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Research Paper

Hyperspectral measurements of yellow rust and fusarium head blight in cereal crops: Part 2: On-line field measurement

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Yellow rust and fusarium head blight cause significant losses in wheat and barley yields. Mapping the spatial distribution of these two fungal diseases at high sampling resolution is essential for variable rate fungicide application (in case of yellow rust) and selective harvest (in case of fusarium head blight). This study implemented a hyperspectral line imager (spectrograph) for on-line measurement of these diseases in wheat and barley in four fields in Bedfordshire, the UK. The % coverage was assessed based on two methods, namely, infield visual assessment (IVA) and photo interpretation assessment (PIA) based on 100-point grid overlaid RGB images. The spectral data and disease assessments were subjected to partial least squares regression (PLSR) analyses with leave-one-out cross-validation. Results showed that both diseases can be measured with similar accuracy, and that the performance is better in wheat, as compared to barley. For fusarium, it was found that PIA analysis was more accurate than IVA. The prediction accuracy obtained with PIA was classified as good to moderately accurate, since residual prediction deviation (RPD) values were 2.27 for wheat and 1.56 for barley, and R^2 values were 0.82 and 0.61, respectively. Similar results were obtained for yellow rust but with IVA, where model performance was classified as moderately accurate in barley (RPD $= 1.67$, $R^2 = 0.72$) and good in wheat (RPD $= 2.19$, $R^2 = 0.78$). It is recommended to adopt the proposed approach to map yellow rust and fusarium head blight in wheat and barley.

1. Introduction

Site specific fungal disease control is a large task for successful production of cereals worldwide, and requires data sampled at high spatial resolution due to in-field variation of these diseases. The severity of these diseases depends mainly on weather conditions, which necessitates information not only on disease spread, but weather conditions too. Yellow rust (*Puccinia striiformis*) is a foliar disease that is common in cool climates, and is one of the most devastating diseases of wheat worldwide, reducing crop yields by up to 7 tonne ha^{-1} in severe epidemics (Bravo, Moshou, West, McCartney, & Ramon, 2003; Ma et al., 2001). In 2009 yellow rust mutations have

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enabled the disease to attack several widely grown genetically resistant cereal crop varieties, including Solstice (Milus, Kristensen, Hovmøller, 2009). Another important fungal disease that attacks cereal crops is fusarium head blight, with the most aggressive and prevalent species (*Fusarium graminearum*), causing mycotoxins in the grain (Brennan, Egan, Cooke, & Doohan, 2005; Desjardin, 2006; Leslie & Summerell, 2006; Rotter, Prelusky, & Pestka, 1996). Fusarium predominantly affects the ear of the crop and has become one of the most important pre-harvest diseases worldwide. Like yellow rust, fusarium head blight also causes reduction in yield quantity and quality and when producing mycotoxins it becomes a significant threat to both humans and animals. Fusarium head blight is a sporadic disease, that is dependent on warm humid weather conditions (Rossi, Ravanetti, Pattori, & Giosue, 2001; Xu, 2003), causing variability of disease presence and level of infection across regions, and years (Jelinek, Pohland, & Wood, 1989). Both yellow rust and fusarium species can survive in soil and weeds occurring in the hedgerows and borders of a field, and fusarium head blight also survives within plant residues even after 2 years, acting as a source of inoculum (Champeil, Dore, & Fourbet, 2004; Imathiu, Edwards, Ray, & Back, 2013; Jenkinson & Parry, 1994). Therefore, control of mycotoxins caused by fusarium fungi is required to prevent toxic contamination reaching the food chain either in milling grain (for human consumption) or as cattle feed (Magan, Hope, Colleate, & Baxter, 2002).

Traditionally, disease detection is carried out manually by human experts using visual assessments of disease coverage throughout the field, a process that can be lengthy, subjective and tiresome (Bock, Poole, Parker, & Gottwald, 2010; Schmale & Bergstrom, 2003). This method is limited in providing high sampling resolution data on spatial variability of crop disease. Therefore, on-line mobile systems are necessary to inform site specific application of fungicides.

