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Effects of weather conditions during different growth phases on yield formation of winter oilseed rape

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ABSTRACT

Winter oilseed rape (WOSR) is an important oil and protein crop in Europe, used in biofuel production and as protein source in livestock farming. In contrast to cereals, WOSR seed yields are still increasing in most countries but yield stability was not improved during the last decades.

In our study, we analyzed the effects of weather conditions during different growth stages on maximum seed yield, maximum oil yield, number of seeds per m^2 and 1000-seed weight to get further information on yield formation processes.

Field trials performed at 34 environments (site × year combinations) representing different soil characteristics and climate regions in Germany were used for the analysis. About 40% of seed yield variability could be explained by weather conditions during specific growth phases. The most important phenological phases thereby were: onset of pods and seeds (BBCH 50–65) and seed development (BBCH 71–79). During onset of pods and seeds, yield was significantly influenced by temperature, radiation and drought stress. Assimilate availability during this phase determines the number of seeds per m^2 (sink size). After flowering, only temperature significantly affected WOSR yield. Temperature is the major parameter determining the duration of growth stages. Lower temperature elongates the time of assimilate production and translocation to the seeds. During this growth stage, seed weight is determined. In our data sets, low sink size was not yield limiting due to compensatory effects between the yield components number of seeds per m^2 and 1000-seed weight. Yield response pattern suggests that WOSR yield is predominantly source-limited, especially during the late reproductive phase.

1. Introduction

Winter oilseed rape (WOSR) is an important oil and protein crop in Europe. With a harvested area of 8.2 Mio ha in 2012 (FAO, 2014) the crop more than doubled its acreage during the last 15 years. In many arable cropping systems WOSR plays an important role as a break crop in cereal crop rotations. Largest production areas of WOSR in Europe are located in France and Germany. In contrast to other grain crops (e.g. winter wheat and barley; Calderini and Slafer, 1998; Finger, 2010; Peltonen-Sainio et al., 2009) seed yield of WOSR is still increasing in most countries due to breeding and optimized crop management; however, yield stability was not improved during the last four decades, and is still lower compared to cereals (Rondanini et al., 2012).

WOSR seed yield is the result of a complex interaction between genotype, soil, weather and management factors on growth and development processes (Habekotté, 1997b; Mendham et al., 1981; Peltonen-Sainio et al., 2010). Temperature, irradiation and precipitation directly and indirectly influence yield formation processes during different growth stages (e.g. Takashima et al., 2013). Temperature mainly determines the duration of growth stages (Habekotté, 1997a). Previous studies showed that the extension of flowering and subsequent growth phases due to low temperatures substantially increase yield potential and oil content of seeds (Gomez and Miralles, 2011; Peltonen-Sainio et al., 2010; Si and Walton, 2004) because of increasing radiation interception, assimilate production and translocation to reproductive organs (Mendham et al., 1981). In contrast, Takashima et al. (2013) found that the duration of pre- and post-flowering phase is not associated with WOSR yield. Assimilates, produced during different growth phases are either used for vegetative dry matter production or to initiate and develop reproductive organs as sinks or they are stored in the vegetative tissue as reserve carbohydrates (Habekotté, 1993). Drought stress, when occurring already before flowering

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(Andersen et al., 1996; Champolivier and Merrien, 1996), predominantly reduces total dry matter production, whereas limited water availability during flowering reduces pod density. Seed weight and oil concentration decrease if water shortage occurs between anthesis and maturity.

Contradictory approaches are used to explain yield reduction either by source-strength or by sink-capacity. Most studies assume that WOSR yield is mainly source-limited. For instance, Habekotté (1993) concluded that the potential number of pods and seeds are not limiting factors for yield formation. In addition, Mogensen et al. (1997) found that seed growth predominantly depends on assimilation of pod hulls during pod and seed development after flowering. Furthermore, Asare and Scarisbrick (1995) recognized that differences in seed weight also depend on weather conditions which in turn suggest that WOSR has a high compensatory capacity between yield components. In contrast to these studies, several other observations (e.g. Gomez and Miralles, 2011; Peltonen-Sainio and Jauhiainen, 2008; Peltonen-Sainio et al., 2010) support the assumption that WOSR yield may be limited by an unusual low sink-size or less successful pollination.

In general, several studies have shown the effects of weather conditions on WOSR seed and oil yield but interactions of temperature, radiation and drought stress within and between growth phases have not yet been analyzed thoroughly. Also the number of sites being analyzed is small for most of the existing studies. The current study therefore has the objective: (i) to identify and quantify the most important weather variables and their interactions during different growth phases; (ii) to analyze the effects of these weather variables on yield formation processes; (iii) to estimate if WOSR yield is predominantly source- or sink-limited by exploring the response of yield components to weather variables.

