Lehr- und Forschungszentrum für Landwirtschaft
Raumberg-Gumpenstein

64. Tagung der Vereinigung der Pflanzenzüchter und Saatgutkaufleute Österreichs 2013, 35 - 41
ISBN: 978-3-902849-00-7

Impact of climate change on cereal growth and its potential yield

Jan Křen[1*], Lubomír Neudert[1], Petr Hlavinka[1], Petr Martinek[2] and Vladimír Smutný[1]

Abstract

Climate and weather are important factors which influence plant growth and development as well as yield quality and quantity. However, it is very difficult to assess the impact of climate on yield development in field crops, because a series of related positive and negative impacts have to be quantified and these are mutually interactive. An increase of CO_2 can stimulate the intensity of photosynthesis and thereby increase biological yield and economic profit. This 'fertilization effect' of CO_2, however, is dependent on the growth stage of a plant and other factors. With regard to yield formation, the indirect effects of increased temperature, in combination with precipitations and global radiation, are of crucial importance. The increased appearance of risk factors has a negative impact on the utilization of yield potential and production quality of crops. For the prediction of the impact of climate change on the yield of winter wheat and spring barley under Czech conditions the model CERES-wheat and CERES-barley were used. The results showed negative impacts of climate change on yield of cereals in the South Moravian plains, which are in contrast to the potential yield increase in the colder locations of the Czech-Moravian Highland which enjoy fertile, well-watered soils. As a consequence of the presumed impacts which might be obtained, adaptation possibilities available in breeding and crop management increasing utilization of cereal yield potential are discussed based on the genotype×environment×management interaction.

Keywords

Adaptation, cereals, genotype by environment by management interactions, yield potential

Introduction

In recent years, a number of research projects and scientific papers have been focused on climate change and its impacts on the global and regional levels (THOMAS et al. 2004, PARRY et al. 2007). In crop production, climate and weather are considered as important factors which influence plant growth and development as well as yield quantity and quality. However, it is very difficult to assess the impact of climate on yield development in field crops, because a series of related positive and negative impacts have to be quantified and these are mutually interactive. The negative impacts of climate change on crop production can be reduced by using adaptive measures that ensure the utilization of the potential yield of field crops under changing conditions (REYNOLDS 2010).

The main impacts of climate change on crop production are listed in *Table 1*. The negative (indirect) effects usually prevail over the positive (direct) ones. That has adverse impacts on the utilization of yield potential due to increased risk of: (i) availability of water (enlargement of dry areas), (ii) water and wind erosion, (iii) lodging of cereal stands, (iv) leaching of nutrients, especially NO_3^- ions, (v) ocurrence of pests and diseases, (vi) influence of terms of crop management measures. This has been reflected in increased variability of grain yields in recent years (*Figure 1*). This contribution is focused on the analysis of climate change effects on cereal grain yield formation and on the possibility of mitigating its negative impact through breeding and crop management.

Material and methods

To assess whether in terms of grain yield positive fertilization effect of CO_2 concentration prevail over the negative impact of increased temperatures and changes in other

Table 1: **The main impacts of climate change on weather, soil and plants**

Changes in	Positive	Negative
Weather	Increase in temperature in colder areas with higher level of moisture.	The increase in temperature combined with precipitation and global radiation cause increase in variability of meteorological elements associated with the occurrence of extreme events (reduction of snow cover, the occurrence of spring frosts, significant periods of drought, heat waves, torrential rains at the expense of drizzle, hails, etc.)
Soil	Increased anaerobic conditions in the topsoil change the dynamics of organic matter transformation in the soil.	Intensive salinisation and alkalinizing processes, crusting, compaction of the soil.
Plants	The increase in CO_2 concentration has a positive effect on the efficiency of photo synthesis and efficient use of water and nutrients (so called CO_2 fertilization effect).	Higher temperature affects evapotranspiration and phenological development of the crop (sum of effective temperatures), acceleration of development and shortening the growing season reduce yield. The increase in CO_2 concentration can increase the proportion of carbohydrate components of biomass.

[1] Department of Agrosystems and Bioclimatology, Faculty of Agronomy, Mendel University in Brno, Zemědělská 1, 613 00 BRNO, Czech Republic
[2] Agrotest Fyto, s.r.o., Havlíčkova 2787, 767 01 KROMĚŘÍŽ, Czech Republic
[*] Corresponding author: Jan KŘEN, kren@mendelu.cz

