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# How do timing, duration, and intensity of drought stress affect the agronomic performance of winter rye?

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ABSTRACT

Winter rye (*Secale cereale* L.) will be especially affected by drought induced yield losses in Central and Eastern Europe in the future because it is predominantly cultivated on low-fertile soils with a poor water-holding capacity. In order to examine the performance of winter rye under different drought conditions, field experiments were carried out during the years 2011, 2012, and 2013 near Braunschweig, Germany. Two sets of genotypes were tested under severe, mild, pre-anthesis, and post-anthesis drought stress in rain-out shelters as well as under rainfed and well-watered conditions. The grain, straw, and total above ground biomass yields, harvest index, grain yield components, leaf area index (LAI), and phenological characteristics were examined, as well as phenotypic correlations between grain yield and further characteristics. Drought induced grain yield reduction ranged from 14 to 57%, while straw yield and harvest index were lesser affected by drought than the grain yield. Under drought conditions, fully ripe was reached up to twelve days earlier than under non water-limited conditions. Pre-anthesis drought mainly reduced spikes m$^{-2}$ and kernels spike$^{-1}$ while drought during grain filling reduced the 1000-kernel weight (TKW) only. The grain yield was positively associated with straw yield, spikes m$^{-2}$, and kernels spike$^{-1}$ under water limited conditions while the TWK was only positively associated with grain yield under drought during grain filling. Consequently, high pre-anthesis biomass as well as high numbers of spikes m$^{-2}$ and kernels spike$^{-1}$ are especially important for obtaining high grain yields under water-limited conditions. Focusing on these traits is, therefore, recommendable for developing drought tolerant rye genotypes.

## 1. Introduction

Rye (*Secale cereale* L.) is an important food, feed, and whole-plant energy crop in Central and Eastern Europe. In these regions, rye is primarily cultivated as winter cereal on 4.8 million hectares (FAO, 2014). Rye has been recognized to be relatively drought tolerant compared to other crops (Schittenhelm et al., 2014; Hlavinka et al., 2009). Therefore, it is predominantly grown on infertile and sandy soils, which are characterised by a low water holding capacity. Although, Central and Eastern Europe have a humid climate, climatologists predict more future summer drought events even for these regions as well as an overall temperature rise (IPCC, 2014). Therefore, rye could be especially affected by drought events.

Drought is the most yield-limiting abiotic stress and affects cereal crops on all levels during all phenological stages. The extent of grain yield loss is depending on the intensity and timing of water shortage as the different stages of development vary in their sensitivity to drought stress (Cattivelli et al., 2008). Grain yield can be dissected into the yield components spikes m$^{-2}$, kernels spike$^{-1}$, and 1000-kernel weight (TKW). These yield components are not equally susceptible to water deficits because they are determined at different stages of plant development (Slafer and Savin, 2004). For example, drought stress during the vegetative phase will affect grain yield mainly by reduced crop density and kernel number (Dolferus et al., 2011) while drought during grain filling results in reduced kernel weight caused by a reduced grain filling duration (Gooding et al., 2003). Generally, grain number is considered to be the main determinant for final grain yield whereas grain weight is less important (Slafer et al., 2014; Chmielewski and Köhn, 2000; Dencic et al., 2000; Lopezcastaneda and Richards, 1994; Giunta et al., 1993).

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As there is hardly any information about the effect of various types of drought on winter rye, the main objectives of this study were to (1) identify the effect of timing, duration, and intensity of water deficit on phenological, morphological and agronomical characteristics, and (2) to examine the relationship between grain yield and other crop characteristics.

## 2. Materials and methods

### 2.1. Field experiments

The trials were conducted during the 2010/11, 2011/12, and 2012/13 growing seasons on the experimental field of the Julius Kühn-Institute near Braunschweig, Germany (52.30 N, 10.44 E, 80 meters above mean sea level). The soil was characterized as Haplic Luvisol (FAO, 1997) with an available water capacity of 120 mm (0–90 cm), and a groundwater level 10 m below ground. Sowing dates were September 30 in 2010, September 26–October 5 in 2011, and September 26–28 in 2012. Seeding density was 230 seeds $m^{-2}$ and plot sizes ranged from 5.6 to 7.2 $m^2$. A total of 130 kg nitrogen $ha^{-1}$ was applied as calcium ammonium nitrate, split into 60 kg N $ha^{-1}$ at the beginning of vegetation and 70 kg N $ha^{-1}$ at the beginning of stem elongation. Growth regulators were used to avoid lodging. Fungicides and pesticides were applied when needed. The trials were divided into two experiments. In Experiment I (2011 and 2012), the winter rye was grown under three levels of water supply: severe drought stress, mild drought stress (2012 only) and well-watered conditions. In Experiment II (2013), 4 water regimes were practiced: early drought stress with water deficit during the vegetative phase (stem elongation to anthesis), late drought stress with water deficit during the generative phase (grain filling to fully ripe), as well as rainfed-and well-watered conditions. All experiments were set up as a 4 × 4 alpha lattice with two replications. Further details about the water regimes are given in Table 1.

