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Variable Rate Application of Plant Protection Products  
(Fungicides on Winter Wheat)

Environment and Agrifood

PhD

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## ABSTRACT

Variable rate application (VRA) has the potential to allow farmers to use the most suitable dose rate of fungicides required for their winter wheat fields. Currently, the dominant practice is to apply fungicides at a uniform dose rate irrespective of in field variability. VRA could reduce fungicide costs, prevent chemical resistance, and reduce environmental damage. Whilst VRA is more commonplace in Nitrogen applications and more recently plant growth regulator (PGR) applications, there is still a hesitancy to use VRA for fungicide applications. With the removal of fungicide active ingredients and resistance to actives, the future of fungicide application is to determine the most appropriate dose and reducing over-spraying where possible. The primary aim of this thesis was to understand how to achieve VRA of fungicides on winter wheat, most effectively and efficiently in the future. To achieve this, several research gaps were investigated. Research was conducted into the 'state of the art' VRA technology finding that the main barriers are cost and perceived risk of inconsistency of effect. A laboratory trial was conducted in 2018 to study the deposition of a dye representative of fungicide through the winter wheat growing season. Destructive sampling was conducted to determine the variation in quantity of dose rate per gram of biomass for each fungicide application timing, finding the later growth stages received the greatest dose but the dose relative to the biomass was lower than earlier growth stages. In 2019, March – June, a field study was conducted over two farms to measure the spatial and temporal variation in volumetric biomass and determine if NDVI is a suitable basis for application decisions, finding that monitoring at T0 and T1 growth stages was best for reflecting canopy variability. From this, a new method was piloted to extract NDVI min and max values from 43,000 winter wheat fields in 2018. This was to understand the range of variation, in NDVI values at T1, in winter wheat fields is enough to continue investing in VRA. Finally, a cost benefit analysis was performed comparing a standard uniform dose and a VRA system, finding a saving of £13.82/ha on one farm from one VRA spray (T1). If a similar saving was made at T0, T2, and T3 an overall saving would be made of £55.28/ha. This study provides methodology for conducting VRA and a foundation for future VRA investigations.

Keywords:

NDVI, Remote Sensing, Variability

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## **LIST OF ABBREVIATIONS**

|       |                                               |
|-------|-----------------------------------------------|
| PPP   | Plant Protection Products                     |
| VRA   | Variable Rate Application                     |
| WW    | Winter Wheat                                  |
| NDVI  | Normalised Difference Vegetation Index        |
| VAGB  | Volumetric estimation of Above Ground Biomass |
| GS    | Growth Stage                                  |
| LE    | Leaf Emergence                                |
| T#    | Timing                                        |
| LiDAR | Light Detection and Ranging                   |
| N     | Nitrogen                                      |
| PGR   | Plant Growth Regulator                        |
| AUDPC | Area Under the Disease Progress Curve         |
| UAV   | Unmanned Aerial Vehicle                       |
| PWM   | Pulse Width Modulation                        |

# **1 Introduction: dose adjustment and optimisation strategies for variable rate application of plant protection products.**

## **1.1 Variable Rate Application**

In 2020 9.9% of the population was suffering with undernourishment and with the global population projected to reach 9.7 billion by 2050, increasing crop yield is an integral part of continued food security, (Food and Agriculture Organisation of the United Nations 2020; Rutgers 2017; Long et al 2015; UNDESA Population Division 2015). The current most common application technique for plant protection products (PPPs) is to treat uniformly across fields, (Dammer, et al. 2008; Berk et al. 2016). However, since fields are not uniform and crop canopies are not expected to grow identically this may not be the best management practice to support the required increased yield. Giving up PPPs is therefore impossible, and a balance between their application and environmental protection must be struck. Under-dosing risks inadequate protection causing production loss from a lack of efficacy, and therefore resistance from pests, diseases, or weeds, (Milner and Boyd 2017; Wiik 2009). Over-dosing of PPPs has no economic return and can lead to surface runoff having levels of pesticides and fungicides that exceed guideline values which causes damage to habitats, endangered species, drinking and livestock water, and irrigation, (Castelnuovo 1994).

Plant protection products comprise a minimum of one approved active substance or synergist including microorganisms, pheromones, or botanical extracts. The use of chemicals that interfere in nature demand high standards of safety requiring rigorous testing and strict regulation, which attributes to high development and production costs, (Lainsbury 2017). Since excess and unused products go to waste, PPPs are the highest variable cost to producers (Forney and Kocher 2017; Tona, et al. 2017). Manufacturer labels dictate a maximum dose rate for the PPPs which is not based on maximum plant retention of the product. Maximum doses are calculated to ensure only safe quantities of the chemical are in the environment while having the maximum effect on the pest or

pathogen. Farmers therefore often apply doses lower than the maximum manufacturer recommended rate as sufficient control can be obtained, (Paveley et al. 2000a; Jørgensen et al. 2017).

Continuous or uniform application of PPPs dose does not reflect variation spatially (within the field) or temporally (between growth stages), (Milner and Boyd 2017). For example, it is not appropriate to apply the same dose to small and large canopy trees, or to early and late winter wheat (WW) growth stages, (Sutton and Unrath 1984; Li et al. 2017). Adjusting doses to suit crop canopies considers how best to match dose rate with plant biomass. This includes crop variety, growth stage, structure of the plant canopy through growth stages, characteristic of the surface of leaf, leaf surface area, flower, or fruit, the maximum dose retention of the plant, nutrient and disease areas within fields and the number of times the crop has been sprayed previously. This method is called Variable Rate Application (VRA). Since so many variables effect the efficacy of PPPs and the efficiency of disease suppression, (Paveley et al., 2000b), tuning the time of application is crucial to achieve an optimal dose. Detecting growth stages by determining biomass will give an understanding of the surface area cover needed and green leaf area detection shows the active canopy.

