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ASSESSMENT OF CEREAL STAND STRUCTURE AND ITS CHANGES DURING THE GROWING SEASON

J. Křen

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Abstract

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Historical evolution of approaches used for the assessment of the cereal stand structure development is presented. Weaknesses and strengths of these approaches are discussed that are based on:
- dividing of cereal yield into yield components and growth analysis,
- modular concept of plant growth,
- use of laws of plant population biology in order to explain autoregulation and compensation in stands.

The presented methods are assessed with respect to labour intensity and possibilities of utilization of obtained information. Other possibilities of diagnostics of the cereal stand state and structure using a current level of knowledge and new technologies enabling to determine spectral characteristics of the stand by areal sensing are outlined. Based on the character of processes influencing the stand structure, the growing season of cereals was divided into the three parts:
1. vegetative, including the period from emergence till the end of tillering (BBCH 10-29),
2. generative, including the period of stem elongation and heading (BBCH 30-59),
3. reproductive, including anthesis, grain formation and maturation (BBCH 60-99).

To optimize the stand structure, data necessary for decision making in cereal crop management practices were proposed for the above listed development stages.

cereals, stand structure development, inter- and intra-plant competition, compensation and autoregulation, possibilities of stand structure assessment

Cereals are economically the most important group of field crops. In the Czech Republic and European countries with advanced agriculture, the largest areas are planted with winter wheat (*Triticum aestivum* L.) and spring barley (*Hordeum vulgare* L.). Detailed knowledge of stand structure and its development including interrelationships among individual plants in the stand (inter- and intra-plant competition) is a significant precondition for effective cropping treatments during the growing season, including agrochemicals application.

To attain higher effectiveness of crop management practices, extensive research on cereal stand structure was conducted in the 1980s and 1990s (Masle-Meynard and Sebillotte, 1981a,b; Porter, 1984; Křen, 1990b,c). The stand state and structure reflect variability in soil and weather conditions as well as cropping treatments. Results of individual methods used for modification of cropping treatments depend on a level of stand organization which is observed – a stand (plant population), plant, plant part (leaf, tiller) (Křen *et al.*, 2007).

Stems and spikes are the most often assessed units of stand structure as for final and resulting expression of all factors affecting stand development. However, they are also reproductive units and basic units of an important cereal adaptation system – tillering (Muravjev, 1973). Therefore, their appropriate assessment allows obtaining information of great biological and economic importance.

The article gives a review of historical evolution of approaches used for the assessment of cereal stand structure. Weaknesses and strengths of these approaches are discussed that are based on:

- dividing of cereal yield into yield components and growth analysis,
- modular concept of plant growth,
- use of laws of plant population biology in order to explain autoregulation and compensation in stands.

Approaches based on dividing of cereal yield and growth analysis

The growth in biology is usually described by observing temporal development of average measurement values. Similarly, for analyses of yield formation a number of formed and reduced yield elements per unit area (tillers, reproductive organs and grains) is observed and their average values are determined (Fig. 1).

The assessment of cereal stands and yield formation is usually based on the classical concept as reported by Heuser (1927/28) and later on by a number of other authors who divided grain yield into spike number per unit area, grain number per spike and grain weight (1000-grain weight). Geometric interpretation of this concept was developed by Grafius (1956). Foltýn and Škorpík (1973) already used complex schemes of yield composed of binomes hierarchically ordered.

