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Interactive effects of water deficit and nitrogen nutrition on winter wheat. Remote sensing methods for their detection

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ABSTRACT

Water and nitrogen (N) deficit are globally the most frequently limiting factors for agricultural crops, while both often occur together. To evaluate the interactive effects of water deficit and N nutrition on remote sensing data, rainout shelter field experiments were conducted in winter wheat during 2013–2014. Canopy spectral reflectance and infrared thermal imaging parameters were correlated to biochemical, physiological, morphological and production characteristics. Correlation analysis revealed that stomatal response to water deficit is best estimated using the NPCI (Normalized Pigment Chlorophyll Index) vegetation index and also by the CWSI (Crop Water Stress Index) thermal index. A variety of vegetation indices can be used to estimate grain yield, among which the best-performing is the Normalized Red Edge-Red Index (NRERI). That index shows the highest correlation irrespective of water deficit and N nutrition. Although none of the indices provided good detection of N content in plants, the total N uptake in wheat grain was reliably estimated by the TCARI/OSAVI (Transformed Chlorophyll Absorption Reflectance Index/Optimized Soil-Adjusted Vegetation Index). The results demonstrated that utilization of N for yield or grain protein formation was largely determined by water availability, and the relationships between vegetation indices and grain protein content thus have a distinct slope under water deficit. In summary, the spectral and thermal indices can provide satisfactory estimation, irrespective of interactions between water and N deficit, for grain yield, N uptake, and stomatal responses. However, when estimating the grain protein content, the water availability should be considered.

1. Introduction

Water deficit (WD) is considered to be the main environmental factor limiting plant growth, photosynthesis, and productivity worldwide (Jones and Corlett, 1992). This fact will increasingly be true in the future under climate change. Despite the recent considerable improvement in understanding plant responses to WD, several knowledge gaps can be highlighted. Most of these gaps relate to unknown interactions among other environmental factors. From the perspective of agricultural practice, the most important interaction with WD is that of nitrogen (N) availability. N is often considered the major limiting factor, after WD, for plant growth and crop productivity. Indeed, N is involved in the functioning of meristematic tissues, in photosynthesis, and in determining the protein content of harvested organs (Xu et al., 2012). Additionally, spatial variation in soil and temporal changes in weather conditions results in high spatiotemporal variability in water and nutrient availability. This, in turn, impacts significantly upon crop productivity and N leaching or runoff from agricultural fields to ground or surface water resources. The availability of water or N can also significantly affect the input use efficiency of the counterpart factor (reviewed by Gonzalez-Dugo et al., 2010) and thus modulate, too, the impacts on production parameters. To be able to estimate in a timely manner the heterogeneity and prevent negative impacts on crop productivity and environment, there is increasing demand for a robust method able to detect small changes in crop growth, physiology, and production parameters as a response to water or nutrient availability on relatively large areas. Such method also should be able to identify the major cause of such changes to optimize following crop management and inputs.

Spectral reflectance and infrared thermography constitute the most

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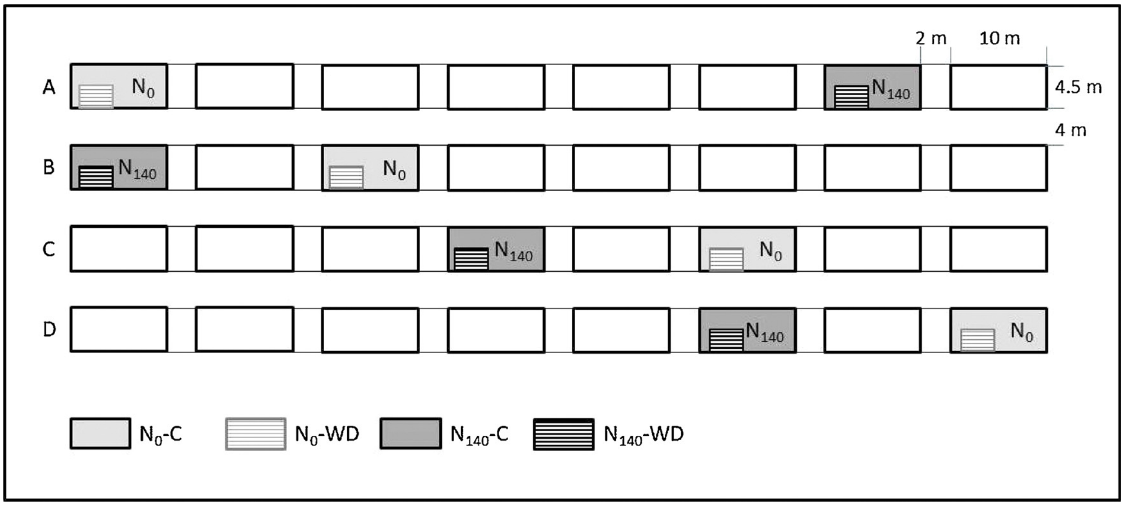