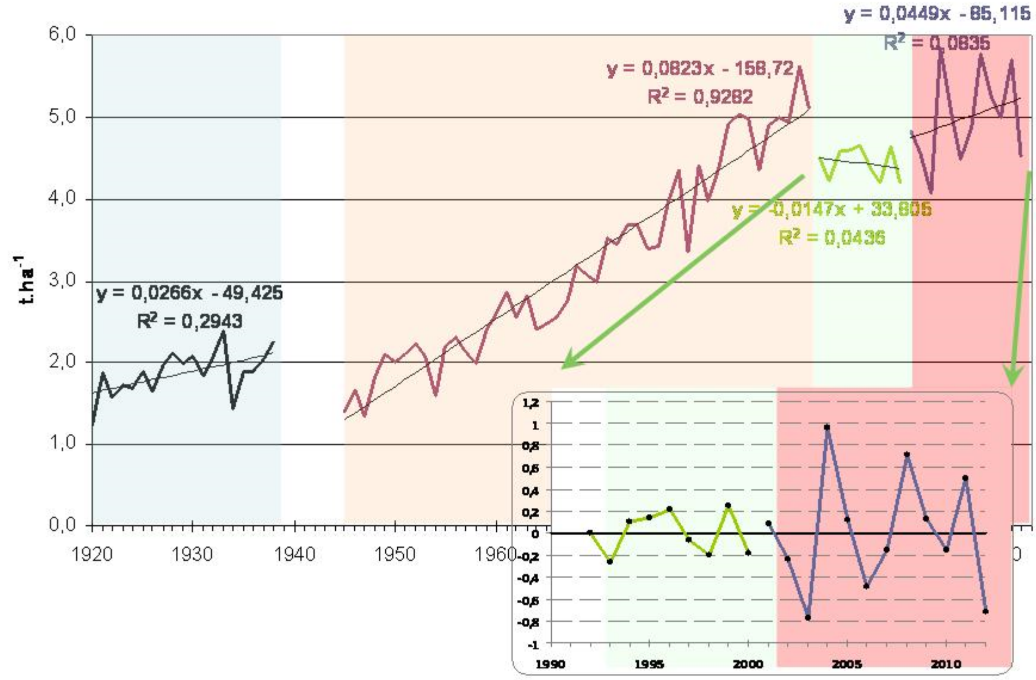

Figure 1: **Development of wheat yield (t.ha-1) in the Czech Republic**

meteorological elements the simulations of yield formation using growth models CERES-Wheat and CERES-Barley was performed. These models were parameterized for the current climate using the results of variety small plot field trials performed by the Central Institute for Supervising and Testing in Agriculture. Meteorological data was subsequently replaced by the outputs of the GCMs (Global Climate Models), which represent the expected climate. Evaluation methodology was described in detail in TRNKA et al. (2004a,b). Basic scenario parameters used for the evaluation of the employed circulation models are listed in *Table 2*.

Results and discussion

Simulation of climate change impact

Figure 2 presents the simulation results corresponding to the variation of emission SRES-A2 scenario and three GCMs (ECHAM - b, HadCM - c and VCAR - d) for winter wheat and spring barley. The maps show the differences between the yield levels in the period 1961-2000 (map a) and 2050 (maps b, c, d).

The performed analyses show: (i) deficit in the water balance in major agricultural regions with negative consequences in arid areas and some positive effects in wet areas in particular years, (ii) asymmetric impact of climate change in different regions, negative effect on yield in dry areas and positive one in areas with suboptimal temperatures, sufficient rainfall and fertile soil, (iii) significant link between the occurrence of drought and variability of yields at the local and national level.

Even if the simulation results obtained were in recent years partly confirmed by the differences of grain yields in agricultural practice (*Figure 3*), it should be emphasized that the model is a tool to recognize the context but provides a simplified picture of reality. Therefore the knowledge of yield formation processes, yield potential utilization and adaptation mechanisms is very important.

Fundamentals about yield formation

Yield potential is defined as the yield of a cultivar when grown in environments to which it is adapted, with non-limiting nutrients and water and with pests, diseases, weeds, lodging and other stresses effectively controlled (EVANS and FISCHER 1999). As such, it is distinguished from potential yield, which is defined as the maximum yield which could be reached by the crop in given environments, as determined, for example, by simulation models with plausible physiological and agronomic assumption.

REYNOLDS et al. (2011) proposed a conceptual platform for the synergistic combination of traits as a model for increasing the yield potential (*Table 3*). Of the listed traits, the

Table 2: **Basic parameters used for the evaluation of models CERES-Wheat and CERES-Barley and for yield simulation**

Characteristic	Source of information
Varieties	winter wheat 'Hana'; spring barley'Akcent'
Locations	7 test sites, representing Czech soil-climatic conditions
Soil database	pedological soil survey (394 soil pits)
Climate database	1961-2000; 125 Czech meteorological stations
Arable land database	Corine Land Cover (CLC2000) 100 m, Vers. 8/2005 (EEA, 2005)
Emission scenario	SRES A2 (with a more rapid increase in greenhouse gases)
Global circulation models	ECHAM, HadCM and NCAR
Grid vector network	500×500 m
CO_2 conc. initial period	350 ppm
Simulation	Potential yield (excl. negative impact of diseases and pests)
Software	ArcGIS using polygon layer of soil types