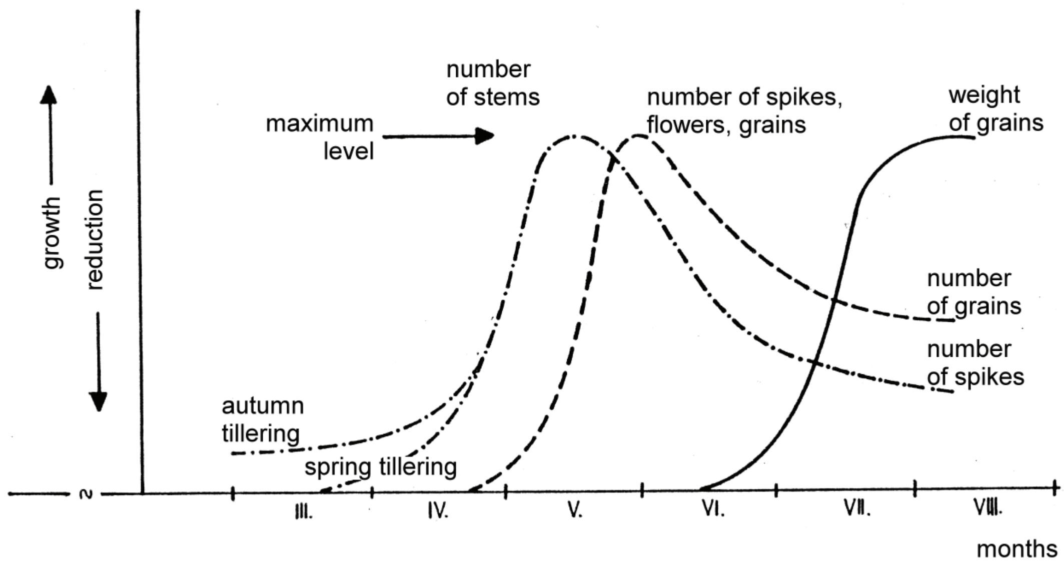
At present, this concept based on the plant number and numbers of formed and reduced tillers per stand unit area prevails in both applied research and practice. It uses advantages of plant as well as stand description on the basis of changes in the tiller number when no destructive analyses and higher labour intensity are needed. Recently, however, the concept has been often criticized because it does not provide enough precise quantification of differences in stands. Hunt (1978) drew an attention to changes in the number and size of plant parts (modules) during plant growth and development. In winter wheat, the identical grain yield can be produced in the Czech conditions at the range from 250 to 550 plants and from 550 to 800 spikes per m^2 (Vlach and Křen, 1983). Therefore, some authors expressed a need of available innovated criteria for stand assessment (Petr *et al.*, 1983b).

Major inaccuracies can occur when selecting a representative sample similarly to other methods used to characterize fields and stands based on sampling. Petr *et al.* (1983b) give a coefficient of variation for the number of productive stems per m^2 of stand at heading from 29.0 to 45.5%. The authors concluded that for accurate characterization of a 10-ha field (at P = 0.05) 52 to 89 productive stems counts from the area of $0.25\,m^2$ are needed. This is the significant limitation of such a method use in both research and practice.

It is evident that the procedures based on the growth analysis are rather labour intensive; their simplification for practical use results in lower accuracy and does not allow to record spatial heterogeneity of the stand.

Plant modular growth and population concept of stem system of the stand

Dividing of yield into individual yield components (Heuser, 1927/28) allowed cereal research and practice to get closer to so-called modular concept of plant and plant growth demographical analyses (Watkinson and White, 1985). The term module was first used by Harper and White (1974) in a study on plant demography. It is usually defined as a monopodial axis terminated by inflorescence or parenchymatic apical meristems. As indicated by



1: *Schematic illustration of dynamics of yield elements formation and reduction in tillering cereals through the growing season (Petr et al., 1983a)*

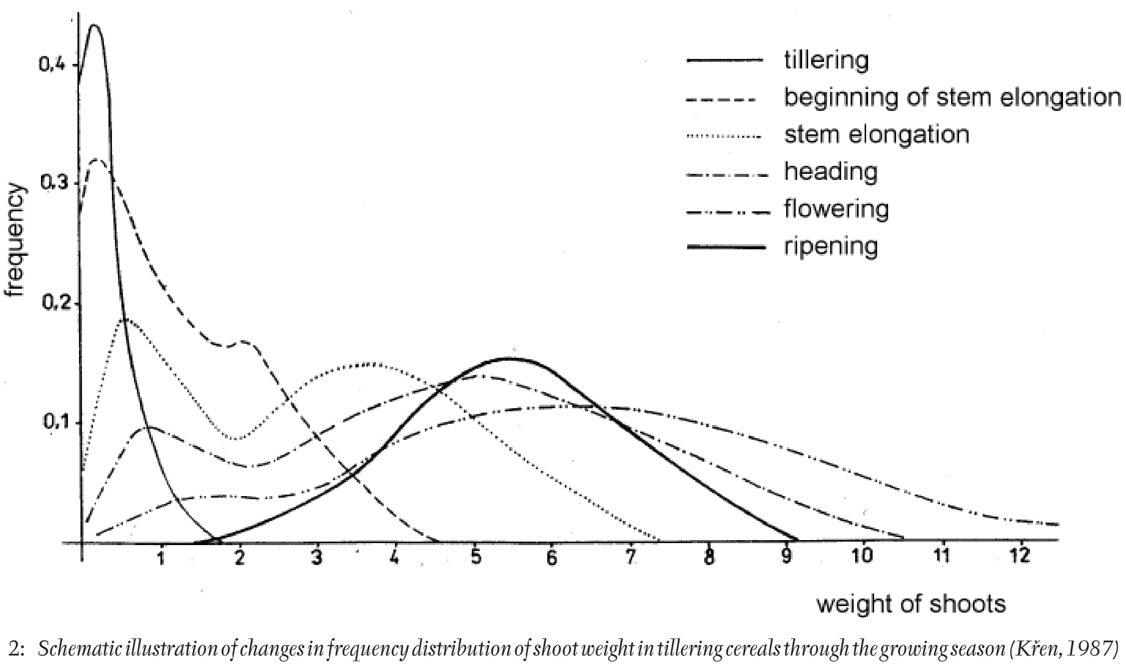
White (1979), examined units are tillers (modules) rather than entire plants in most studies on cereals.

