THE CROP JOURNAL 3 (2015) 200–210

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The Crop Journal

Grain yield losses in yellow-rusted durum wheat estimated using digital and conventional parameters under field conditions

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A R T I C L E I N F O

Article history:
Received 17 December 2014
Received in revised form
25 February 2015
Accepted 3 March 2015
Available online 11 April 2015

Keywords:
Wheat yellow rust
Field phenotyping
NDVI
Phenology, *Puccinia striiformis*
RGB-based indices
Triticum durum

A B S T R A C T

The biotrophic fungus *Puccinia striiformis* f. sp. *tritici* is the causal agent of the yellow rust in wheat. Between the years 2010–2013 a new strain of this pathogen (Warrior/Ambition), against which the present cultivated wheat varieties have no resistance, appeared and spread rapidly. It threatens cereal production in most of Europe. The search for sources of resistance to this strain is proposed as the most efficient and safe solution to ensure high grain production. This will be helped by the development of high performance and low cost techniques for field phenotyping. In this study we analyzed vegetation indices in the Red, Green, Blue (RGB) images of crop canopies under field conditions. We evaluated their accuracy in predicting grain yield and assessing disease severity in comparison to other field measurements including the Normalized Difference Vegetation Index (NDVI), leaf chlorophyll content, stomatal conductance, and canopy temperature. We also discuss yield components and agronomic parameters in relation to grain yield and disease severity. RGB-based indices proved to be accurate predictors of grain yield and grain yield losses associated with yellow rust ($R^2 = 0.581$ and $R^2 = 0.536$, respectively), far surpassing the predictive ability of NDVI ($R^2 = 0.118$ and $R^2 = 0.128$, respectively). In comparison to potential yield, we found the presence of disease to be correlated with reductions in the number of grains per spike, grains per square meter, kernel weight and harvest index. Grain yield losses in the presence of yellow rust were also greater in later heading varieties. The combination of RGB-based indices and days to heading together explained 70.9% of the variability in grain yield and 62.7% of the yield losses.

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Peer review under responsibility of Crop Science Society of China and Institute of Crop Science, CAAS.

http://dx.doi.org/10.1016/j.cj.2015.03.003
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1. Introduction

Wheat is the second most cultivated cereal in Spain [1] and the most widely cultivated cereal worldwide, with over 218 Mha in cultivation [2]. *Puccinia striiformis* is the causal agent of yellow rust in grasses and has been described as infecting a wide variety of cultivated cereals, including wheat, rye, barley and triticale. The *forma specialis* (f. sp.) *tritici* primarily infects wheat. The presence and severity of this fungal disease in Mediterranean and temperate cultivars has not been of importance until recently. The use of wheat varieties resistant to this pathogen had previously ensured that losses were minimal in the Mediterranean region [3]; however, the presence of a new *Pst* race called the Warrior/ Ambition race, first described during 2009/2010 in the United Kingdom, Germany, Denmark, France and Scandinavia, has severely affected winter wheat production in recent years [4]. One year after it was first discovered in Europe, its presence was also detected in Spain [4] and the disease spread extensively during the 2012/2013 winter wheat season. Several epidemic events resulting in serious crop damage and widespread yield losses in Spain [3] have since been recorded. The rapid spread of this strain was favored by the climatic conditions of the 2012/2013 season: cool temperatures during spring, high humidity and prolonged rainy conditions [5].

P. striiformis f. sp. *tritici* has a great capacity for dispersal and for variation [6]. The new Warrior/Ambition strain is virulent for most of the currently deployed resistance genes [3] and can therefore parasitize most of the wheat varieties presently grown around the world. In addition, this fungus spreads by wind over hundreds of kilometers, germinates quickly at low temperatures (7–10 °C) [6,7], and infects wheat crops at a relatively early growth stage. The most apparent visible sign of infection is the orange-yellowish mass of urediniospores being produced by uredinia arranged in long, narrow stripes along the leaf veins. Development of resistant varieties is essential for effective control; however, to date no variety with resistance to the strain has been recommended in Spain [8]. There is an urgent need to develop improved high throughput field phenotyping approaches for breeding for yellow rust resistance in wheat.

The diversity of existing wheat varieties provides a source of genetic variability from which we can select a high number of features of interest, such as drought and salinity tolerance, improvements in nutrient use efficiency or, in our case, disease resistance. Phenomics arises as a complex and integrative discipline that tries to characterize plant functional traits related to specific conditions from the cell to community level. However, it is considered a major bottleneck with regard to the advancement of crop breeding [9–13]. Thus, high-performance phenotyping systems are required to understand the relationships between genotype, phenotype and environment. Phenotyping requires that the studied trait and the chosen methodology for its measurement are appropriate for the purpose of the investigation.

There are currently several criteria for field phenotyping by monitoring and analyzing different plant traits as a response to stress conditions. However, most of these techniques are time-consuming, unrepresentative of the whole plot and/or require sampling, laboratory processing and costly equipment. Visible and near infrared (VNIR) spectral measurements have high performance in characterizing physiological and biochemical processes as well as agronomic traits at both crop and leaf levels [14–20], whereas, thermal imaging enables rapid observations of plant water status and their cooling ability [9,10]. Both approaches can be integrated as part of field-monitoring platforms, but their implementation is expensive. As an alternative, vegetation indices based on conventional digital Red, Green, Blue (RGB) digital imaging are high-performance, low-cost techniques for predicting plant and crop traits, and can be based on processing pictures of either crop canopies or single leaves [21]. The use of these technologies is currently expanding due to their versatility and affordability. Some of their proven applications are: the development of predictive models for crop yield under specific growing conditions [22], crop growth assessment under water stress conditions [23], fertilization monitoring and nitrogen requirements [24], LAI (leaf area index) for lodging risk evaluation in winter wheat [25], and quantification of pollen release [26].

The efficacy of RGB digital methods for the evaluation of a pest or disease at the leaf level has also been reported, including powdery mildew on cucumber leaves [27], assessment of foliar disease symptom severities in corn, wheat and soybean [28], determination of the impact of disease severity of specific grain diseases [29], and of different types of fungal diseases in wheat [30,31]. In all these cases image analysis techniques were employed to detect the presence of the pest or disease and the infected, necrotic and/or dry areas using scans or photographic images of leaves or other plant parts. This approach has proven highly accurate in its predictions, but is cumbersome and time consuming in practice because it requires manually intensive and destructive harvesting and photographing the plant organs of interest. Studies on sensitivity of crops to biotic stress using hyperspectral crop canopy data have been conducted previously [32–35], but no previous studies using digital RGB cameras at the canopy level are known to the authors. Thus, the development of prediction models of grain yield (GY) and crop pathogen sensitivity using digital RGB photography of crop canopies represents a novel and practical alternative to other remote sensing approaches, such as VNIR-derived vegetation indices, for wheat phenotyping under field conditions.

The objective of this study was to assess the sensitivity of autumn sown wheat varieties to yellow rust under field conditions using different methodologies. First, we assessed the performance and accuracy of RGB indices in comparison to the Normalized Difference Vegetation Index (NDVI) for prediction of grain yield losses associated with yellow rust. Second, we evaluated the performance of other agronomic metrics commonly used in field phenotyping (leaf chlorophyll content, stomatal conductance and canopy temperature) and their relationships with GY and disease severity. Third, we investigated the effects of yellow rust on the relationships between common agronomic parameters, GY and the grain yield loss index (GYLI). Finally, we combined the best remotely-sensed vegetation indices and agronomic metrics in stepwise multivariate predictive models of GY and GYLI.

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