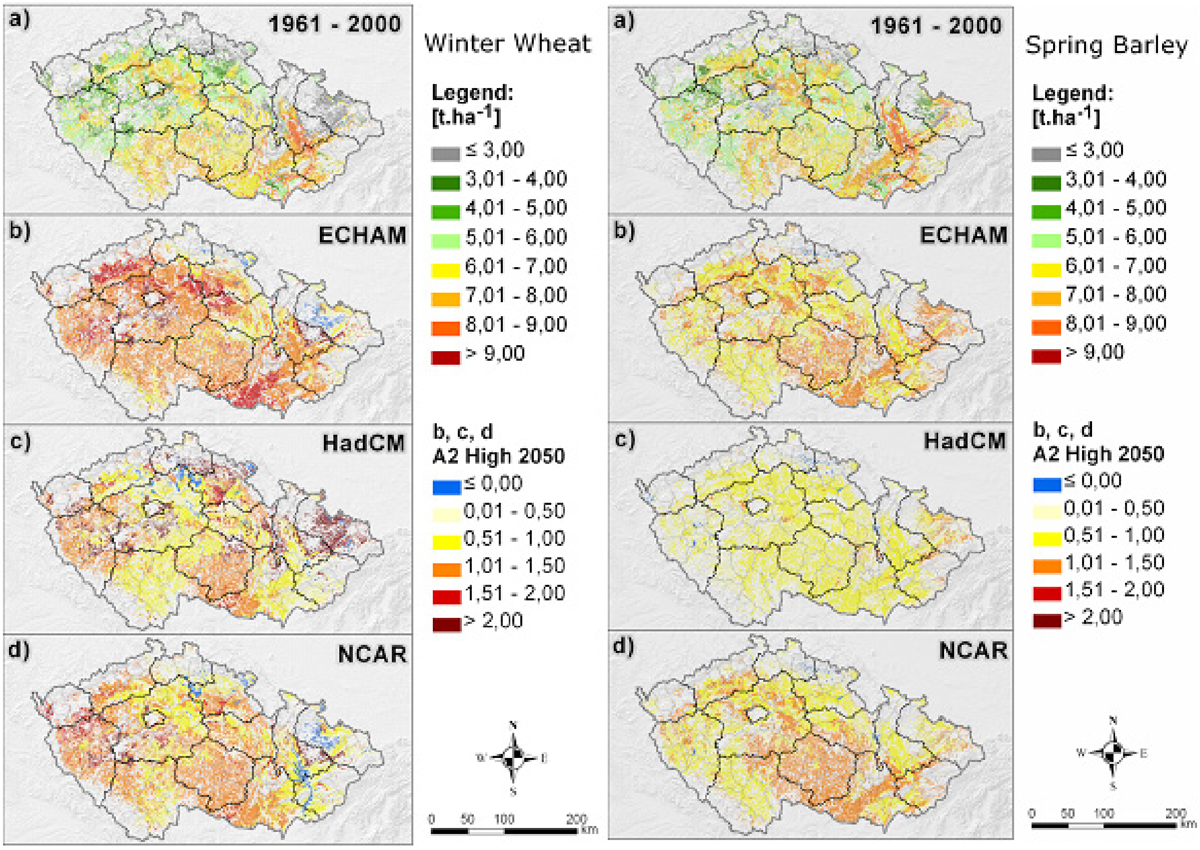

Figure 2: **Potential yield (t.ha^{-1}) of winter wheat (left) and spring barley (right) in the Czech Republic for the climatic conditions in 1961-2000 (a) and the difference between this yield level and the simulated yields for 2050 according to the emission SRES-A2 variant and three global circulation models of climate change (b: ECHAM; c: HadCM; d: VCAR).** The median of 99 simulation results for grid on arable land is depicted (ŽALUD 2009).

