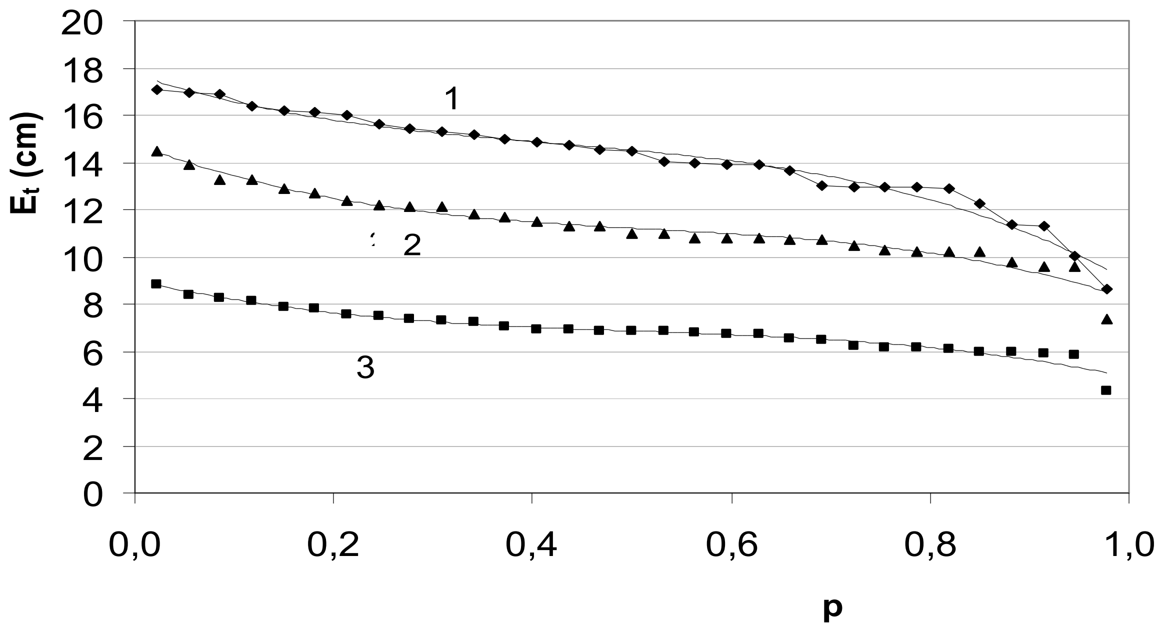

Fig. 1. Curve of exceedance seasonal transpiration totals E_t of maize canopy (1), winter wheat (2) and spring barley (3) in years 1971-2000 and 2003, Most pri Bratislave site, South Slovakia.

Method

Characteristics of soil water regime (SWR) were estimated by retrospective mathematical modeling for 31 years. Seasonal courses of daily characteristics of soil water regime were calculated; among them soil water content, soil water potential, daily totals of potential evapotranspiration and their components- transpiration and evaporation. They were calculated assuming stable properties of soil and plant; meteorological characteristics were changed only and they were measured at meteorological stations.

Simulation model HYDRUS – ET - version 1- (Šimůnek et al., 1997) was used. It is modification of well – known one dimensional model HYDRUS (version 6.1) and HYDRUS1D with interactive graphical interface. This program is based on governing Richards equation describing transport of water in variably saturated porous media and convective – dispersion equation for transport of solute and heat as well. Richards equation involves the term to calculate, water extraction by roots. Subroutine describing rain and irrigation water interception as well as evapotranspiration and its components calculation is a part of the model HYDRUS – ET. Modified version of the Penman – Monteith and Budagovskij method for calculation of evapotranspiration was incorporated in the model used (Novák, 1995).

