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Mid-season prediction of grain yield and protein content of spring barley cultivars using high-throughput spectral sensing

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ABSTRACT

The ability to forecast grain yields and protein contents of spring barley is of particular interest for the malting and brewing industry, as well as for plant breeding. However, methods for early prediction of grain yield and protein content should ideally be timesaving, non-destructive and inexpensive. In this 3-year study using the mobile phenotyping platform PhenoTrac 4, proximally sensed reflectance data of 34 cultivars were used to develop vegetation indices and to calibrate PLSR models, followed by subsequent validation in independent field trials. A comparison among PLSR, the NDVI and REIP indices and an optimized vegetation index indicated that PLSR and REIP (R^2 = 0.71-0.95) gave superior predictions of grain yield. Furthermore, it was possible to distinguish the performance of different cultivars. In contrast, protein content could not be predicted reliably. As an alternative, a PLSR model of leaf N uptake at anthesis was tested to predict grain protein content. Satisfactory correlations were obtained with R^2 = 0.61, but protein content was considerably overestimated. The results show that tractor-based proximal sensing is a high-throughput, non-destructive and precise method to predict the grain yield of spring barley and could be a suitable tool to deliver information for the brewing industry and plant breeders.

1. Introduction

Spring barley (*Hordeum vulgare* L.) is the most important crop for malt and beer production. More than 60% of the global production comes from the European Union, the Balkan countries, Russia and Canada (FAO, 2015). A reliable forecast of grain yield and protein content before harvest would be useful, especially for the malting and brewing industry. It would simplify the acquisition and management of raw materials (Weissteiner and Ku, 2005). A solid prediction of yield parameters is also a major advantage for plant breeders (Ferrio et al., 2005). Knowing the performance of different cultivars in the early stages of breeding saves costs and time, since this makes it possible to focus on high-performance cultivars only (Royo et al., 2003). However, a practical method for predicting yield parameters needs to be timesaving, non-destructive and cost-efficient (accounting for both labor and analytic costs). Spectral proximal sensing fulfills these requirements (Prasad et al., 2007; White et al., 2012; Xiu-liang et al., 2014). In addition to common vegetation indices such as the NDVI (Aparicio et al., 2000) and the REIP (Pettersson et al., 2006), new methods such as the contour map method and Partial Least Squares Regression (PLSR) have been found to be useful for yield prediction (Elsayed et al., 2015; Rischbeck et al., 2016).

Different approaches have been tested for in-season estimation of yield parameters. For winter wheat, Raun et al. (2001) and Moges et al. (2005) found strong relationships between the NDVI and grain yield. However, Xue et al. (2007) stated that vegetation indices such as the GNDVI or NDVI did not provide a reliable prediction of protein content. The PLSR method was used to predict the yields of twenty-five durum wheat cultivars by Ferrio et al. (2005). They concluded that it worked better for ranking different genotypes than for making accurate predictions of their grain yields. Other studies used the PLSR method to estimate the grain yield and protein content of spring wheat (Øvergaard et al., 2013a, 2013b) and winter wheat (Xiu-liang et al., 2014). Their predictions of protein content were more accurate than predictions using vegetation indices. Additionally, Øvergaard et al. (2013a, 2013b) highlighted the importance of using several years of data to construct a stable PLSR model.

Yield predictions have also been made for spring barley. Hansen et al. (2002) evaluated predictions of grain yield and protein content by comparing ten vegetation indices and PLSR under different nitrogen fertilizer levels and seeding densities. Good relationships were found between grain yield and PLSR; however, only poor results were obtained for protein content. A better prediction was obtained by Söderström et al. (2010), by combining spectral sensing with weather

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data. Weissteiner and Kuhbauch (2005) developed a model using satellite spectral remote sensing and ancillary data such as meteorological or pedological data. In different drought stress scenarios, Elsayed et al. (2015) compared vegetation indices against PLSR, and Rischbeck et al. (2016) found that PLSR models were improved when spectral sensing was combined with plant canopy thermal data.

Although several authors emphasized the need for a fast and inexpensive method to predict yield and protein content before harvest, most of them used hand-held field spectrometers or satellite data (Weissteiner and Ku 2005; Söderström et al., 2010) with coarse spatial resolution. Only a few authors used vehicle-based spectral proximal sensing to estimate plant traits (Mistele and Schmidhalter, 2008; Erdle et al., 2013; Kipp et al., 2014; Becker and Schmidhalter, 2017). To the best of our knowledge, there have been only a few studies that used independent datasets to validate PLSR models. No studies using ground-based spectral proximal sensing evaluated their models using independent field trials. Most authors were primarily seeking to optimize fertilization strategies, and very few studies were seeking to advance breeding-related phenotyping.

To evaluate PLSR modeling, we evaluated the spectral signatures of approximately 30 spring barley cultivars. The aims of this work were (i) to find optimized vegetation indices, (ii) to create PLSR models that could predict the grain yield and protein content of spring barley, (iii) to compare the performance of different vegetation indices and PLSR using independent field trials and (iv) to test whether a regionalized model could be developed for predicting grain yield and protein content independent of years and varying agronomic and pedological conditions, (v) to highlight the advantages of vehicle-based sensing in this context.