It has been stated that optical technologies are available for development into suitable disease detection systems, but with many challengers still required to be overcome (West et al., 2003). Although on-line applications are still rather limited, optical techniques have the potential to be integrated with agricultural vehicles. Optical (both remote and proximal) methods can provide non-invasive, high sampling resolution data that are necessary for monitoring and mapping of crop diseases. Among optical sensing methods, hyperspectral and multispectral imaging techniques are among the best candidates, as they have been used in disease and stress monitoring (Hahn, 2009). Non-mobile (off-line) field and laboratory methods for disease classification and plant growing conditions have been studied and demonstrated (Roggo, Duponchel, & Huvenne, 2003; Wu, Feng, Zhang, & He, 2008). The early success in field studies for hyperspectral image-based detection of yellow rust (Bravo et al., 2003; Moshou et al., 2004) focused on the presence of yellow rust in the field, not necessarily the severity. Moshou et al. (2005) implemented a data fusion approach of a hyperspectral (450–900 nm) and fluorescence (550–690 nm) imaging techniques for yellow rust detection in winter wheat, reporting 94.5% accuracy. Other common attempts with hyperspectral and multispectral imagery are targeted to leaves rather than the canopy (Bock et al., 2010). Huang et al. (2015) successfully provided quantitative assessment of yellow rust in winter wheat, by hyperspectral measurement of individual infected leaves. Zhou et al. (2015) used low cost RGB images for quantification of yellow rust, reporting 74% and 81% detection accuracies. Zhao et al. (2016) focused on two sensitive bands (558 nm and 856 nm) in the wavelength ranges of 550–680 nm and 750–1300 nm to detect yellow rust with 90.6% accuracy. Krishna et al. (2014) used remote hyperspectral data in 350–2500 nm range for quantitative identification of yellow rust. To the best of our knowledge there are no reports in the literature on on-line application of proximally captured hyperspectral imagery for simultaneous assessment and mapping of yellow rust and fusarium head blight in wheat and barley. Such analyses in laboratory conditions was discussed in Part 1 of this study (Whetton, Waine, & Mouazen, 2017b), where plants in trays were subjected to variable water stress, and were inoculated with yellow rust and fusarium head blight. The aim of this paper is to implement a hyperspectral imager for on-line measurement of yellow rust and fusarium head blight in wheat and barley grown commercially outdoors in the fields.

2. Materials and methods

2.1. *Field sites*

Field measurements were conducted in four different sites through the 2015 cropping season. These sites were located at Duck End farm, Wilstead, Bedfordshire, UK (52°05′46.3″N 0°26′41.4″W), with an average annual rainfall of 598 mm. The farm has a three year crop rotation of oil seed rape, winter wheat and winter barley. Fields varied in size between 12, 10, 7 and 4 ha (Table 1), to allow for pattern identification of diseases with different field size. This is because yellow rust and fusarium head blight occurrence in the field often begins nearer the hedgerows, and the spread pattern throughout the growing season may well depend on the shape and size of the field. Winter wheat was grown in three fields, whereas winter barley was grown in the 10 ha field only. The largest and smallest winter wheat fields were scanned at two different intervals. Timing and growth stage of measurement in each field is shown in Table 1. Growth stage in this study refers to the Zadok's scale (Zadoks, Chang, & Konzak, 1974). The dominant soil texture types in the fields are shown in Table 1, with sand fractions due to underlying gravel deposits.

2.2. *Soil moisture content measurement*

An on-line visible and near infrared (vis-NIR) spectroscopy soil sensor developed by Mouazen (2006) was used in this study to measure gravimetric soil moisture content (MC) in field 4, with the objective of studying the influence of MC on crop disease spatial distribution. The system consists of a subsoiler, opening a smooth-bottom trench at 15 cm depth (Mouazen, Anthonis, & Ramon, 2005). The sensor was mounted on a three-point linkage of a tractor travelling at a speed of 3 km h^{-1} and collecting soil spectral data at 10 m parallel intervals. In order to measure soil spectra an AgroSpec mobile, fibre type, vis–NIR spectrophotometer (Tec5 Technology for