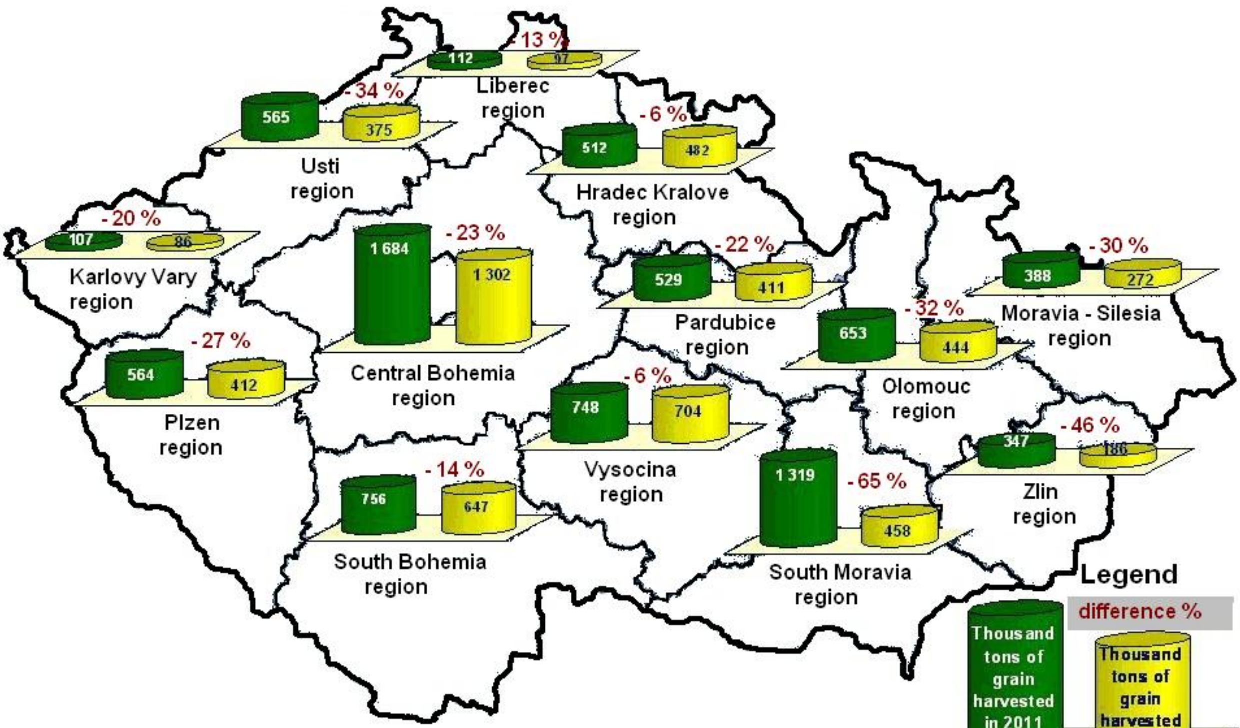

Figure 3: **Comparison of cereal production (×1000 t; 2012 vs. 2011) in individual regions of the Czech Republic**

Table 3: **Model of yield potential traits - a conceptual platform for combination of synergistic traits (REYNOLDS et al. 2011)**

Sink	Source
Pre grain filling	
Increase partitioning to developing spike	Light interception
Reduce floret abortion	Radiation use efficiency (RUE)
Optimize phenological pattern	Rubisco
Lodging resistance	C4 type traits
Grain filling	
Partitioning to grain (Rht)	Canopy photosynthesis
Spike capacity	Cellular (e.g. heat tolerance)
Abort weak tillers	Light distribution
Adequate roots for resource capture	N distribution/partitioning
	Spike photosynthesis

following are important for adaptation to climate change: (a) in the source: light interception, canopy photosynthesis, heat tolerance, (b) in the sink: abort weak tillers, floret abortion, roots for resource capture, phenological pattern and lodging.

The use of vegetation and production factors and biological potential of varieties is conditioned by activities of both breeders and growers of field crops. The aim of breeders should be to create varieties with high and stable yields and required grain quality. The aim of growers is to utilize such biological potential. Stability of grain yield and quality is achieved by the breeder through homeostasis of a variety and by the grower through ensuring stability of the environment, i.e. the modification of farming practices, and optimization of crop management. The role of breeding and crop management in utilization of the potential yield can be explained based on the interaction of G×E×M (*Figure 4*), where *G* is the variety and its biological potential, *E* the environmental components not influenced or partly influenced by the grower (E_S, soil and climatic conditions of the site; E_W, weather; E_E, prices of inputs and outputs), and *M* the environmental components influenced by the grower (crop management as a set of measures used during the growing season and modified according to the requirements of variety, site conditions, course of weather, intensity of farming, way of production use, prices of inputs and outputs, etc.).

Optimization of the system (harmonization of all components based on their importance and functions) should be directed to: (i) maximum biological potential of yield and production quality utilization, (ii) maximum profitability of inputs, (iii) reduction of the negative impacts of farming on the environment. In practice it means the choice of the proper crop variety and decision about consecutive crop management measures that should be performed in the right place, at the right time, and at the right intensity.

The roles of individual components of the system in yield creation are shown in *Figure 5*. The graph shows that the utilized level of the variety yield potential (*G*) is limited by uncontrollable environmental components (*E*). Crop management practices (*M*) should eliminate the negative effects of environmental components by the realization of potential yield, the level of which is in ideal conditions identical with yield potential.