Zhu et al. (2011), tested differing spray rates to find the optimum spray deposition for various size tree liners in ornamental production. Destructive sampling was used to determine spray deposition of a tracer dye, Brilliant Sulfaflavine, which was then used for recommendations of spray to various tree heights. The study observed that higher doses were suited for larger canopy and smaller doses for smaller canopies.

Thomas (1986) found that areas of wheat crops that were receiving a late application of spray could have three times the negative impact and frequently suffer the same level of *Septoria tritici* as untreated crops. The most appropriate time for application was between the flag leaf to ear emergence as this was most cost effective for reduction of foliar diseases. A survey from 1991 found that in one in three cases of fungicide treatment, the application was too late for peak effectivity (Cook, et al. 1999). It is clear therefore that there is a lack of

understanding in industry between fungicide activity and the spray application timing. Reducing unnecessary applications will improve the economics behind disease control, as will understanding fungicide properties for maximum efficacy within the field (Jordan et al., 1986 as cited in (Cook, et al. 1999).

This introduction chapter aims to describe the current 'state of the art' in dose adjustment and optimisation of PPP dose rates and to explore the baseline doses required within the crop canopy throughout the growth stages. The VRA technology needed to suit the spatio-temporal changes seen within field and canopies exists in research, but there is a slow uptake commercially. However, a unifying issue in the research is the missing component of a baseline input of PPP. The dose adjustments are based on recommendations from manufacturers or by agronomist suggestions of a % of the manufacturer recommended dose, assuming the relationship is linear (Dammer et al., 2008). This relationship is unknown, but if identified the necessary quantity for each growth stage can be programmed into the specialist machinery and plant dose adjustment and optimisation technology research should show more consistent results. Understanding where the misapplied doses occur, the decision factors for dose quantity and the methods of application are the steps towards best practice PPP use, safety, and traceability.

## **1.2 'State of the art' in dose adjustments**

### **1.2.1 Variable Rate Application Sprayers**

In conventional spray systems, dose delivery is adjusted by nozzle type, flow rate, and speed of travel. For VRA systems to achieve adjusted dose, spray flow can be adjusted by output control, on/off control and varying the concentration of active chemical in the dilutant. Output control was first used for adjusting the pressure to keep uniform spray deposition when the speed of travel changed, developing into the basis for VRA dosing. However, changing the pressure in such a way can distort spray droplet size and alter the pattern of application, therefore bypass nozzles, cluster nozzle systems, variable orifice nozzles and pulse width modulation were developed as alternatives to flow variation (Sudduth et al. 2019). On/off control, or section control, is the simplest form of VRA dose

adjustment, with the options of dose as full, or none (Figure 1-1). Good spatial resolution of between 3-6m can be achieved by switching off sections of boom (Miller 2019). It is optimal for reducing overlapped spraying, predominately in irregularly shaped fields and a major benefit is the ability to avert the spray from landing on field margins or water ways (Sudduth et al. 2019). Individual On/off nozzles would improve resolution up to 0.5m, excellent for a disease incidence based VRA for systemic application and for control of zonal application of protectant fungicides (Miller 2019).

Using a direct injection of active into a dilutant would allow control of dose to be suited to the biomass of the plant, reducing leaching and over application. Further benefits can be found in the separation of tank water from the active, lessening contamination of the spray system and reducing flushing requirements whilst also having the capability for changing the chemical formulation to suit high spatial variability, (Miller 2019). Theoretically, a constant pressure from dilutant is required for droplet consistency, but in studies differences in dose application arose from changes in operating speed (Miller 2019). The major downfall of direct injection is in the risk of improper mixing of the tank and therefore an undesired mix of active chemical concentrations on targets, (Sudduth et al. 2019).

Bypass nozzles work by returning part of the flow back to the tank using constant pressure to keep dose pattern and droplet size consistent, (Han, Bode, and Hummel 1986). However, this does not seem to be at the forefront of research.

Changing nozzles during spraying would achieve desired droplet size for the required dose, either to reduce spray drift or margin spraying, or to achieve better coverage on smaller plants. A nozzle cluster provides a solution; having up to four nozzles in a single holder, the option to change individual cluster arrangements or multiples along the boom gives a greater variable coverage. Another option would be to use variable orifice nozzles which adjust the aperture of the nozzle with pressure. Unfortunately, this is an erratic variation and gives unpredictable spray patterns. Pulse width modulation (PWM) is the rapid on/off of power supply to the system, directing nozzles to stay open or closed for desired periods of time, (Miller 2019). This is effective in reducing field margin spraying

and controlling drift, (Miller 2019). The issue with PWM is that the dose rate error, between the pulses as the spray cone changes, may vary beyond  $\pm 10\%$  (Mangus et al. 2017).

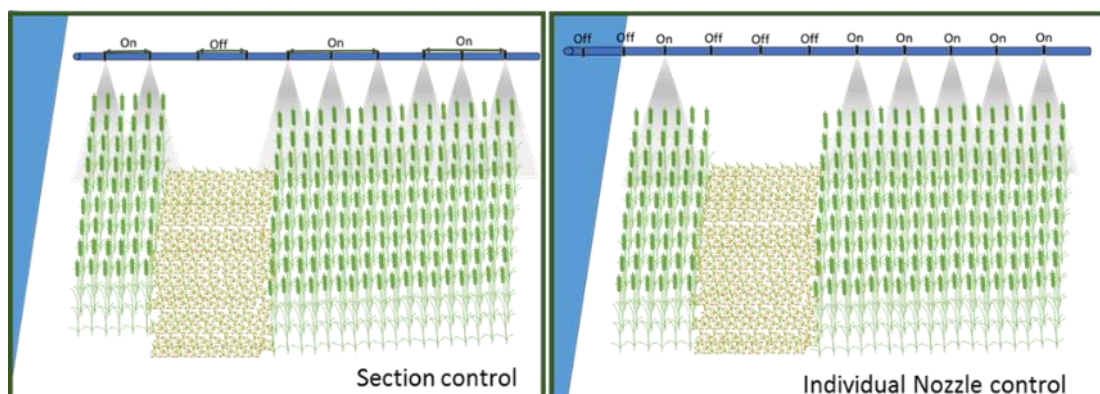


**Figure 1-1: Section control (left) and individual nozzle control (right) examples of variable rate control, where systems are turned off over pathways and over rivers to prevent excess spraying.**

