Europ. J. Agronomy 86 (2017) 93–102

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Yield formation of Central-European winter wheat cultivars on a large scale perspective

T. Rose*, S. Nagler, H. Kage

Institute of Crop Science and Plant Breeding, Christian-Albrechts-University, 24118 Kiel, Germany

ARTICLE INFO

Article history:
Received 2 September 2016
Received in revised form 3 March 2017
Accepted 12 March 2017

Keywords:
Winter wheat
Harvest index
Light use efficiency
Radiation interception
Yield formation

ABSTRACT

Improvement of grain yield potential for winter wheat (*Triticum aestivum*) may become harder to achieve in the future because an increase of harvest index has been largely exploited by breeders. Therefore, it is of high interest to detect how the components of the yield equation $GY = Q \times LUE \times HI$ (GY: grain yield, Q: radiation interception, LUE: light use efficiency, HI: harvest index) contribute to the explanation of yield differences of modern high yielding wheat varieties. To gain more insight in the variability of the parameters in the above equation and their contribution to grain yield, a field experiment was carried out in two seasons using a set of 9 recent German winter wheat cultivars (among them a hybrid cultivar and its parent lines).

Beneath combine harvest, sequential harvests by hand were conducted (4 in the growing season 2013–2014, 5 in the growing season 2014–2015) to ascertain the above-ground biomass, the leaf area index and the harvest index (at the final harvest). Non-destructive measurements with a plant canopy analyzer to measure leaf area indices and mean tilt angles were conducted 4 times in 2014 and 9 times in 2015. Light absorption was calculated based on interpolated values of leaf area indices and mean tilt angles. Light use efficiency was calculated based on the linear relationship between above-ground biomasses at hand harvests and the related quantities of absorbed radiation.

For all parameters of yield formation besides light use efficiency ($P = 0.073$) statistically significant differences regarding the cultivars can be observed. Our results suggest that grain yield of modern German cultivars can be explained to a similar extent by differences in harvest indices (adj. r^2: 0.77) and total biomass accumulation (adj. r^2: 0.61). Variation in biomass accumulation partly can be explained by light use efficiency differences and to a lesser extent by differences in radiation interception. Most of the differences in biomass accumulation result, however, from differences in the accumulation of biomass from mid flowering to the final yield which for methodological reasons could not be further dissected to effects of light use efficiency and radiation interception. This information gap was described by the introduced parameter late performance. Various combinations of high and low performance, regarding the parameters of yield formation, exist in the analyzed set of cultivars.

1. Introduction

Wheat (*Triticum* spp.) ranks on third place in worldwide food supply. Its products cover 18% of worlds calorie as well as 20% of worlds protein demand (data: FAO STAT, 2017, average of the years 2009–2011). Central-European winter wheat production achieves above-average yields and therefore has got major importance for worldwide wheat supply.

After a continuing worldwide increase of yield levels in the second half of the 20th century (Calderini and Slafer, 1998), farm level wheat yields reached a plateau at the end of the 20th century in most countries with high yield levels, including France, United Kingdom and Germany (Lin and Huybers, 2012). In contrast, potential wheat yields still seem to rise continuously as indicated by trials under near optimum growth conditions in France (Brisson et al., 2010), the United States (Battenfield et al., 2013) and the United Kingdom (Mackay et al., 2010).

* Corresponding author.
E-mail address: rose@pflanzenbau.uni-kiel.de (T. Rose).

http://dx.doi.org/10.1016/j.eja.2017.03.003
1161-0301/

Table 1
Detailed information about the grown cultivars taken from the Descriptive Variety List (Bundessortenamt, 2016; Bundessortenamt, 2003) of the German Federal Plant Variety Office. Higher values characterize later (ear emergence, ripening), taller (height), more susceptible (winter losses, lodging) and higher yielding (yield) cultivars. German baking quality groups are: E (highest), A, B and C (lowest).

Cultivar	Release	Emergence of Ear	Ripening	Height	Yield	Quality Group
'Anapolis'	2013	5	6	3	8	C
'Brilliant'	2005	5	5	4	5	A
'Dekan'	1999	5	5	4	5	B
'Hybery'	2010	–	–	–	–	[a]B
'Norin'	2011	4	4	4	5	E
'Piko'[b]	1994	6	6	5	4	B
'Solehio'	2008	2	4	4	7	(A)
'Sur.99820'	–	–	–	–	–	–
'Toras'	2004	5	5	5	4	A

[a] BPS in French classification.
[b] Descriptive Variety List (2003).

Table 2
Dates for destructive and non-destructive measurements of above-ground biomass, LAI and MTA in both growing seasons. Integers in parentheses identify the accompanying development stage (BBCH).