White (1979) and Porter (1983a,b) report that plants can be studied as developing modular systems and their growth can be described similarly to processes of population type. In accordance with these authors, the validity of laws of population biology for autonomous units (modules), for stems (Křen, 1990a) as well as grains (Křen *et al.*, 1992), has been proved.

The growth and development of cereal plants consist of a number of growth and development stages of modules (leaves, shoots, stems and grains) that ovelap one another. Therefore, the growth and development of individual leaves and shoots are more determined than those of entire plant. The growth of entire plant does not stop unless the growth and development of the last module is finished, whereas the first formed modules finished their growth and development earlier. The size and properties of leaves and stems in the stand depend not only on their position on the plant, however, on the position of plants in the stand, i.e. on micro-conditions influencing the growth of individual plants (Křen, 1990b). Thus, in cereal stands the variability of site conditions is reflected in changes of inter- and intra-plant relationships, which is expressed by changes in variability of plant modular parts (Křen, 1990c).

This concept enables to explain compensatory and autoregulatory processes in cereal stands by modification of both the number and size of plant parts. The stand structure can be described by density distribution (histogram, polygon) of their weight. The density distribution in tiller and stem weight dynamically changes during the growing season (Fig. 2). At the beginning of tillering (BBCH 21-25), it corresponds to log-normal distribution. Stem growth and tiller differentiation are expressed by increasing the frequency of higher weight categories. The polygon is shaped as a bimodal curve whose left part is residue of log-normal distribution (vegetative tillers) and right part indicates rising near-normal distribution of productive stems. The bimodal curve characterizes the structure development (stand organization) over the whole generative period of growth (BBCH 30-61). Withering away non-productive tillers results in dissolving the left peak and the right part becomes robust due to intensive growth of surviving stems. The frequency polygon reaches a definitive shape of distribution, near to normal, not before terminating the stand organization at anthesis (BBCH 61).

At anthesis, stem weight can be considered as valuable information that indirectly indicates both a reproductive value and spike productivity born by the stem. Connections between the growth and assimilate accumulation and realization of wheat reproduction organs are referred by Nátrová (1981). Rawson and Evans (1971) report a close linear correlation (r = 0.94) between stem weight at heading and final grain number per spike. Likewise, in our earlier study (Křen and Vlach, 1984) focused on the verification of these relationship we found a highly significant linear correlation between stem weight and a number of embryos after anthesis (r = 0.91 – 0.94). The proportion of stem weight per embryo was characteristic of low variation (CV = 12.40 – 15.63 %) and cultivar specificity. It can be assumed that the stem weight belonging on an embryo can be considered as a basic factor determining the grain number per spike (Křen and Vlach, 1984).



2: *Schematic illustration of changes in frequency distribution of shoot weight in tillering cereals through the growing season (Křen, 1987)*

The above mentioned facts suggest that the amount of aboveground biomass at anthesis (BBCH 65) is critical for yield formation. It can be attained by different ways, a large number of weak stems with small spikes or, conversely, a lower number of strong stems with big spikes. Therefore, for effective stand management of small-grain cereals it is important to assess the amount of biomass of productive stems per stand unit area or proportion of this "productive" biomass of the total amount of aboveground biomass.