## 1.2.2 Case Studies for VRA systems

### 1.2.2.1 Disease incidence variable rate application

The data required by disease incidence based VRA systems for triggering the rate of dose can be described as offline or online, referring to the connection to the tractor. Offline is labour intensive as field maps are used for highlighting distribution of disease and fed into an operation with multiple sprays of different intensities. Data samples are time sensitive as disease conditions may change between inspection and spraying. Online uses real-time data to detect disease and adjust spray applications accordingly. It requires the use of an automatic disease detection facility and regular monitoring of the field. Comparatively, there is minimal labour involved and spraying can be carried out in a single operation, (Dammer et al. 2009; Grisso et al. 2011; Searcy et al. 1989).

Camera-based decisions systems include phenotyping for target-oriented fungicide application in potatoes, and camera controlled field sprayers for fungicide application in winter wheat, (Dammer, Dworak, and Selbeck 2016; Tackenberg et al. 2017). Sensor-based decision systems include

proPlantexpert.com (University of Münster 1996) for various disease infection rates on winter wheat, (Dammer et al. 2015a). Optical handheld instruments such as LAI2000® and SunScan® are more time-efficient methods for measuring LAI, however, can be costly. Dynamic crop models are another method but are highly complex and require information for multiple inputs (Dammer, Wollny, and Giebel 2008).

A review by Song et al, 2015, on the VRA system called “Smart Sprayer,” which comprises target detection systems and spraying control systems for precision management, highlighted challenges of light condition and how this effects spectral reflectance. Furthermore, crossed leaves were also found to distort the canopy reflectance leading to a misclassification for machine vision detection and growth stage detection from colour analysis. The cost of which is the misinterpretation of data as the spectral reflection changes.

#### **1.2.2.2 Canopy-sized based variable application**

In Citrus fruit production, the removal of whole trees creates a big gap in the canopy which in a uniform spray creates waste resulting in needless costs and environmental damage. By using selected application based on different tree size classes, in mature groves, VRA has led to a cost saving of between 15%-50% (Schumann et al. 2010). Ultra-low-volume (ULV) sprayers can be used to reduce the amount of active chemical ingredient needed per acre and can reduce the application times. This is only suitable for pesticides/fungicides and non-nutrient sprays as high concentrations of nutrients in low spraying volumes can lead to nozzle clogging and foliage damage. This technology is used for viewing, analysing, and locating gaps in the groves and tree sizes. Hoop sprayers which loop over the canopy are utilised to improve the direction of spray and therefore cause a more targeted distribution, reducing the amount which goes off-target (Schumann et al. 2010).

The UK PACE (Pesticide dose rate Adjustment to the Crop Environment) scheme, used a Light Detection and Ranging (LiDAR) based rapid characterisation program to understand variation in orchard canopies (Cross and Walklate 2008). The results showed canopy variation including tree height

accounted for 90% of the variation in pesticide deposits. The scheme was launched so that a consistent dose could be achieved on each tree, suiting canopy density and height, (Cross and Walklate 2008).

Chen et al, 2013, compared a new variable-rate air-assisted sprayer to a normal air-assisted sprayer and a conventional air-blaster sprayer at three growth stages in orchards. Laser scanning technology determined canopy characteristics such as: height, width, foliage density and volume. The VRA achieved a better uniformity in spray coverage at all growth stages and only consumed 27% to 53% of the spray mixture, improving efficiency and accuracy whilst reducing the quantity of off-target spray.

A review of PPP application techniques in orchards, (Berk et al. 2016), explains the use of modelling tree canopies to understand appropriate dose rates. Tree canopies were modelled by Tree Row Volume, where the manual measurements of the canopy had large inaccuracies which led to miscalculation of PPP deposition. As an alternative, canopy height models calculated from spectral and ultrasonic sensors attached to sprayers provide the basic level of estimation; whereas advanced models use measurements from aerial photographs mapped by GIS and LiDAR. The review also focused on different surveying methods for the distribution of crops; manually, aerial imagery, and by vehicle. It is also possible to map yield variability using harvesters, (Ehlert and Dammer 2006a). There is potential reduction in PPP using canopy density dependent spraying techniques for bed-grown crops such as potatoes; expressly in the early season with the first sprayings (van de Zande et al. 2008). The review found that despite growth in height or leaf mass, if the crop covers the soil surface completely then it is possible to match biological efficacy whilst reducing PPP dosing. When developing the density-dependent spraying systems, if diseases are detected before visual symptoms, then a more target-oriented spray system can be created.

