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Evaluating management zone maps for variable rate fungicide application and selective harvest

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ABSTRACT

Currently the majority of crop protection approaches are based on homogeneous rate fungicide application (HRFA) over the entire field area. With the increasing pressures on fungicide applications, associated with increased environmental impact and cost, an alternative approach based on variable rate fungicide application (VRFA) and selective harvest (SH) is needed. This study was undertaken to evaluate the economic viability of adopting VRSA and SH in winter wheat and the environmental benefit in terms of chemical reduction is also discussed. High resolution data of crop canopy properties, yellow rust, fusarium head blight (FHB), soil properties and yield were subjected to *k*-means cluster analysis to develop management zone (MZ) maps for one field in Bedfordshire, UK. Virtual cost-benefit analysis for VRFA was performed on three fungicide application timings, namely, T1 and T2 focused on yellow rust, and T3 focused on FHB. Cost-benefit analysis was also applied to SH, which assumed different selling prices between healthy and grain downgraded due to mycotoxin infection. Results showed that in this study VRFA allowed for fungicide reductions of 22.24% at T1 and T2 and 25.93% at T3 when compared to HRFA. SH reduced the risk of market rejection due to low quality and high mycotoxin content. Gross profit of combining SH and VRFA was £83.35 per hectare per year, divided into SH £48.04 ha^{-1}, and VRFA £8.8 ha^{-1} for T1 and T2 and £17.7 ha^{-1} for T3. Total profit when considering soil and crop scanning costs would be £66.85 ha^{-1} per year, which is roughly equivalent to €80 or \$90 ha^{-1} per year. This study was restricted to a single field but demonstrates the potential of fungicide reductions and economic viability of this MZ concept.

1. Introduction

High crop yields would ideally be achieved with minimal environment impact. Conventional agricultural practice has led to increased crop yields, but depends on the unsustainable management of external inputs, posing severe environmental problems (Pimentel et al., 1995; Hole et al., 2005). Considerable yield losses occur due to crop diseases, requiring the development of sustainable approaches to crop disease management. Variable rate management of farm external inputs is a potential approach to achieve this. Site-specific management requires high resolution data on all relevant factors. High resolution data collection for specific diseases, crop canopy, and soil properties is possible with the use of on-line crop and soil sensors (Kuang et al., 2012; Kuang and Mouazen, 2013; Whetton et al., 2018a). Fusing these different layers of information allows for the creation of management zones (MZ). This study will focus on and explore the potential use of these MZ for variable rate fungicide application (VRFA, where the rate of fungicide can be varied in response to requirement), and selective harvest (SH, where grain can be harvested separately in areas of high and low quality).

Yellow rust is a foliar fungal disease that is linked with a long history of yield loss. Yield loss is mostly attributed to a reduction in the number of grains per ear, and the weight of individual grains (Herrera-Foessel et al., 2006). Across the globe, yield losses due to yellow rust are reported to be between 10 and 70% (Chen, 2005), with susceptible varieties often being > 50% (Safavi, 2015). Historically, Doodson et al. (1964) reported yield losses of 64.5% in individual infected plants, whilst Doling and Doodson (1968) attributed yield loss reductions of up to 30% to the cultivation of resistant spring and winter wheat varieties.

Fusarium head blight (FHB) is a sporadic ear disease, with level of infection varying across regions and years (Jelinek et al., 1989). FHB can result in yield losses, economic losses (direct and indirect) and negative influences on human and animal health (Paul et al., 2005). The direct economic loss is attributed to reduced grain quantity and

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size, while indirect loss is due to reduced quality, and mycotoxin contamination (a secondary metabolite of the fusarium mould), associated with market rejection or downgrading of grain (Parry et al., 1995). The downgrading of grain can occur if a portion of the harvested grain is of lower quality, this can reduce the overall quality or cause the harvested grain to surpass the mycotoxin health limits. With the increased awareness of food security, and the knowledge that one third of food is currently lost or wasted, innovative studies are needed to maximise yields and quality of yield reaching the market (Gustavsson et al., 2011). It is estimated that without the use of crop protectants and fungicides about 50% of wheat yield can be lost due to pests (Oerke, 2006). To generate similar yield levels, an expansion of the extent of arable land will be required and combined with inefficient application of external inputs, this may lead to increased levels of greenhouse gas (GHG) emissions (Mahmuti et al., 2009; Berry et al., 2010; Burney et al., 2010; Carlton et al., 2010). Use of fungicides for disease control on wheat, barley and oilseed rape is estimated to save emissions in excess of 1.5 Mt CO2-e in each cropping season (Hughes et al. 2011), while reductions in external inputs is also linked to decreased emissions (Lin et al., 2011).

Soil characteristics affect the crop growth and yield, e.g. more fertile soil leads to stronger and more resistive plants if plant density is controlled (Sylvester-Bradley and Kindred, 2009). Microclimate conditions also affect crop growth and disease spread with a greater occurrence of fungal diseases observed in denser canopies, but a conclusive regression relationship through multiple years and fields has not been found, potentially due to the confounding effects of weather (Rozalski et al., 1998). An essential step towards site specific plant protection is information about crop disease in the field, collected at high sampling resolution. However, information on crop disease alone is not sufficient for an integrated decision support system, due to the influence of other factors e.g., relevant soil properties, microclimate conditions and crop canopy characteristics (Sylvester-Bradley and Kindred, 2009). To our best knowledge, no assessments exist examining the environmental and economic benefits of VRFA for yellow rust and FHB, and SH based on fusion of high sampling resolution data, of soil characteristics, crop growth and diseases, and microclimate conditions.