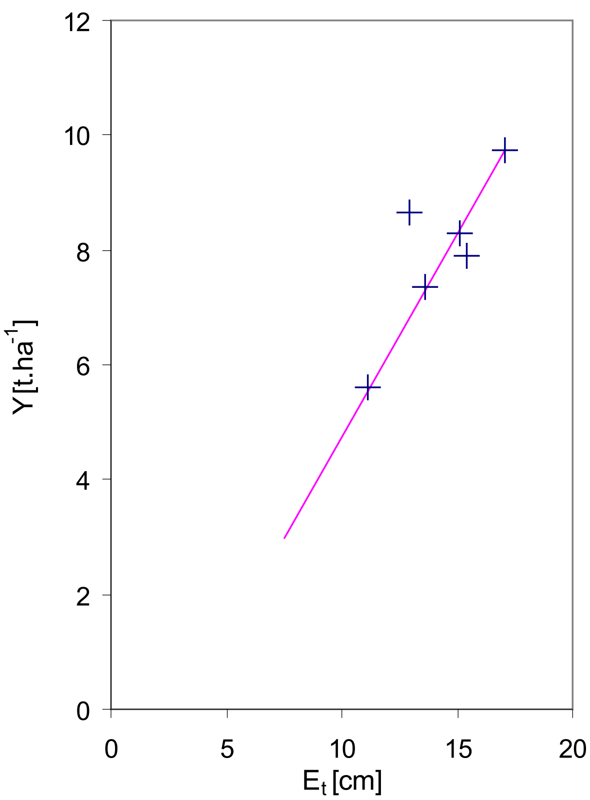

Fig.2. Dry maize grains yield *Y* and transpiration totals of maize E_t, during its vegetation period. Empirical relationship represents 5 seasons within the time interval 1971-2000 and 2003. Most pri Bratislave site, South Slovakia.

Soil

The basic characteristics of soil used in simulation procedure are in Tab.1

Tab.1.Charakteristics of sandy loam soil (Haplic Chernozem) at Most pri Bratislave, Southern Slovakia (Experimental field of Hydromeliorácie, s.e., Bratislava).

θ_v [$m^3\ m^{-3}$]	0.18
θ_{la} [$m^3\ m^{-3}$]	0.28
θ_{fc} [$m^3\ m^{-3}$]	0.35
θ_s [$m^3\ m^{-3}$]	0.4
K [$m\ s^{-1}$]	$5.6.\ 10^{-7}$
α [-]	0.0577
n [-]	1.299

θ_v – volumetric soil water content corresponding to the wilting point [cm^3cm^{-3}], θ_{fc} – soil water content corresponding to the „field capacity“[cm^3cm^{-3}], θ_s – water content of the saturated soil [cm^3cm^{-3}], θ_{la} - volumetric soil water content corresponding to the “limited availability” of soil water by plants [cm^3cm^{-3}], K_s – hydraulic conductivity of the soil saturated with water (saturated hydraulic conductivity) [$m.s^{-1}$], α [cm^{-1}] and n [-] – van Genuchten’s equation coefficients (van Genuchten, 1980).