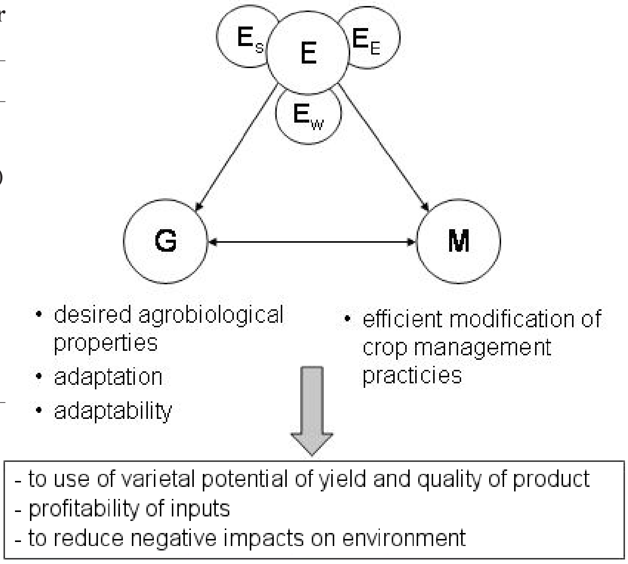

Figure 4: **Genotype by environment by management interaction (G×E×M)**

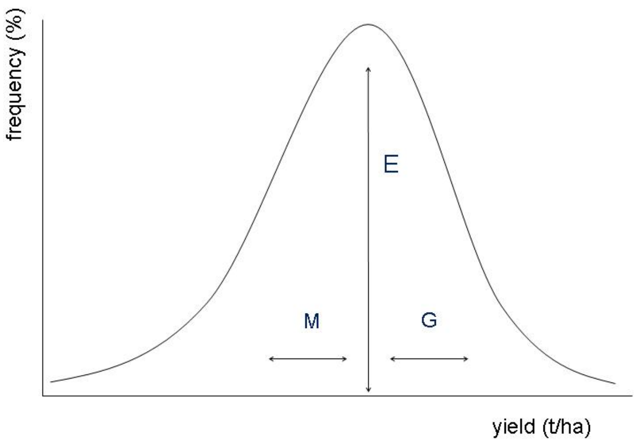

Figure 5: **The role of individual components of the interaction G×E×M**

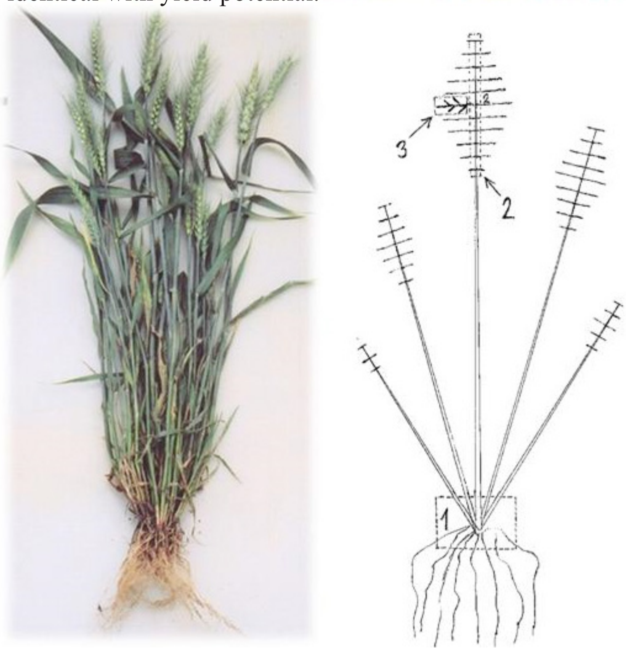

Figure 6: **The modular structure of cereal plant (wheat) and its hierarchical organization**