The aim of this paper is to apply a multi-sensor and data fusion approach for the delineation of MZ maps for VRFA and SH. It will evaluate whether these approaches could have potential economic benefits. This study focuses on the potential economic benefits, using a virtual cost-benefit analysis, of heterogeneous fungicide applications and selective harvest based on high sample data, compared to a conventional practice.

2. Materials and methods

2.1. Field site

One study field of 10.8 ha with cereal crop production was selected for this study. It is located at Duck End Farm, a commercial family farm in Wilstead, Bedfordshire, UK (52°05′46.3″N 0°26′41.4″W), with an average annual rainfall of 598 mm. The northern part of the field is a clay soil, whereas the southern part is a sandy clay soil. The farmer uses a 3-year crop rotation of barley, wheat and oil seed rape. The experiment was carried out in 2015 during the winter wheat rotation. Yellow rust and FHB were observed in the field. Measurement dates of soil, crop canopy, diseases, micro-climate conditions, and yield in relation to growth stages are shown in Table 1. Detailed information about the collection of each dataset is further described below.

2.2. Disease and canopy data collection

A push broom hyperspectral imager (spectrograph) (HS spectral camera PS model from Gilden Photonics Ltd., UK) using a spectral range of 400 and 750 nm was used. The imager along with a halogen light source were mounted on a tractor, by means of a metal frame for on-line measurement of yellow rust and FHB. The optimal configurations include an integration time of 50 ms, a camera height of 0.3 m and light height and distance of 1.2 m and a camera angle of 10°. Measurement was carried out at a forward travel speed of approximately 4 km h^{-1}, and line images were captured at 1 sec frequency, which is subsequently logged and geo-located with a sub-meter accuracy, using a differential global positioning system (DGPS) (EZ-Guide 250, Trimble, California, USA). At 5 locations per hectare ground truth plots were selected (Fig. 1), where manual disease assessment and recognition of yellow rust and FHB were made (0 for no infection, 1 for less than 5% infected heads (FHB) or leaf area (yellow rust), 2 for up to 10%, 3 for up to 30%, 4 for up to 50%, and 5 being a heavy infection of over 50%) and applied to calibration models. Whilst the NIR is a key spectral region for detecting early disease symptoms, successful models for crop disease detection have been built using the visual spectrum, highlighting the significance of the 500 nm, 600 nm, and 650 nm wavebands (Sasaki et al., 1999; Thomas et al., 2017). The models utilised in this study were classed as a good accuracy 0.78 and 0.82 R^2 for the detection of established yellow rust and FHB, respectively. The methodologies and models for application of the hyperspectral imager and crop disease detection was utilised from our previous (Whetton et al., 2017, 2018a and 2018b).

At the same 60 ground truth locations, data of leaf area index (LAI) was collected with use of a Sunscan (V1, Delta-T devices, Cambridge, UK) sensor, while air humidity and temperature were measured with a hand-held device (Testo 610, Hampshire, UK), positioning the sensor just under the flag leaf. Yield was measured with on-board yield sensor of the farmer's combine harvester (New Holland, CX8070 model) and normalised difference vegetation index (NDVI) was measured with an online Crop Circle sensor (Crop Circle ACS 470, Holland Scientific, Lincoln, NE USA).

Table 1
Date of different measurement as related to crop growth stages according to the BBCH scale (Lancahsire et al., 1991).

Parameter	Date of measurement	Growth stage
Yield	September 2015	NA
NDVI and LAI	May 2015	43
Soil properties (MC, TN, OC, CEC)	September 2014	NA
Yellow rust early	May 2015	43
Yellow rust late	July 2015	70
Fusarium head blight	July 2015	70
Canopy data (humidity, temperature)	May 2015	43

NDVI is normalised difference vegetation index; LAI is leaf area index; MC is moisture content; TN: is total nitrogen; CEC is cation exchange capacity; OC is organic carbon.

2.3. On-line soil measurement

An on-line visible and near infrared (vis-NIR) spectroscopy sensor (Mouazen, 2006) was used to measure soil total nitrogen (TN), organic carbon (OC), moisture content (MC) and cation exchange capacity (CEC). It consists of a mobile, fibre type, AgroSpec visible and near infrared (vis-NIR) spectrophotometer (tec5 Technology for Spectroscopy, Germany) with a measurement range of 305–2200 nm, and a differential global positioning system (DGPS) (EZ-Guide 250, Trimble, USA) to record the position of the on-line measured spectra with submetre accuracy. The spectrophotometer was linked with an optical probe by means of two optical fibres. The optical probe was attached to the underside of a subsoiler, which penetrated the soil opening a smooth trench. The probe was illuminated by a 20w light source and collected diffuse reflected spectra at 1 sec frequency. A detailed description of the system can be found in Kuang and Mouazen (2013). On-line measurement was carried out in 2014, after the harvest of the