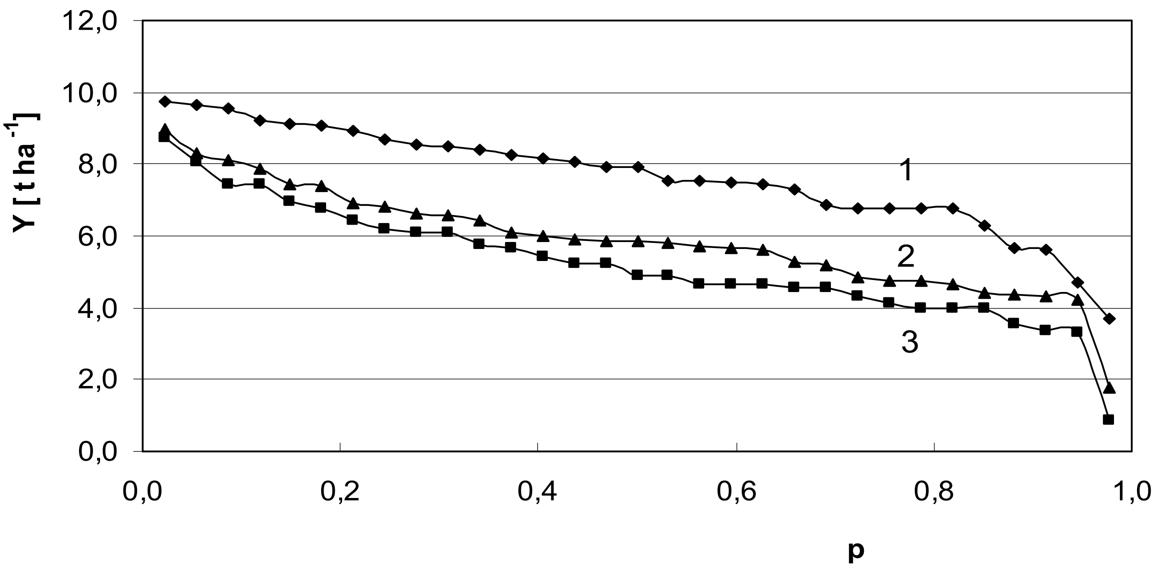

Fig.3. Curve of exceedance dry grain yields Y , of maize (1), winter wheat (2) and spring barley (3) during the seasons 1971-2000 and 2003, Most pri Bratislave site, Southern Slovakia.

Canopies

Three types of plants (canopies) were chosen for analysis: maize, winter wheat and spring barley. The only source of water were precipitation, no irrigation was used. Duration of growth seasons of particular plants (Tab.2) were different; different were seasonal transpiration totals too. Actual growth period of winter wheat is longer than it is noted in the table, which does not include autumn and winter period of growth. It is assumed transpiration during winter period and plant production is not significant, the most influential period is „warm“ period.

Table 2. Seasons of crops duration

Plant	Growth period	Number of days
Maize	May 5 – September 16	134
Winter wheat	April 1 – June 25	86
Spring barley	April 7 – June 25	79

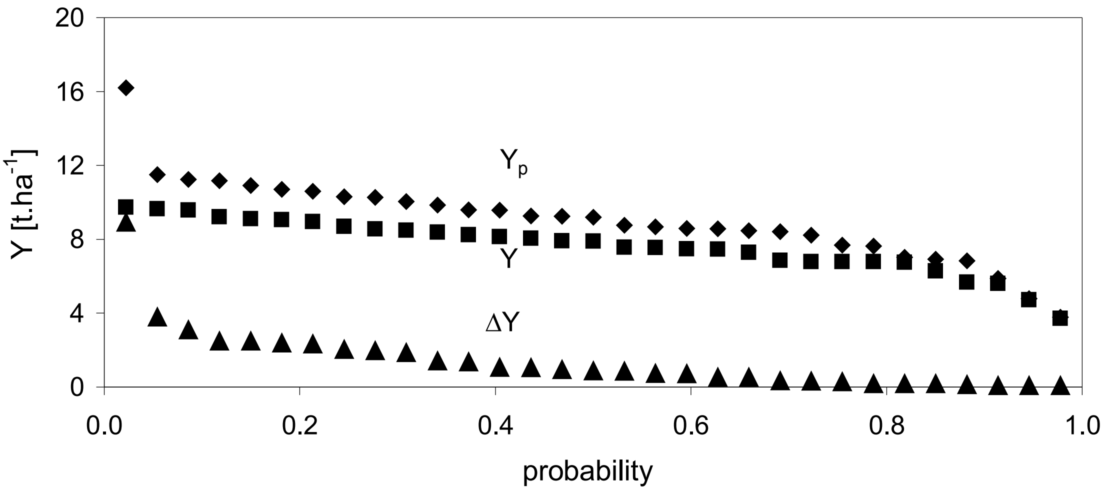

Fig. 4. Exceedance curves of the corn grain yield (Y), the calculated potential yield (Y_p), and their difference (ΔY), for the 1971-2000 and 2003 growing seasons at Most pri Bratislave, Slovakia

Results and discussion

Three types of plants (canopies) were chosen for analysis: maize, winter wheat and spring barley. Transpiration totals E_t were calculated retrospectively for 31 seasons (Fig.1). They are presented as empirical curves of exceedance for years 1971–2000 and 2003, the last was extraordinary hot. Length of vegetation periods of winter wheat and spring barley are close, but transpiration totals are quite different (Tab.3). Reasons are natural; meteorological conditions during their vegetation periods are different. Precipitation totals and air temperature are the most important factors. Winter wheat stage of ontogenesis during early part of spring vegetation period allowed quite different –higher - transpiration and growth rate.