Severe drought in 2011 and 2012, as well as early drought in 2013 were created by growing the winter rye crops under a 50 m long, 10 m wide, and 4 m high foil tunnel (CASADO, Douville, France). This stationary rain-out shelter was covered by a 200 μm polythene foil, which was mounted at the beginning of stem elongation in each year. In order to attain good ventilation and to minimize the microclimatic effects of the rain-out shelter as good as possible, the front and the side of the rain-out shelter were open. In order to measure the remaining microclimatic rain-out shelter effects, air temperature, relative humidity, and solar radiation were recorded periodically. Mild (2012) and late drought stress (2013) were attained by means of a mobile rain-out shelter (Götsch & Fälschle, Alerheim, Germany) which was 24 m long, 12 m wide, and 5 m high. This mobile shelter automatically covered the experimental plots during rainfall events only, and therefore allowed normal climatic conditions all the other time. Under well-watered conditions and in the stationary rain-out shelter (early drought, irrigation during grain filling only), plants were additionally watered by drip irrigation. The plants grown in the mobile rain-out shelter were irrigated by a shelter-based overhead sprinkling facility.

### 2.2. Plant material

In both experiments a set of each 16 winter rye (*S. cereale* L.) genotypes were examined. In Experiment I (2011–2012) 15 genotypes were composed of three parental inbred lines (Lo115-N, Lo90-N, and Lo117-N) as well as 12 $F_{2:4}$ lines selected from the two biparental $F_1$ populations Lo115-N × Lo90-N and Lo115-N × Lo117-N. These 15 genotypes were out-crossed to the same cytoplasmic male sterile tester. In Experiment II (2013), 15 advanced breeding populations were studied. All these genotypes were selected from a larger set of genotypes, which was used in a genotyping project (Hübner et al., 2013). The different genotypes were used to ensure a representative sample of winter rye. These genotypes will, however, not be presented and discussed individually. Additionally, the hybrid rye cultivar 'Palazzo' was used as a check in both experiments, which has shown a yield performance similar to the other 15 genotypes in previous trials. All plant materials were provided by the KWS LOCHOW GmbH, Bergen, Germany.

### 2.3. Climate conditions

Air temperature and precipitation were recorded at 2 m height with a iMETOS weather station (Pessl Instruments, Weiz, Austria) located on the experimental field. The agrometeorological advisory system 'Agrowetter' from the German Weather Service (DWD, 2014) was used for irrigation scheduling.

### 2.4. Phenological data

Plant development was recorded using the BBCH scale for cereals (Hack et al., 1992). The beginning of stem elongation (BBCH 30), beginning of anthesis (BBCH 61), full senescence, and fully ripe (BBCH 89) were recorded as day of year (DOY).

### 2.5. Agronomic data

Harvest took place at fully ripe (BBCH 89) in each year. Whole plants of the entire plots were hand-harvested in 2011. In 2012 and 2013 only the whole plants of a 0.5 $m^2$ portion of the plots were hand-harvested while the rest of the plots were harvested with a Nursery Master plot combine (Wintersteiger, Ried, Austria). The hand-harvested plants were separated into ears and straw; the ears were threshed and winnowed, and the chaff added to the straw fraction. Grain and straw samples were oven-dried to constant weight at 105 °C for 24 h. Grain yield, straw yield, and total aboveground biomass yield (hereafter referred to as biomass yield) were calculated on the basis of 0% water content in t $ha^{-1}$. The harvest index was calculated as the ratio of grain yield to biomass yield. The yield components spikes $m^{-2}$, kernels $spike^{-1}$, and 1000-kernel weight (TKW) were determined from the hand-harvested plant samples.

### 2.6. Leaf area index

Starting at the beginning of stem elongation, the green leaf area index (hereafter referred to as LAI) was measured weekly with a SunScan canopy analysis system (Delta-T Devices, Cambridge, UK). Eight measurements were taken per plot in 50 cm intervals while maintaining a distance of 50 cm to the front and back edges of the plot; the eight values were averaged. When senescence started, the SunScan was held over the senescent leaf layer to record the photosynthetic active leaves only. The mean of all LAI measurements in one season is referred to as $LAI_{mean}$. Additionally, the LAI that intercepts 95% of the incoming photosynthetic active radiation (PAR) was calculated according to Brougham (1958).

### 2.7. Soil water content

The course of the soil moisture was recorded in 2012 and 2013 using the portable soil moisture probe Diviner 2000 (Sentek Technologies, Stepney, Australia). Plastic tubes with a diameter of 5 cm were installed to a depth of up to 150 cm in 24 and 32 plots in 2012 and 2013, respectively, in which soil moisture readings were taken at 10 cm intervals from 5 to 125 cm twice a week from the beginning of vegetation to harvest. The soil water content was also