2. Materials and methods

2.1. Long-term datasets

Seed yield and oil yield data, standardized to $t\,ha^{-1}$ at 91% dry matter, were available from different field experiments with varying nitrogen application levels in spring at 14 sites in Germany between 2006 and 2011 (year of harvest). From a subset of these field experiments, also 1000-seed weights were taken. Overall, the field trials represent 34 environments (site × year combinations). The experimental sites thereby covered a range of climate regions and soil conditions, representing different growth regions for WOSR in Germany. Positions and main characteristics of the locations are given in Table 1.

Nitrogen fertilization experiments with different sowing dates and nitrogen applications in autumn and spring were performed at 10 sites across Germany between 2006 and 2009 (Union zur Förderung von Oel- und Proteinpflanzen e.V., UFOP). Detailed information on these experiments are given in Henke et al. (2009). Similar experiments started in 2009 at four sites in Saxony. These experiments were coordinated by Sächsische Landesamt für Umwelt, Landwirtschaft und Geologie (LfULG) and lasted for three seasons until 2011.

Management factors, as sowing date, plant establishment and crop protection were handled according to the best possible practice to allow for optimal yield formation.

Three WOSR varieties were used in the field trials. The varieties Trabant and Visby are hybrids, while NK Fair is an open pollinating variety. In order to account for yield differences due to variety choice, variety-specific yield potentials were considered but no further investigations were pursued in the current study to explain the effects in detail.

2.2. Data processing

The data sets included late sowing dates and treatments without N fertilization in autumn. A poor crop establishment before winter therefore occurred in some environments. In order to prevent poor canopy development after winter as a major source of yield variation only data from crops with sufficient development and nitrogen uptake before winter (>20 $kg\,N\,ha^{-1}$) were considered.

Yield data with different N application levels in spring were used to estimate the amount of fertilizer (N_{max}), required to achieve maximum seed yield (Y_{max}) and maximum oil yield (OilY_{max}), ex post for every combination of sowing date and N application in autumn in each environment. The calculation was based on quadratic polynomial nitrogen response functions ($Y = a + b \times N_{max} + c \times (N_{max})^2 + \varepsilon$), where a is the intercept, b is the linear coefficient, c is the quadratic coefficient and ε is the error term. The functional maximum describes the relationship between N_{max} and Y_{max} or OilY_{max}. According to Henke et al. (2007), quadratic response functions are useful to describe the relation between WOSR seed yield and N fertilization in agronomic ranges, especially under different climate and soil conditions present in our data set.

1000-Seed weight under non-limiting conditions and Y_{max} were used to calculate seed density (number of seeds per m^2) at harvest.

Y_{max} and OilY_{max}, as well as number of seeds per m^2 and 1000-seed weight were used in the present study as dependent variables to investigate the effects of weather conditions independent of nitrogen fertilization in spring. Oil concentration of seeds at N_{max} was also tested as dependent variable, but the response patterns to weather conditions were not consistent and beyond meaningful interpretation.

2.3. Phenological phases

Effects of weather conditions on Y_{max}, OilY_{max} and yield components were investigated for several growth stages of WOSR. Therefore, the following major phenophases according to the BBCH scale (Lancashire et al., 1991) were defined: Germination and emergence (00–10), leaf development (11–19), stem elongation (30–39), flowering (60–69), seed development (71–79), and ripening (80–89). Further potentially yield determining phases were chosen: first, the onset of pods and seeds from the beginning of inflorescence emergence until mid-flowering (BBCH 50–65). Second, the critical phase for pod and seed abortion, lasting about 300 °Cd after mid-flowering (e.g. Berry and Spink, 2006; Habekotté, 1993; Mendham et al., 1981).

2.4. Meteorological records

Weather data were recorded directly at the experimental sites or at the closest representative weather station. Daily data of mean, maximum and minimum temperature, precipitation, relative air humidity, wind speed, and total incident solar radiation were available.

A drought stress index (DI) was calculated from the site specific plant available water content of the effective rooting depth and the daily climatic water balance. Therefore, potential evaporation (ETP) was estimated according to the empirical Penman equation (Penman, 1956).

The daily ETP values were multiplied with a crop coefficient (DVWK, 1996), which differs monthly to consider the development of WOSR. The climatic water balance was calculated by subtracting the corrected daily ETP from the daily precipitation sum.

Assuming soil water content across the effective rooting depth after winter at field capacity, the actual soil water content was calculated on a daily basis by considering the daily climatic water