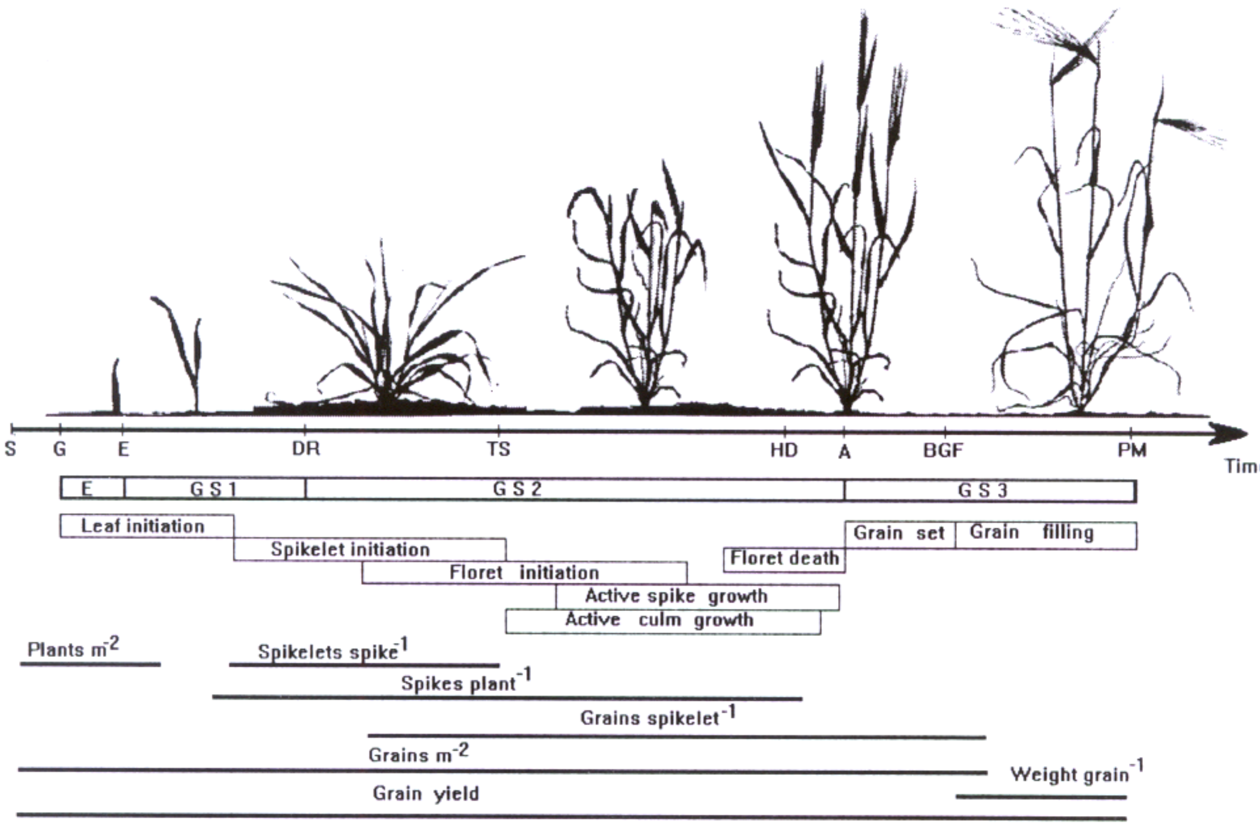

Figure 7: **The course of cereal plant growth (ACEVEDO et al. 2002)**

Climate change increases the role of environment (*E*) in this system, i.e. increases the importance of uncontrollable environmental factors and thus the risk of negative effects (damage of crop stands, lower effectiveness of cropping measures). The knowledge of adaptation to the negative impacts of climate change is therefore of great importance.

Adaptability and formation of yield elements

Grasses in general, and thus the cereals own high level of adaptability due to their modular structure (ARBER 1941, WHITE 1979, PORTER 1983a,b). Classic wheat morphotype (*Figure 6*) responds to changes of environment (ability of resources) using few (three) levels of branching (hierarchical structures - tillers in tillering node, spikelets in the spike, grains in the spikelets) and grain filling. These metameric organs (*Figure 7*) allow plants to respond to environmental changes during their growth and development (ACEVEDO et al. 2002). Hierarchical organisation of plants (NICOLIS et al. 1977) ensures their reproduction even in unfavourable conditions (MIRALLES and SLAFER 2007), when increase of apical dominance and inter-and intra-plant competition and decrease of crop yield occur. On the other hand, high yield in favourable conditions is associated with the decrease of apical dominance and competition in the stand. Thus, adaptability relies on the formation, growth, and reduction of metameric organs used by plants to respond to environmental changes (MASLE-MEYNARD and SEBILLOTTE 1981a,b, REYNOLDS et al. 2005). Cereal plants can thus be investigated as developing modular systems and their growth can be described analogously to the processes of population type, and source×sink theory can be used to explain the regulation processes at plant level (KREN et al. 1992, KŘEN 2012).

Adaptation possibilities

Basic possibilities of adaptation to the negative impacts of climate change and their mitigation during the grain yield formation are shown in *Table 4*.

Breeding

Breeding for higher grain yield resulted in changes of plant proportions, stand architecture (stand density increases) and extended duration of the canopy assimilation (AUSTIN et al. 1980). A significant increase in yield potential has been associated with the achievement of a number of physiological and morphological changes in plants. The consequence was a significant increase in grain weight in spike and shortening of straw (increased harvest index value). These improved the resistance to lodging and increased the number of ears per unit area. Since the mid-1990s, the upward trend in yields and production has begun to slow mainly due to environmental and energy limits. The trend in decreasing yield stability and a gradual slowing down or stopping shortening of straw in new varieties has also been observed. Further shortening of the stem is genetically feasible, but currently it is constrained by ecological limits (FOULKES et al. 2011).