Commercially available since 2004, CROP-Meter is a mechanical sensor which uses an online method to gather real-time, small-scale vegetation data in high spatial resolution. The system works on computers with field spreaders to apply

VRA of fungicide to suit up to date crop canopy characteristics (Ehlert and Dammer 2006a). The sensor sits in a physical pendulum that sweeps through the cereal crop canopy with the deflection angle correlating to the crop biomass. CROP-meter showed an average 20% reduction in active use with no negative affect on yield, (Dammer, Bottger, and Ehlert 2003). Further trials showed sensor-driven application methods did not increase disease incidence from reduced fungicide rates when compared to a standard application rate (Dammer and Ehlert 2006; Ehlert and Dammer 2006b). CROP-meter data was then correlated by (Dammer et al., 2008), to LAI data from handheld optical imagers and used to calibrate the VRA system. These data from the LAI optical handheld devices were correlated with a simple model where  $LAI^* = (cropheight (m) \times number\ of\ tillers (m^{-2}))/100$ , which gives farmers a less intense and cheaper process. CROP-meter was also used to control variable application rates for fungicide spraying on wheat, where agronomists chose the min and max inputs of fungicide to suit their site. Results showed reduced application rates for Nitrogen (14.6%) fungicides (23.1%) and growth regulators (23.1%), however, despite reduction there was an increase in yield (3.1%), (Dammer, et al. 2008). A similar, more recent, paper studied dose rates which were decided linearly, with inputs described as min (50L/ha) and max (200L/ha) (Tackenberg et al. 2018).

Ehlert and Dammer (2006a) developed a system called CROP-meter for site-specific Nitrogen, fungicide, and growth regulator application for cereal crops. The decision factor for CROP-meter application rate was the moisture level within the field and if water stress levels were high the application would be low as the absorption by the roots would be minimal. In areas where there was little vegetation, to reduce the risk of lodging, a rule was made that application of growth regulator would be sparse. Based on the lack of surface area for receiving dose, the same principle of reduction was applied to the rate of fungicide application.

The development of a sensor-based VRA system for fungicide on wheat, produced a linear correlation between the camera sensor values for LAI and the observed LAI and biomass. Following validation, the sensor was able to control

the VRA system saving 8% of spray liquid compared to uniform dose, without changing the yield and disease incidence, (Tackenberg, et al. 2016a). To achieve this the camera detected green canopy and adjusted the voltage message to the sprayer to suit the plant requirement. The system showed savings of 44%, 45% and 1% for each strip with the last having a low level of heterogeneity when compared to the first two accounting for the significant difference, (Tackenberg, et al. 2016a).

Advancing with VRA systems requires a more fundamental approach, understanding the decision basis for application and the understanding of the impact of efficacy as the dose rate changes, is vital if there is value to be had in VRA research.

### **1.3 Establishment and Optimisation of appropriate baseline dose rate**

At present the focus of VRA research is on spatial variation within fields, seeking to understand the impact of changing the dose rates to match either crop parameters such as biomass or the level of disease incidence. The baseline dose rate refers to the minimum level of dose required by the plants that is scaled up relative to biomass until the maximum level of dose required is achieved. In research conducted by Dammer et al. 2015b; and Tackenberg et al. 2017, minimum and maximum input of dose values for VRA machine testing were decided by agronomists or by farmers on a L/ha basis. It is uncertain if the most appropriate dose is applied as the assumption is the baseline dose rate and canopy development relationship is linear, Figure 1-2.

Product labels have not changed in 40 years and have a single recommended dose rate for all stages of growth. There is a lack of published research into the dose relating to plant biomass and how it changes over time or with plant physiological changes. There is also minimal research on where the dose is deposited within the canopy as the plants grow through the season. For PPP application this relationship is fundamental to establishing the baseline dose rates for VRA input. Only when this is understood should operational farm factors be taken into account to optimise the baseline dose rate.

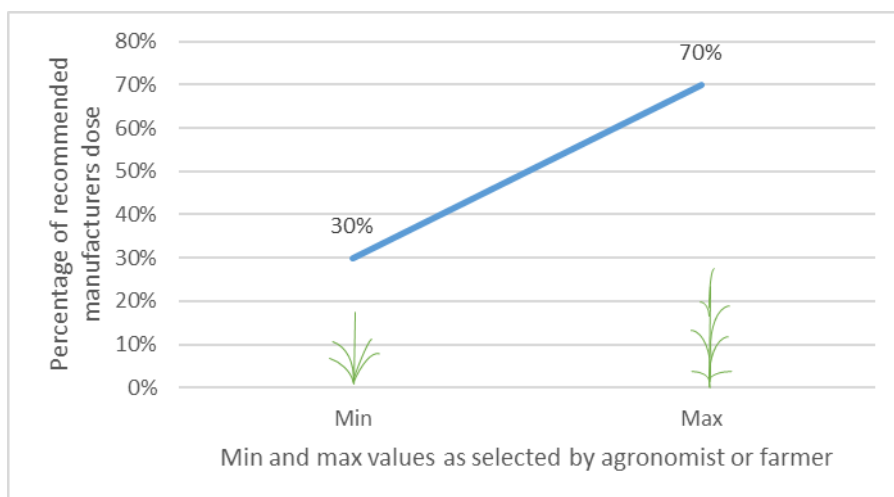


**Figure 1-2: Minimum and Maximum inputs for a variable rate application to suit canopy height**

### **1.3.1 Crop establishment phase**

According to the international standard ISSN 0250-8052, dose expression for PPPs reporting is inconsistent. The most common method of described dose expression is dose per L/ha or % added chemical in water. A dose expressed in this way leads to a variation in the deposition of active per unit of plant material (European and Mediterranean Plant Protection Organization 2021). Following is a brief description of the current techniques and limitations for understanding PPP dose deposition. Modelling and destructive sampling are both used for indicating deposit distribution within crop canopies. Other methods which use photography or sensor technologies remain unpublished, so the level of development is unknown.