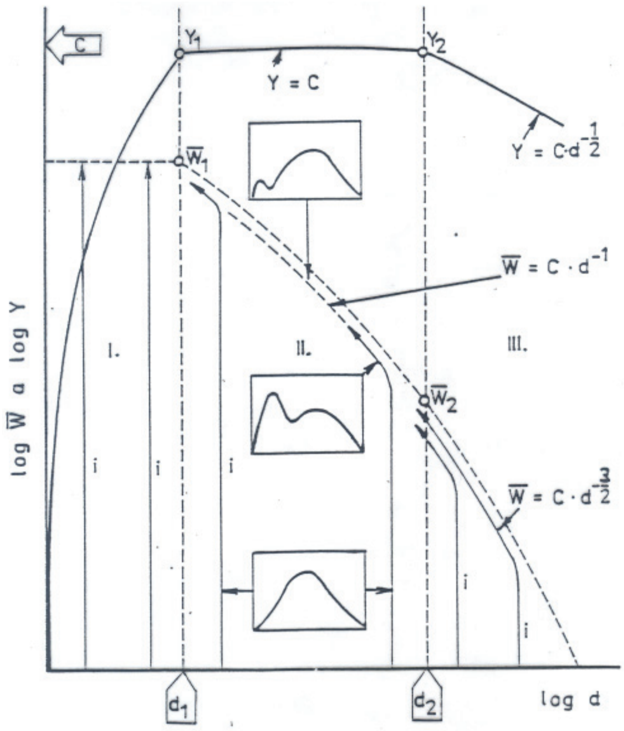
Autoregulation and compensation in the stand

The organization and micro-conditions of individual plants in the stand considerably affect their performance. However, they are of relatively less importance for determination of yield per unit area (Mack and Harper, 1977). They considerably influence the yield beyond the limits of genotype autoregulation ability. Consequently, the stand is usually interpreted as plants growing per unit area rather than individuals assembled in the population, and their interrelationships are most frequently measured as an average or average reaction (e.g. De Wit, 1960).

However, some authors have earlier referred to relationships between the average and other statistical parameters – variance and skewness (Koyama and Kira, 1956; Malet, 1979). Křen (1990b,c) documented that these parameters enabled to evaluate intra-plant relations. Errors in evaluating the stand associated with autoregulation can be eliminated by variability analyses when the tiller number, individual tillers weight and total weight of aboveground biomass per unit area are determined. So, the results can be affected mostly by heterogeneity of soil conditions or non-uniform cropping treatments.

The canopy closure can be established both through an increased number of stems and their increased size (weight). Stand productivity, as a result of compensatory and autoregulatory processes, depends on total productive stem weight per unit area and is limited by site productivity (carrying capacity that represents a summary of all sources which are available to plants in given space and time).

The rules of stand autoregulation in relation to site productivity are illustrated in Fig. 3. The equations show dependence of the yield (Y) and average plant weight (W) on stand density (plant number per unit area). The bottom-up arrows (i) show plant growth at various initial densities on a horizontal axis. The polygons in boxes illustrate



3: *Schematic illustration of relationships during the plant growth in monoculture, elaborated according to Slavíková (1986) and Křen (1987). More detailed explanation is given in chapter Autoregulation and compensation in the stand.*
$\overline{w}$ – average plant size in stand (dashed line),
Y – population biomass weight – yield (solid line),
d – population density (plant number per stand unit area),
axis x = log d, axis y = log $\overline{w}$ or log Y

a character of weight distribution for individual plants (or stems) in the stand. A vertical course of the arrows shows the increase in biomass by different initial population density. Left curving part of arrow means that further plant growth continues to the prejudice of population density, i.e. self-thinning takes place due to competition. The interval of small densities, in which the plant growth is not affected by competition, is designated region I. At these densities, final weight of average plant is determined above all by specific and varietal properties and site conditions. In region II so-called law of "final constant yield" holds (Koyama and Kira, 1956), i.e. total biomass per unit area (yield) does not depend on plant density and average plant weight is indirectly proportional to plant density. It means that the competition within the interval of these densities is much lower than at high densities causing extensive stand self-thinning. Total biomass per unit area (yield) equals the value of site carrying capacity (C). Region III comprises high densities when self-thinning takes place. So-called "ecological law −3/2" is valid (Yoda *et al.*, 1963). At the growth of a dense plant population, strong self-thinning comes already at the beginning of the growing season. The increase in biomass of an average plant and mortality are partly compensated for between each other, therefore, total biomass of the population can increase with decreasing density of individuals per unit area.

The scheme in Fig. 3 shows that the identical yield of aboveground biomass can be obtained by lower plant density and a longer period of their growth or vice versa. This logically results in mutual compensation of plant density and size. At the interval of force of the law of final constant yield, the relationship between a plant density logarithm and a logarithm of their average weight can be always characterized by linear regression function with a value of regression coefficient $b = -1$. The distance of the line from the coordinate origin is given by the site carrying capacity (C). In practice it means that at the formation of biomass amount corresponding to site carrying capacity self-thinning takes place during the further growth.

Changes in the number and size of shoots in cereal stand during the growing season are analogical to changes in natural plant populations and can be illustrated using frequency curves (Fig. 3 – polygons in boxes). A large potential number of shoots capable to reproduce are formed by tillering. This amount, however, reduces to a final spike number, which usually corresponds to 1/2 to 1/4 of the tiller number at the beginning of stem elongation (BBCH 31), by the period of anthesis (BBCH 61), when the organization of stand structure is finished.