It is also becoming apparent that a higher yield can be achieved more easily when formed by a higher proportion

Table 4: **The main issues to be addressed in climate change by utilization of cereal yield potential**

Issue	Mitigation strategy	
	Breeding	Crop management
Drought	Earliness Optimize phenological pattern Large root system	Choice of crop Suitable previous crops Minimum soil tillage Early sowing Nitrogen application
Frosts without snow	Frost resistance	Time of sowing Growth regulators Balanced crop nutrition
Increased frequency of extreme weather	Adaptability Lodging resistance Resistance to diseases and pests	Application of fertilizers, growth regulators and pesticides Timely modification of cropping measures

of the polysaccharide (starch) components of grains and a lower proportion of the protein component. This is probably related to the amount of metabolic energy that the plant needs for the synthesis of a unit amount of protein and starch, and this difference may enhance the increase in the concentration of CO_2 in the atmosphere in the future (NÁTR 2000).

Cereal varieties should have the following properties that allow adaptation and mitigation of the negative impacts of climate change:

- lower transpiration coefficient, more powerful and deeper root system or faster growth and earlier ripening,
- resistance to frost and low temperatures in winter and during regeneration periods,
- resistance to drought in the tillering-earing stage,
- lower level of inter- and intra-plant competition,
- resistance to lodging (stem length is probably ecologically limited),
- resistance to selected biotic harmful agents,
- adaptability to climatic extremes (probably negatively correlated with the increase of harvest index and potential yield).

Cereal growers should take the above properties into consideration during decisions making concerning varieties and varieties assortment. It should be noted that varieties performing all these requirements are hard to find, and if they do, unfortunately they usually provide low but stable yields (universal organism usually shows average performance).

Crop management

Decision making about cropping measures is a crucial farming activity. Farmers spend most of the working time with implementation of crop management practices. The basic problem, which has to be solved, is the balance of production factors in space and time, i.e. making them available to the needs of developing crops while controlling crop structure according to their levels. In doing so, growers face a number of agronomic, economic and administrative problems:

- implementation of crop measures in right agrotechnical terms, according to the needs of stands depending on the weather,
- achieving good prices of inputs and output,
- compliance with all accounting and administrative requirements.

From this point of view the crop management practices feature economically implemented agronomic knowledge in mostly uncontrolled environments. Impacts of climate change affect terms and methods of crop management practices and result in their efficiency and in the level of yield potential utilization.

From the view of the above considerations about the grain yield formation and of the increasing importance of *E* in the G×E×M system (as a result of climate change), it would be useful to create varietal crop management practices. This is complicated by difficult orientation of growers in numerous registered varieties and in their various properties. On the other hand, it is worth highlighting the stagnation of the rising trend in the potential yield of new varieties in small plot field experiments and in practice (AHLEMEYER and FRIEDT 2012). Therefore, the concept based on the optimization of all three components of G×E×M interaction, in particular of the links between G×E (choice adaptable varieties) and E×M (cropping measures modified according to the weather course), seems to be promising.

Crop management practices should be implemented as a coherent set of optimized cropping measures for specific site conditions and for a certain way of using the produced grain. It is important to:

- determine the economically efficient intensity of growing dependent on the changing prices of seeds, agrochemicals, agricultural machinery and production;
- be flexible in diagnosing the state of crop stand and subsequent modification of cropping measures according to weather changes (adaptability).

It should be noted that with the increasing importance of uncontrollable environmental components (*E*) as a result of climate change high intensification is economically and ecologically risky. This situation can be solved by the establishing and improving the early warning systems (e.g. agrometeorological monitoring).

Conclusions

We can assume that breeding and growing of field crops always include the endeavour to eliminate the impact of climatic and weather conditions on soil and growth processes. The utilization of yield potential of cereal cultivars under the conditions of changing climate requires both the grown cultivars and the growers' activities to be more adaptable.

Successful implementation of this approach in practice requires broad knowledge and experience including the need to solve often opposed biological or agronomic and economic requirements.

Acknowledgement

This study was supported by the Ministry of Agriculture of the Czech Republic, projects No. QI111A133 and QJ1310055.

References

ACEVEDO E, SILVA P, SILVA H, 2002: Wheat growth and physiology. In: CURTIS BC, RAJARAM S, GOMEZ MACPHERSON H (eds.), Bread wheat improvement and production. FAO Plant Production and Protection Series 30. Food and Agriculture Organization of the United Nations, Rome, Italy.

AHLEMEYER J, FRIEDT W, 2012: Winterweizenerträge in Deutschland stabil auf hohem Niveau. Welchen Einfluss hat der Züchtungsfortschritt? Getreide Magazin 6/2012, 38-41.