2. Materials and methods

2.1. Field experiments

Field experiments were conducted in Germany at the Dürnast Research Station of the Technical University of Munich (11°41′60″E, 48°23′60″N), from 2013 to 2015. The field sites are located in a hilly, Tertiary landscape. The annual precipitation is approximately 800 mm, and the average temperature is 7.5 °C.

2.1.1. Weather conditions

The year 2013 was characterized by cold and wet weather conditions during March that led to a delayed sowing of about 4 weeks. Heavy rainfalls amounting to 159 mm at the beginning of June flooded the eastern part of the field trials and a subsequent heat wave with an average temperature of 19.7 °C during July led to accelerated ripeness. The average temperatures during the growing seasons (April − August) of 2014 and 2015 were 14.6 and 15.8 °C, respectively, and thus higher than the longtime average of 13.4 °C. Regarding rainfall, more precipitation was registered in 2014 with 97.8 mm compared to 2015 with 74.8 mm in this period. The longtime average of precipitation is 88.8 mm. While rainfall during anthesis in June was in the normal range in 2015, dry conditions were recorded during this period in 2014. No irrigation was applied in all trial years.

2.1.2. Field experiments used for the development of PLSR calibration models (calibration experiments)

Table 1
Overview of spring barley cultivars grown in different years.

Cultivar	Usage	2013	2014	2015
Aspen	Malting	X	X	X
Barke	Malting	X	X	X
Baronesse	Malting	X	X	X
Br8993a3	–	X		
Braemar	Malting	X	X	X
Calcule	Fodder	X	X	X
Carina	Malting	X	X	X
Djamila	Fodder	X	X	X
Eunova	Fodder	X	X	X
Grace	Malting	X	X	X
Hora[a]	Human food			X
IPZ 24727	Malting	X	X	X
Irina	Malting	X	X	X
Lawina[a]	Human food	X		
Mackay [AUS]	Malting	X	X	X
Marthe	Malting	X	X	X
Melius	Malting	X	X	X
Paradiesgerste[a]	Human food			X
Pirona[a]	Human food		X	X
Power	Malting	X	X	X
Quench	Malting	X	X	X
Salome	Malting	X	X	X
Scarlett	Malting	X	X	X
Shakira	Malting	X	X	X
Sissy	Malting	X	X	X
Solist	Malting	X	X	X
Streif	Fodder	X	X	X
Trumpf/Triumph	Malting	X	X	X
Union	Malting	X	X	X
Ursa	Malting	X	X	X
UTA	Malting			X
Vespa	Fodder	X	X	X
Volla	Malting	X	X	X
Wiebke	Malting	X	X	X

[a] hull-less barley.

The 3-year study, conducted by the Chair of Plant Nutrition, used 30–34 spring barley cultivars (Table 1) in a randomized block design with 4 replicates. The cultivars were chosen to represent different uses. Along with malting and fodder barley cultivars, four hull-less barley cultivars used for human food were cultivated. Due to seed limitations, the cultivar Pirona could be tested in only two of the three years. Plots consisted of 12 rows, 10.9 m in length (16.35 m^2). The soils are characterized as tertiary sediments with secondary deposits of Pleistocene loess as the predominant soil material on the field sites Hüttacker and D8 used in 2013 and 2014 as calibration (development) sites, respectively. The composition of the area is a consequence of Pleistocene loess deposition and subsequent erosion in the periglacial time period and Holocene erosion and deposition. According to the German Soil Survey (Bodenkundliche Kartieranleitung, 2005), fine-silty Dystric Eutrochrept and fine-loamy Typic Udifluvent are the dominant soil types. The upper part of the calibration site D1 used in 2015 represents tertiary sediments of the Upper Freshwater Molasse forming an alternating sequence of gravels, sands, silts and clays. Brown Earths (Eutrochrepts) and in small loess areas Parabrown Earth (Typic Agrudalfs) are dominating, whereas the lower parts of the D1 are similar to the D8 and Hüttacker field sites.

Sowing dates, sowing density and spikes per square meter are indicated in Table 2. Nitrogen fertilization was given as one dressing at 70 kg N ha^{-1} across all three years.

2.1.3. Independent validation experiments for the application of PLSR models

Field experiments used for evaluating the PLSR models were provided by the Chair of Phytopathology at the Technical University of Munich. These field experiments were located approximately 3 km from the Dürnast Research Station. The soils used on the validation sites are similar to the nearby Hüttacker site which was used for the calibration experiment in 2013. Methods for sensor measurements, grain harvest and protein-content determinations were similar to those used in the other field experiments. Plots consisted of 12 planting rows, 7.5 m in length (11.25 m^2).

2.1.3.1. Validation experiment 1 (IV-1). For experiment IV-1, the cultivars Grace and Scarlett were grown under 3 nitrogen fertilizer levels with 8 and 12 replicates in 2013 and 2014, respectively. In 2015,