Fig. 1. Field layout of the experiment showing the size of plots, the distance between plots and placement of experimental rainout shelters (hatched rectangles). Experimental treatments (N_0: 0 kg ha^{-1} and N_{140}: 140 kg ha^{-1}) used within this study were part of larger experiment (data not shown). Experimental layout was identical for both experimental sites Vetrolam and Babicka.

promising approaches in remote sensing of crop canopies to detect spatial variability of either N or WD (reviewed by Pinter et al., 2003; Bandyopadhyay et al., 2014). By providing both spatial and temporal information, remote sensing based on spectral reflectance may function as an important source of data for site-specific crop management to improve nutrient and water use efficiency and reduce N losses. Spectral reflectance of crop canopies in individual spectral bands is determined by various morphological, structural, and physiological parameters. Statistically significant correlations often have been found among spectral characteristics and chlorophyll content, nutrition status, aboveground biomass, and WD (reviewed by Hatfield et al., 2008). Several vegetation indices have been used to estimate effects of WD on crop productivity and stability. For example, Peñuelas et al. (1997) developed the Water Index (WI) based on reflectance at 900 and 970 nm to estimate water status in plants. In other studies, different spectral indices are used for estimation of drought effects, such as the Photochemical Reflectance Index (PRI; Elsheery and Cao, 2008), Brown Pigment Index (BPI, Peñuelas et al., 2004), and Simple Ratio or Normalized Difference Vegetation Index (SR, NDVI, Aparicio et al., 2000). Correspondingly, several vegetation indices have been proposed for non-destructive estimation of plant N status in field crops. It has been demonstrated that, due to the rapid saturation of vegetation indices based on reflectance in the blue and red bands (Merzlyak and Gitelson, 1995), higher linearity of response to N status, and thus improved reliability of detection at medium and high levels of N supply, is achieved with indices using red-edge (e.g., Klem et al., 2014; Li et al., 2014) or green (Gitelson et al., 2003; Xue et al., 2004) reflectance bands. However, there are only isolated studies dealing with the combined effect of WD and N nutrition on canopy reflectance (e.g., Peñuelas et al., 1994). The possibility for simultaneous evaluation of the WD and N status effects and their interactions in terms of the physiological responses, crop yield and quality using spectral reflectance remains insufficiently explored. This lack of knowledge may lead to misinterpretation in evaluating the impact of WD and undermine decision processes regarding N nutrition.

Recently, increased attention has been devoted to the use of infrared thermal imaging for detecting plant responses to WD. This has included the development of several water stress indices (reviewed by Maes and Steppe, 2012), but interactions between the effect of N nutrition and WD on thermal data are yet almost unknown.

The primary aim of this study was therefore to examine perspective ways for simultaneous evaluation of WD and N status in winter wheat via spectral reflectance and infrared thermal imaging and to explore direct relationships of reflectance and thermal parameters with plant physiology, morphology, grain yield, and quality. We thus formulated the following hypotheses: (1) WD and N deficiency both cause a similar reduction in morphometric and production parameters. (2) Nitrogen fertilization alleviates negative effects of WD. (3) The WD and N effects on physiological parameters can be separated using specific vegetation and thermal indices. (4) Final grain yield and protein content can be predicted using spectral reflectance irrespective of stress type.

2. Materials and methods

2.1. Experimental site and design

The experiment was conducted at two experimental sites near the municipality of Banín in the Czech Republic (Babicka – 49°40.4' N, 16°27.5' E; 460 m a.s.l. and Vetrolam – 49°39.9' N, 16°28.4' E; 475 m a.s.l.) during two growing seasons 2013 and 2014. The location is characterized by a mean annual temperature of 7.6 °C and mean sum of precipitation 629 mm (long-term averages 2000–2012). The soil type at the sites belongs to Retisols (FAO soil groups). Plots of size 45 m^2 (4.5 × 10 m) were sown with winter wheat (*Triticum aestivum*) variety Tiguan. The sowing density was 3.5 million of germinating seeds per hectare with row distance 0.125 m. The plots were separated within blocks by buffering strips of 2 m, sown with winter wheat, while the blocks were separated by 4 m grass strips. The plots were randomized in blocks, and each combination of WD and N nutrition treatment was replicated four times at each site (see Fig. 1). For manipulating incident precipitation, rainout shelters were constructed over the experimental plot. The rainout shelters consisted of a wood frame covered by polycarbonate transparent strips. The strips were arranged as louvers to exclude precipitation completely from the experimental plot while still enabling sufficient air movement and minimizing temperature and relative humidity artifacts. The upper part (0.3 m) of the side wall was also covered by polycarbonate strips to avoid an effect of horizontal precipitation. The roof had a 20° incline, and on its lowest side was mounted a gutter that channeled the intercepted water out of the plot. A trench 0.2 m wide was dug and sheathed with a steel barrier to separate the soil of the roofed plots from the neighboring soil.

The rainout shelters were installed at the middle of stem elongation (8 May 2013 and 6 May 2014) to simulate WD at both sites. The simulated WD lasted until early milk ripening stage (12 June 2013 and 8 June 2014). Control (C) treatment plots without rainout shelters were exposed to natural precipitation. During the experiment, soil moisture