The destructive method of sampling, following the International Standard (ISO 24253-2:2015), provides accurate assessments of dose deposition. A known quantity of dye is sprayed onto the target, individual plants within the canopy are then cut and washed off with a known quantity of water. The samples are run through a spectrophotometer set at the known wavelength of the dye and the concentration of colour is measured to determine the quantity of dye applied and dose rate determined. Fruit, leaf, and stem deposits can be separated within these samples to understand distribution penetration within canopies. The

limitation with destructive sampling is that the individual plants cannot be tested more than once. As the canopy ages, the interaction with the dose deposition changes. Canopy growth is never identical, therefore having multiple canopies to represent one to sample through time is not representative without sufficient replication. A non-destructive sensing method for quantification of dose deposition within crop canopies would allow access to interactions with spray through the age of the canopy. The development of a sensing method to understand dose deposition would allow for a more robust understanding of the efficacy of the PPP within the canopy. A canopy could be monitored from the beginning of the season to the end without destructive sampling and sprayed using a tracer dye (water soluble) which could be used to calculate deposition and relate back to biomass on the same canopy.

Off target spray deposition meant for crop canopies can also land on the soil or be lost in airborne and sedimenting-spray-drift. Spray mass balance (SMB) can be used to determine the deposition distribution of spray within the crop canopy. A study reviewed SMB and concluded the most difficult calculation is airborne drift (Jensen and Olesen, 2014). Airborne-spray-drift was calculated as the difference between the amounts deposited and the dye recovered from: the canopy, the ground and sedimenting-spray-drift. Boom and tunnel sprayers were more effective at detecting the placement of spray in the canopy than when compared to the traditional fruit tree/vineyard sprayers as the recovery analysis found that large proportions of the spray were missing. This highlights the uncertainty of whether the airborne-spray-drift calculation may be representative, and cause for concern in the accuracy of the developed methods for detecting the known spray fractions, (Jensen and Olesen 2014).

### **1.3.2 Optimising operational farm factors**

Spatial variability and the management of spatial variability has been the focus of precision agriculture research in recent history (Tremblay 2019). Growing conditions differ greatly from one location to another, providing a challenge to the best-managed fields. This difference can aid in the understanding of the link between soil property variation and irregular crop performance, (McBratney, et al

2003; Webster 2000). To optimise crop production to suit field variation, an understanding of soil spatial variability and the ability for managing these factors should be aligned as a main strategy basing inputs on localised needs for fertilizer, soil pH correction, water availability and plant protection products (Adamchuk et al. 2010). Key field factors for VRA include accounting for heterogeneous landscapes in large fields or across a collection of small land parcels, (Oerke et al. 2010; Thompson and Robert 1994), and the level of accuracy required for mapping these landscapes, (Palmer 1994). Examples of variable field traits include soil properties, namely nutrient availability, soil type, water availability and management history.

Historic management of fields is an influencing factor, as important as naturally occurring variation. Historical tillage practices influence soil organic matter and more recent practices now have double the organic matter available, (Adamchuk et al. 2010). Climate, topography, parent material, organisms, and time all cause variation in soil development (Adamchuk et al. 2010). The distance over which variation occurs for soil properties differs for specific characteristics. Soil nitrate is variable across shorter distances varying between mm and m, and soil carbon is variable across m and km. Key characteristics of dynamic soil properties: soil moisture, microbial activity, water soluble salts, nutrient concentration in soil solution, and soil redox potential. Some properties are dynamic through seasons, others are more static and are dynamic over years. An example of daily temporal change is the shallow depth of soil: deeper in the soil, the temperature is constant.

Heterogeneity in fields is induced by management practices and natural formations – static and dynamic variables. Production economics rule the management of these field variables (Adamchuk et al. 2010). Microclimates across fields can lead to potential differences of 7.5°C, (Bravo et al. 2003), this combined with soil variation and water distribution within fields can lead to major differences in canopy biomass. Using qualitative and quantitative assessment of soil properties to spot consistent patterns (nutrients, topology, and historic management) in the spatial data would support the decision to use a VR site-specific programme.

Coarse sampling of soil is most economical, but it may not fairly represent the spatial variability (McBratney et al. 2003). Decision-making for PPP application is impaired by seasonal effects, especially rainfall (Tremblay 2019) therefore considerations of climate variation should be as important as spatial variation in VRA.

Canopy variation is defined here as the growth stage differences within a crop population, at a specific time. Transient differences in environment and physiological intensity can influence a very small difference in a population to an exaggerated difference with time, (Milthorpe and Moorby 1974). Figure 1-3 illustrates a simulated variable field of WW at early and late growth stages. The rate of growth could be influenced by environmental conditions, considered later, or due to human factors e.g., not setting the correct level of fertilizer or seeding, changing the rate of application, or seeding, doubling the coverage, or forgetting to turn it off or due to poor establishment of crop in some areas. The target for the desired PPP deposition will impact input dose baselines for VRA. Herbicides, pesticides, and fungicides targets are different shapes and structures, sizes, and surfaces. For simplicity, this thesis has decided to focus on fungicide targets, more specifically on how the factors listed below impact the dose deposition and therefore should influence dose baselines.

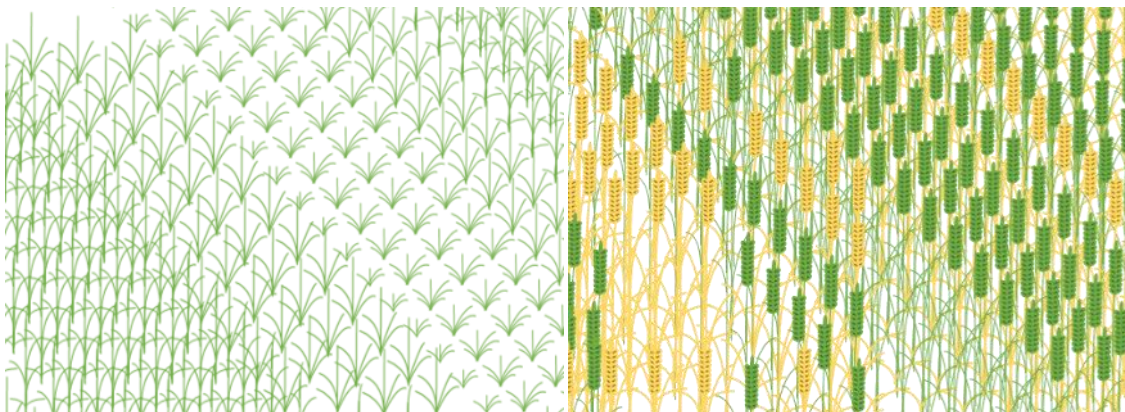


**Figure 1-3: Potential variability within field at key spray timings. Left: T0-T1, right: Ear**

Target properties of interest when optimising dose rate decisions include plant height, leaf angle, leaf surface properties, and leaf properties such as thickness,