Growing Season	Destructive Measurements	Non-Destructive Measurements
2013–2014	March 10th (21), April 22nd (30), May 19th (38), June 10th (66), July 29th (92)	April 22nd, May 5th, May 19th, June 10th
2014–2015	November 26th (22), March 9th (23), April 20th (31), May 18th (38), June 22nd (68), August 3rd (88)	April 7th, April 20th, May 4th, May 18th, June 1st, June 15th, June 22nd, June 30th, July 3th

Yield formation can be analyzed by using the Eq. (1) of Monteith and Moss (1977):

$$GY = \underbrace{\sum_{sowing}^{harvest} R_{PAR} \cdot LI \cdot LUE \cdot (1 - stress)}_{Biomass} \cdot HI \quad (1)$$

which calculates grain yield (*GY*) as the product of incident photosynthetically active radiation (R_{PAR}), fraction of intercepted light (*LI*), light use efficiency (*LUE*), level of unfavorable conditions (*stress*) and harvest index (*HI*).

The equation can further be aggregated to the term: *GY* is the product of above-ground biomass (*Biomass*) and *HI*. How these factors influence the grain yield of bread wheat (*Triticum aestivum*) in the near future, is of great interest for breeders. It has been argued that *HI* for high-yielding wheat cultivars is near its theoretical maximum; therefore, it has to be expected that yield improvement in the future has to rely on improvements of total biomass (Shearman et al., 2005; Parry et al., 2011; Reynolds et al., 2012; Gaju et al., 2016).

Austin (1980) supposed the theoretical maximum for *HI* is 0.62; Foulkes et al. (2011) and Shearman et al. (2005) increased this value to 0.64 and 0.66, respectively. Foulkes et al. (2011) describe a stable plateau for realized *HI* values of about 0.50–0.55 since the early nineties. Spink et al. (2000) reports a cultivar reaching a *HI* of 0.61 in the UK. Shearman et al. (2005) observed maximum values of 0.53 and Brancourt-Hulmel et al. (2003) of only 0.46.

Many studies observe a strong correlation between *GY* and *HI* (Austin et al., 1980, 1989; Slafer and Andrade, 1989; Siddique et al., 1989; Brancourt-Hulmel et al., 2003; Acreche et al., 2008; Zheng et al., 2011; Tian et al., 2011) and fail to show any influence of *Biomass*. Other studies show a contribution of *Biomass* to genotypic differences in *GY* beneath *HI* (Hucl and Baker, 1987; Donmez et al., 2001; Shearman et al., 2005; Sanchez-Garcia et al., 2012; Beche et al., 2014; Gaju et al., 2016). Only a few studies detect no influence of *HI* at all (Waddington et al., 1986; Silva et al., 2014). Many of the studies which observe a contribution of *Biomass* are conducted with spring wheat cultivars. It is also possible that relative importance of the influencing variables is depending on local conditions, hence climate at the trial site and origin of the cultivars have to be considered.

As preceding step of yield formation, *Biomass* is the product of R_{PAR}, *LI*, *LUE* and *stress* whereupon R_{PAR} and *LI* can be aggregated to the quantity of absorbed radiation (*Q*). Because *stress* is difficult to distinguish, it becomes mostly a part of *LUE*.

LUE is defined as the ratio of above-ground biomass production and *Q* in a given period. It is influenced by many physiological and environmental conditions but also by crop architecture; the latter mainly determines radiation distribution by the crops leaf angle distribution (Zhu et al., 2010). Shearman et al. (2005) observed *LUE* values of winter wheat from 2.33 to 2.64 g MJ^{-1} during the period GS 31 to GS 61 as well as 398–461 MJ m^{-2} absorbed radiation. Different light saturated photosynthetic rates of land races and modern wheat cultivars correlate to their grain yield performance (Gaju et al., 2016). This has been shown by Reynolds et al. (2000) for warm climate adopted wheat cultivars, too. The disregard of below-ground biomass causes minor discrepancy, because fraction of root biomass at mid flowering only reaches 10–15% (Reynolds et al., 2009).

The objective of the presented study is to analyze yield differences between wheat cultivars in terms of Eq. (1) using a set of recent cultivars from Germany. A detailed knowledge of the parameters of yield formation and their genotypic differences is necessary for genotype-specific modeling of growth processes and the estimation of possible capabilities in the breeding process.

2. Material and methods

2.1. Site and soil

The field trials were conducted during two years (growing seasons 2013–2014 and 2014–2015) at the Hohenschulen Experimental Farm (northern Germany, 54°18′51.2″N 9°59′28.8″E, 30 m a.s.l). The soil is characterized as a pseudogleyic sandy loam (Luvisol: 170 g kg^{-1} clay, pH 6.7, 13 g kg^{-1} C_{org}, 1.1 g kg^{-1} N_{org} in 0–30cm). The climate of northern Germany is humid temperate with a long-term mean annual temperature at the location of 8.8 °C and mean annual precipitation of 751 mm, whereof 396 mm occur during the main growing season (March–August).

In the season 2013–2014 temperatures above-average occurred from December to May with the exception of a cold period at the end of January. Superior levels of global radiation occurred in