ARBER A, 1941: The interpretation of leaf and root in the angiosperms. Biol Rev 16, 81-103.

AUSTIN RB, BINGHAM J, BLACKWELL RD, EVANS LT, FORD MA, MORGAN CL, TAYLOR M, 1980: Genetic improvements in winter wheat yields since 1900 and associated physiological changes. J Agric Sci 94, 675-689.

EEA, 2005: Corine land cover 2000 (CLC2000) 100 m - version 8/2005. European Environment Agency, Copenhagen, Denmark. [http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2000-clc2000-100-m-version-8-2005]

EVANS LT, FISCHER RA, 1999: Yield potential: Its definition, measurement, and significance. Crop Sci 39, 1544-1551.

FOULKES MJ, SLAFER GA, DAVIES WJ, BERRY PM, SYLVESTER-BRADLEY R, MARTRE P, CALDERINI DF, GRIFFITHS S, REYNOLDS MP, 2011: Raising yield potential of wheat. III. Optimizing partitioning to grain while maintaining lodging resistance. J Exp Bot 62, 469-486.

KREN J, VAN KEULEN H, GRASHOFF C, 1992: Grain growth in oats: experimentation and modeling. Research report, Centre for Agrobiological Research (CABO-DLO), Wageningen, The Netherlands.

KŘEN J, 2012: Assessment of cereal stand structure and its changes during the growing season. Acta Univ Agric Silv Mendel Brun 40, 243-249.

MASLE-MEYNARD J, SEBILLOTTE M, 1981a : Etude de l'hétérogénéité d'un peuplement de blé d'hiver. I. Notion de structure du peuplement. Agronomie 1, 207-215.

MASLE-MEYNARD J, SEBILLOTTE M, 1981b: Etude de l'hétérogénéité d'un peuplement de blé d'hiver. II. Origine des différentes categories d'individus du peuplement: éléments de description de se structure. Agronomie 1, 216-224.

MIRALLES DJ, SLAFER GA, 2007: Sink limitations to yield in wheat: how could it be reduced? J Agric Sci 145, 139-149.

NÁTR L, 2000: Koncentrace CO_2 a rostliny. ISV Publishing House, Praha, Czech Republic, 257 pp.

NICOLIS JS, PROTONATORIOS EN, VOULODEMOV I, 1977: Control Markov chain models for biological hierarchies. J Theor Biol 68, 563-581.

PARRY ML, CANZIANI OF, PALUTIKOF JP, VAN DER LINDEN PJ, HANSON CE (eds), 2007: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, pp. 541-580.

PORTER JR, 1983a: A modular approach to analysis of plant growth. I. Theory and principles. New Phytol 94, 183-190.

PORTER JR, 1983b: A modular approach to analysis of plant growth. II. Methods and results. New Phytol 94, 91-200.

REYNOLDS M P, PELLEGRINESHI A, SKOVMAND B, 2005: Sink-limitation to yield and biomass: a summary of some investigations in spring wheat. Ann Appl Biol 146, 39-49.

REYNOLDS MP, 2010: Climate change and crop production. CABI Climate Change Series, Vol. 1. CABI, Wallingford, UK.

REYNOLDS MP, BONNETT D, CHAPMAN SC, FURBANK RT, MANES Y, MATER DE, PARRY MAJ, 2011: Raising yield potential of wheat. I. Overview of a consortium approach and breeding strategies. J Exp Bot 62, 439-452.

THOMAS CD, CAMERON A, GREEN RE, BAKKENES M, BEAUMONT LJ, COLLINGHAM YC, ERASMUS BFN, FEREIRA DE SIGUEIRA M, GRAINGER A, HANNAH L, HUGHES L, HUNTLEY B, VAN JAARSVELD AS, MIDGLEY GF, MILES L, ORTEGA-HUERTA MA, TOWNSEND PETERSON A, PHILLIPS OL, WILLIAMS SE, 2004: Extinction risk from climate change. Nature 427, 145-148.

TRNKA M, DOBROVSKÝ M, SEMERÁDOVÁ D, ŽALUD Z, 2004a: Projection of uncertanities in climate change scenarios into expected winter wheat yields. Theor Appl Climatol 77, 229-249.

TRNKA M, DOBROVSKÝ M, ŽALUD Z, 2004b: Climate change impact and adaptation strategies in spring barley production in the Czech Republic. Climate Change 64, 227-255.

WHITE J, 1979: The plant as a metapopulation. Ann Rev Ecol Syst 10, 109-145.

ŽALUD Z (ed.), 2009: Změna klimatu a české zemědělství - dopady a adaptace. Folia Univ Agric Silv Mendel Brun 2 (10), 155 pp.