The presented rules reveal that the stand structure is always a result of a response of the plant population to site conditions. Their good knowledge should be a basis for assessment of stand structure, which will enable more effective utilisation of vegetation factors of the location, cropping treatments and properties of varieties.

From this point of view, the development of root system is of a great significance. Strong root system is important for nutrients and water uptake, and leads directly to increasing the site carrying capacity. By the lower density of plants, they form more tillers and more roots. The rooted tillers exhibit better tolerance to unfavourable conditions. It leads to a general conclusion that to ensure high yield it is necessary to obtain as high number of productive stems and their biomass amount as possible by as the lowest plant number per unit area as possible. These are requirements for optimum development of plants in the stand and canopy closure. However, this general standpoint can be hardly implemented in practice since a large number of factors influencing the plant growth and development are impossible to control completely. Growers should take into consideration that the site productivity and duration of the growing season do not exhibit stable values that would enable to determine exactly sowing time, appropriate seeding rate and stand development during the vegetation. In particular cases, ability of knowing how to respond to the weather course in individual years using a way of stand establishment and consecutive cropping treatments is important. Thus, effective methods for the assessment of the stand during the growing season can be a valuable tool for farmers.

Possibilities of innovations in stand structure assessment

The stand structure depends on:

- initial plant number,
- available sources and their change during the growing season.

The value of obtained information should be adequate to consumed labour. In this respect, a sample size is of great importance. In general, it governs that with the increasing size and number of samples the exactness of results increases, however, labour intensity is also higher. The two problems (labour intensity as well as the value of obtained information) are to be solved, i.e. what information is provided by plant and stem analysis and how to use it.

Classical methods for the assessment of stand structure based on counting plants and stems (spikes) per unit area of the stand are labour consuming and interpretation of results is often difficult. They provide information on plant and stem numbers and/or their size (weight), however, they do not allow assessing the relationships in the stand (inter- and intra-plant competition).

Using a current level of knowledge and novel technologies could enable to make diagnostics of stand state and structure (to assess the amount of produced biomass and its structure) more effective. Based on data published over the last years (Flowers *et al.*, 2001 and 2003; Phillips *et al.*, 2004;

Reyniers *et al.*, 2006), it can be assumed that spectral characteristics and area sensing of stands can be used for this purposes.

Based on the character of processes influencing the stand structure, the growing season of cereals was divided into the three parts:

1. vegetative, including the period from emergence till the end of tillering (BBCH 10-29),
2. generative, including the period of stem elongation and heading (BBCH 30-59),
3. reproductive, including anthesis, grain formation and maturation (BBCH 60-99).

To optimize the stand structure in the mentioned growing season parts in practice (for cropping treatment decisions), the following data (traits) are important:

In the period of vegetative growth and development (BBCH 10-29):

- plant number per unit area,
- tiller number per unit area,
- tiller number per average plant,
- total biomass weight per area (fresh weight and dry weight),
- average plant weight,
- average tiller weight,
- distribution uniformity per area – plants, tillers, biomass,
- leaf area index (LAI).

In the period of generative growth and development (BBCH 30-59):

- plant number per unit area,
- tiller number per unit area,
- tiller number per average plant,
- total biomass weight per area (fresh matter and dry matter),
- uniformity of distribution per area – plants, tillers, biomass, LAI,

information on productive biomass

- total biomass weight of productive tillers per unit area (fresh weight and dry weight),
- productive tiller number per unit area,
- average productive tiller weight,

information on non-productive biomass

- total biomass weight on non-productive tillers per unit area (fresh weight and dry weight),
- non-productive tiller number per unit area.

In the reproductive period (BBCH 60-99):

- total biomass weight per area (fresh weight and dry weight),
- distribution uniformity per area – biomass, LAI,

information on productive biomass

- total biomass weight of productive tillers per unit area (fresh weight and dry weight),
- productive stem (spike) number per unit area,
- average productive stem weight,

information on non-productive biomass

- total biomass weight of non-productive tillers (stems) per unit area (fresh weight and dry weight).

The following works are focused on possibilities of direct and indirect measurement of listed traits aiming at improvement of cereal canopy assessment.

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Address

prof. Ing. Jan Křen, CSc., Ústav agrosystémů a bioklimatologie, Mendelova univerzita v Brně, Zemědělská 1, 613 00 Brno, e-mail: kren@mendelu.cz