Tab.3 presents characteristics of transpiration of the three canopies under study in season of years 1971 –2000 and 2003. Minimum transpiration totals were calculated for all the three canopies in year 1988, maximum transpiration totals were calculated for cereals in 1996, but yield of maize was the lowest (as well as transpiration total) in the season 1985. The reason of it was high precipitation total during the second part of the year 1996. It confirms quantitatively well known empirical information: particular vegetation period is of different suitability for different canopies.

Table 3. Transpiration characteristics of different canopies during their vegetation period. Average values were calculated for 31 seasons by modeling. (E_t is seasonal average transpiration total, E_{tp} is seasonal average potential transpiration total, $E_{t,d}$ is daily average transpiration total.

Canopy	**E_t** mm/year	**E_{tp}** mm/year	**E_t /E_{tp}**	**$E_{t,d}$** mm/year
Maize	144	161	0,88	1,07
Winter wheat	113	148	0,78	1,13
Spring barley	68,9	82	0,83	0,87

Empirical curve of exceedance of dry grain yields Y of maize canopy (1), winter wheat (2) and spring barley (3) during the seasons in seasons 1971- 2000 and 2003, Most pri Bratislave site is shown in Fig.3. Curves of exceedance in Fig. 3 were calculated using relationship presented in Fig. 2. This empirical relationship is relating weight of dry maize grains yield Y and transpiration totals of maize, during its vegetation period E_t. Relationship (Fig.2) represents 5 seasons within the time interval 1971-2000 and 2003. Such type of relationships were estimated using field data even for other two canopies (not shown here).

The optimal soil water regime for plant growth is, when soil water content is not limiting transpiration, i.e. when there is potential transpiration. Exceedance curves of the corn grain yield (Y) and the calculated potential yield (Y_p), and the difference (ΔY), for the 1971-2000 and 2003 growing seasons at Most pri Bratislave calculated from corresponding exceedance curve of potential transpiration totals E_{tp}, (Fig.4) demonstrates relatively low capacity of soil water regime optimization for the maize grain yield increase. The average maize grain yield (Y) was estimated to be 7.64 t ha^{-1}, and the average potential yield (Y_p) 9.03 t ha^{-1}. This means that the difference was ΔY =1.4 t ha^{-1}, which represents 18% of the average yield. The question now arises whether or not it would be reasonable (cost-effective) to design and operate an irrigation or drainage system that will optimize the soil water regime such that the dry grain yield increases by some of all of the 1.4 t ha^{-1}.

Conclusions

1. Mathematical model HYDRUS – ET with incorporated method of evapotranspiration and its components calculation using Penman– Monteith method modified by Budagovskij and Novák, was applied to calculate seasonal transpiration totals of three canopies (maize, spring barley and winter wheat) for 31 seasons in Southern Slovakia site. Empirical curves of exceedance of seasonal transpiration totals were designed.
2. Empirical curves of exceedance of grain yields of the three above mentioned canopies (maize, spring barley and winter wheat) were estimated, using empirical relationship between grain yield (Y) and seasonal transpiration totals (E_t) - Fig.2. Relatively homogeneous field of grain yields (as an exception is the season 2003) demonstrates favorable conditions of South Slovakia for growth of cereals without irrigation. Irrigation practice of course can increase yields.
3. Exceedance curves of the corn grain yield (Y), the calculated potential yield (Y_p), and the difference (ΔY), for the 1971-2000 and 2003 growing seasons at Most pri Bratislave calculated from corresponding exceedance curve of potential transpiration totals E_{tp}, (Fig.4) demonstrates relatively low capacity of soil water regime optimization for the maize grain yield increase. The average maize grain yield (Y) was estimated to be 7.64 t ha^{-1}, and the

average potential yield (Y_p) 9.03 t ha^{-1}. This means that the difference was ΔY =1.4 t ha^{-1}, which represents 18% of the average yield. It is a question of cost –expenses analysis whether or not it would be reasonable (cost-effective) to design and operate an irrigation or drainage system that will optimize the soil water regime such that the dry grain yield increases by some of all of the 1.4 t ha^{-1} difference. The decision to optimize soil water regime depends on situation on the world cereals market; but crop production efficiency by soil water regime optimization is becoming very actual, especially taking into account performing climate changes (Kutilek and Nielsen, 2010).

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