leaf size, arrangement of leaves and canopy intersection. Type of crop is important but currently considered in PPP application decisions, whereas variety of crop is not often considered but can have an impact on spray deposition. In wheat, height can vary between 0.3m - 1.5m depending on variety and plant growth regulator use has a significant impact on the quantity of biomass, (Gooding and Davis 1997). The angle of the leaf when attached to the stem and the angle of the tiller also differs between varieties,

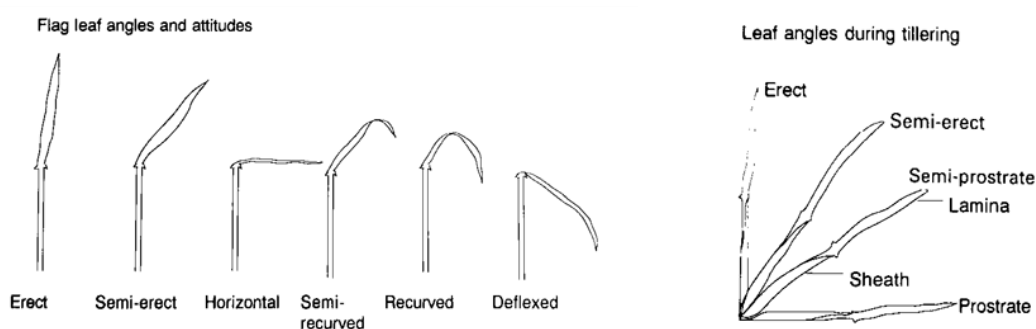


Figure 1-4, this influences the quantity and location of spray deposited on the plant, (Gooding and Davis 1997). The target surface of the PPP will influence the dose-baseline received, as it influences the quantity the target is able to absorb, or quantity required for sufficient coverage. Variety impacts the level of pubescence and glaucousness of leaves for example, wheat varieties are generally glabrous with few small hairs, but varieties exist with high levels of pubescence e.g., Russian spring wheat 'Saratovskaya' 29. Individual varieties have been bred to naturally resist pests and diseases so this should be considered as a factor in VRA to avoid over spraying and resistance, (Gooding and Davis 1997). The level of pubescence will impact the dye deposition so quantity applied and measured should be considered. Variety resistance should also be considered; if the variety has a natural ability to fight infection, then an argument could be made for the quantity sprayed to be reduced. Bearded and non-bearded varieties, ear structure, number of spikelets, and size of spikelets change the amount of dose collected by the plant, meaning that dose baselines should consider variety of cereal and the structure of the variety. Fungicides aimed at cereal crops are targeted at leaf, stem or ear depending on the timing

of application, so consideration of the structure and surface characteristics of the area is vital to VRAs.

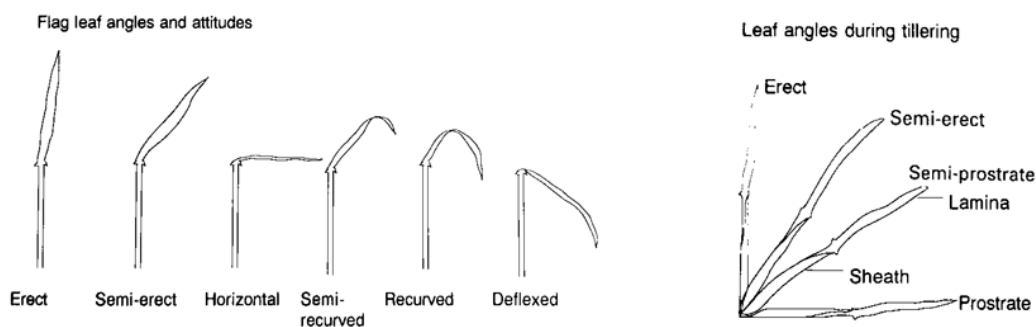


**Figure 1-4: Angles and attitudes of leaf at flag and tillering, (Gooding and Davis, 1997).**

A study on the effects of timing of Nitrogen (N) application interactions with required fungicide application dose rates found the earlier the application of N, the higher the dose of fungicide required (Olesen et al. 2003a). A linear correlation was discovered between optimal fungicide dose and N application rates over a minimum threshold. If the efficacy of the fungicide was higher, then higher rates of N was also required. Fungicide application timing and rate of N application on wheat was investigated in Denmark and observed a varying level of disease over a period of three years (Olesen et al. 2003b). The application of N meant the Area Under the Disease Progress Curve (AUDPC) was increased, especially from early applications. When N and fungicide dose increased, there were no interactions between the factors, however grain yields increased. In cases where N was applied early, it was found there was a higher exigence for disease control. In this trial diseases such as Septoria leaf spot and powdery mildew were the main diseases of interest (Olesen et al. 2003b). However, since response will vary between fungal species it is important not to generalise and use doses experimentally validated for a specific target species.

The chemistry of active ingredients required for plant protection is a fine balance to achieve the desired spread and coverage. Combinations of adjuvants to perform the desired wetting effect of chemicals on a surface, spacing of nozzles,

type of nozzles, angle combinations alongside plant breeding for coverage are all researched. Despite this, over the last 30 years, the quantity per ha dose rate has remained unchanged (Department for Environment, Food, and Rural Affairs 2017). To understand the dose baseline needed for optimum efficacy, several factors should be considered: distribution of active ingredients within the spray, mode of action of the spray, water quantity, actives and additives quantities, and the state of agitation within the tank.

PPP mode of action is an important consideration in VRA since interactions, such as translocation and environmental vulnerability, of PPPs within the canopy vary based on it. For example, contact pesticides work on the basis protection of the surface for prevention of fungal development. Protectant, also known as contact, fungicides cannot penetrate plant tissues, are susceptible to environmental wearing, and cannot transfer to new plant growth. In contrast, systemic PPPs penetrate plant cuticles and can be translocated through the plant vascular system, meaning new growth is not left unprotected and the AI is not susceptible to environmental wear. This translocation enables protection as with contact PPPs but also fights established infection to cure or inhibit (Cremlyn 1991). Efficacy and efficiency of the fungicide should be considered as these factors will determine the potential reduction of dose applied.

Active ingredients of most PPPs are insoluble in water; therefore, PPPs include surfactants for suspension. These surfactants also impact the surface tension hence affecting the leaf spread, as lower surface tension improves the spread. If the PPP separates within the water, there is the potential for a nozzle blockage to cause uneven spraying. Adjuvants are also used in some formulations as they improve the properties of the PPP either as an activator or as a modifier. Activators enhance the efficacy of the active, allowing for a reduced quantity in dose application, but in some cases are essential to the function of the active. Modifiers either increase the spreadability, the stickiness or reduce evaporation of the pesticide by foaming or increasing viscosity of the PPP, (Cremlyn 1991). If the tank is settled, the PPP is not in suspension within the water and the spray dose distribution will be uneven.

Adjusting application and operation procedures to implement optimal dose strategy is critical for efficacious use of PPPs. Multiple dose adjustment technologies have been developed for VRA, either based on disease incidence or canopy parameters. Investigating the assumed linear relationship by users of PPPs would allow progress with optimisation. Optimisation of the dose rate will come from understanding spatial and temporal variability and operational factors that also cause variation in canopy mass.

## **1.4 Conclusions and research gap**

When creating a VRA system, consideration of these key factors is paramount; for adjustment there are a range of nozzle technologies which have been discussed and there are many case studies based on disease and canopy biomass; for optimisation, operational factors such as soil variation, canopy structure variation, nutrient interaction and active chemical composition will all impact the optimisation of the system.

For VRA, PPP strategies must consider both adjustment and optimisation but until the baseline of how PPPs relate to biomass is established, there will be a fundamental issue. Optimisation should be the focus of the research moving forward, as the true potential of current VRA systems is not being exploited due to the assumed linear dose rate.

Implementing most appropriate management strategies for PPP application will encourage enhanced, productive cropping and least wasteful practice, meeting the demands of our population and preventing further avoidable environmental damage.

### **1.4.1 Rational for project**

This review of the literature has highlighted several areas of study within VRA and has approached the subject by looking at several different aspects of how the industry can move forward with VRA. This review found there are many areas of study required to progress with VRA applications of fungicides. Therefore, this project addresses several topics across VRA of fungicides to assemble the basis for future work. This project studies the variation in dose across fungicide timings,

the suitability of a precision agriculture method of monitor canopies to inform application decisions and enquires into the suitability of using VRA across the UK by understanding the variability in NDVI in one region of the UK. Finally, this study also investigates the financial implications of VRA as without understanding this, the continued work into VRA may be fruitless.

### **1.4.2 Aim and Objectives**

This research program aims to answer the following research questions:

#### **Aim:**

Is there a case for precision application of fungicides on winter wheat as the basis for variate rate applications?

#### **Objectives:**

1. What is the current 'state of the art' technology for VRA of PPPs?
2. What is the variation in spray deposition in winter wheat canopies?
3. Are NDVI estimates of biophysical parameters suitable for determining temporal and spatial variability of biomass for fungicide applications?
4. What is the range of NDVI variation in winter wheat canopies in the East of England at T1?
5. What and where is the economic benefit of VRA?

## 2 Quantification of spray deposition in developing winter wheat canopies

### 2.1 Introduction

As public perception of chemicals in agriculture influences policy and with the increase in research into environmental impacts of chemical use, there is a systematic removal of effective active chemistry (The Anderson Centre, 2014). Fungicides are essential for winter wheat (WW), *Triticum aestivum*, production to meet the food demands of the current population. Some chemical actives are becoming less effective due to over-use and increased resistance of pests, diseases, or weeds (Keulemans et al., 2019). The ability to combat yield impacting pests, diseases or weeds is therefore more difficult. Plant Protection Products (PPPs) are likely to become more expensive as the Environmental Land Management scheme looks to focus on rejuvenating and protecting the countryside (The Agriculture Bill, 2020). The application of PPPs needs to be used with maximum efficacy and minimum excess, saving farmers money, preventing resistance to available chemistry, and limiting further environmental damage.

Fungicides have different modes of action for different targets, it is therefore important to select applications which suit the mode of action. Applications of systemic fungicides for combating disease presence are based on disease detection and monitoring. For protectant/contact fungicides, application decisions are based on growth stage or leaf emergence. These decisions account for timing of applications and dose rate is decided by agronomists and farmers applying a percentage of the recommended dose. Decision making varies based on training, experience, money, and regional characteristics, so there is no consistent method across the UK. Manufacturer recommended dose rates cover a wide range of Growth Stages (GSs). Epoxiconazole, used for treating diseases such as some rusts and Septoria has the same dose rate for GS32 (second node detectable) to GS59 (ear completely emerged above flag leaf ligule), (Crop Smart, 2018). The Agriculture and Horticulture Development Board (AHDB) wheat growth guide found that there is approximately 10 tonne/ha above ground

biomass difference between those two growth stages (AHDB, 2018). Since the same dose rate is suggested for both growth stages there is an increased risk of resistance to fungicides as an unknown level of control is used.

In the UK, WW fungicide regimes use up to 4 fungicide sprays and an ear wash at the end of the season. The key spray timings are T0, T1, T2 and T3, see Figure 2-1. T0 applications are unusual but the spray is aimed at reducing early inoculum levels present in wheat crop canopies followed by T1, 3 weeks later. T1 is applied when leaf 3 is fully emerged at growth stage 32 (GS32). The primary purpose is to protect leaf 2 as it emerges as this leaf contributes 25% to the final yield. T2 applications are on the flag leaf (GS39), which accounts for 45% contribution to yield, and infection of later leaves is detrimental to photosynthesis capabilities and inhibits high yields (Allen-Stevens 2017). T3 applications are conducted at the start of flowering (GS61) (AHDB, 2018).

There are conflicting recommendations for the optimal timing of fungicide applications. One perspective argues that early applications of T1 better protect tillers, and others argue aiming for leaf 3 fully emerged as the most important factor (AHDB, 2018; Allen-Stevens, 2017). Another suggestion includes delaying application of T2 until GS42, as this prolongs greening, but also recommends GS39 for T2 (Kilburn, 2016). Survey data from Bayer (Allen-Stevens, 2017), identified that grower responses were variable with only 45% knowing the optimum spray timing for T1, GS32, and 46% of responses believing spraying of T1 should occur with leaf 3 half emerged. Accuracy in determining full emergence of leaf 3 for application is difficult and the spray window is narrow as weather and regional characteristics will influence this. This is compounded by the variation in GS and biomass of individual wheat plants within each field. The start of April is the recommended time to start checking WW fields for growth stages in anticipation of GS32 likely to occur mid- April depending on region and weather. Risk from disease pressure is also a determining factor for the spraying window. Areas of high risk require precision timing; areas of low risk can be sprayed outside of the growth stage and leaf emergence window. For practical reasons

spraying of leaf 3 (T1) often occurs before or after the optimal window, despite the importance of timing (Jones, 2017).

Considering variation in decisions is essential for optimal delivery of fungicide dose. Farm management influences application rate variation, whereas variation in deposition of fungicide include the differences between crop varieties as they display different canopy characteristics such as surface texture (glaucousness), height, leaf angle and tiller angle which will also influence spray deposition (Gooding and Davis, 1997). Other factors also include operator driving precision, surface interactions of spray with the crop canopy, machine calibration errors, and wind direction and speed (Chaplin et al. 1995). Key factors that influence the deposition and distribution of spray include the concentration of active and a mix of chemistry, nozzle type, age, and pressure, Figure 2-2.

Quantifying fungicide deposition on WW canopies can be achieved using tracer dyes. Sampling is destructive which removes the chance to understand a single canopy or plant and how it develops over time. Destructive sampling is also time consuming, resource heavy and requires expertise (Butler Ellis et al. 2012). A field experiment was conducted on WW using the tracer dye Brilliant Sulfolavine to evaluate methods of measuring deposition, in  $\mu\text{l/g}$ , of spray liquid recovered. The study found there was high variability in the measurements at different heights and required further testing (Wolters et al. 2008).

Destructive sampling however means the same canopy cannot be monitored until the end of the season. Tiller number and height of the canopy are two key factors which can be monitored non-destructively. Using a statistical model, canopy biomass (g) can be calculated from height (Feng et al. 2018). This allows infield measurements that estimate biomass and could later be used with satellite imagery measurements to determine key growth stages in the canopy. From this, spray decisions can be made using remote sensing technologies.

The aim of this chapter is to answer the question posed in the thesis objectives: What is the variation in spray deposition in winter wheat canopies? Furthermore, presented here are the findings of a study on spray deposition within WW canopies at fungicide application timing. It looks at the variation in dose

deposition, and relationship between height and weight of the winter wheat plants to understand the deposition relative to canopy variation and age, and the appropriateness of height as an indicator of biomass.

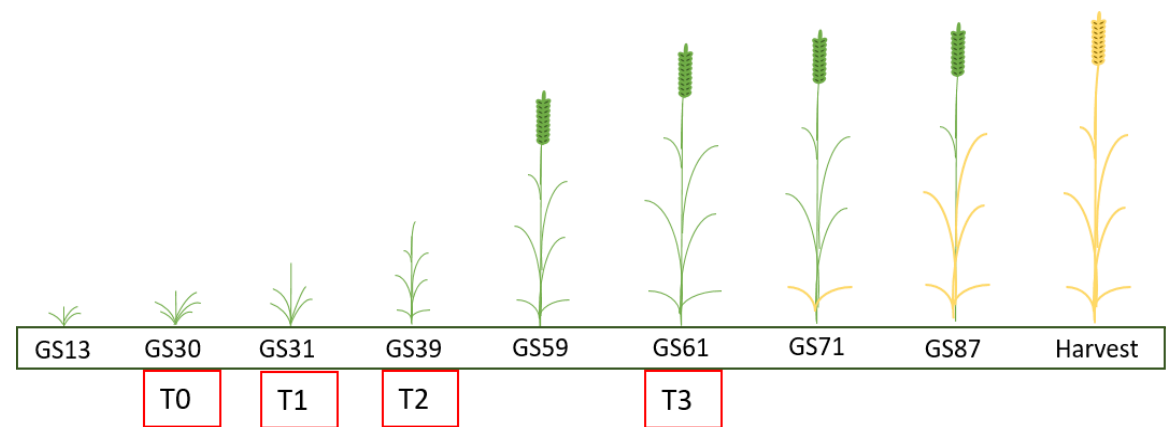


**Figure 2-1: Winter Wheat growth based on Zadok’s growth stages with key fungicide timings**

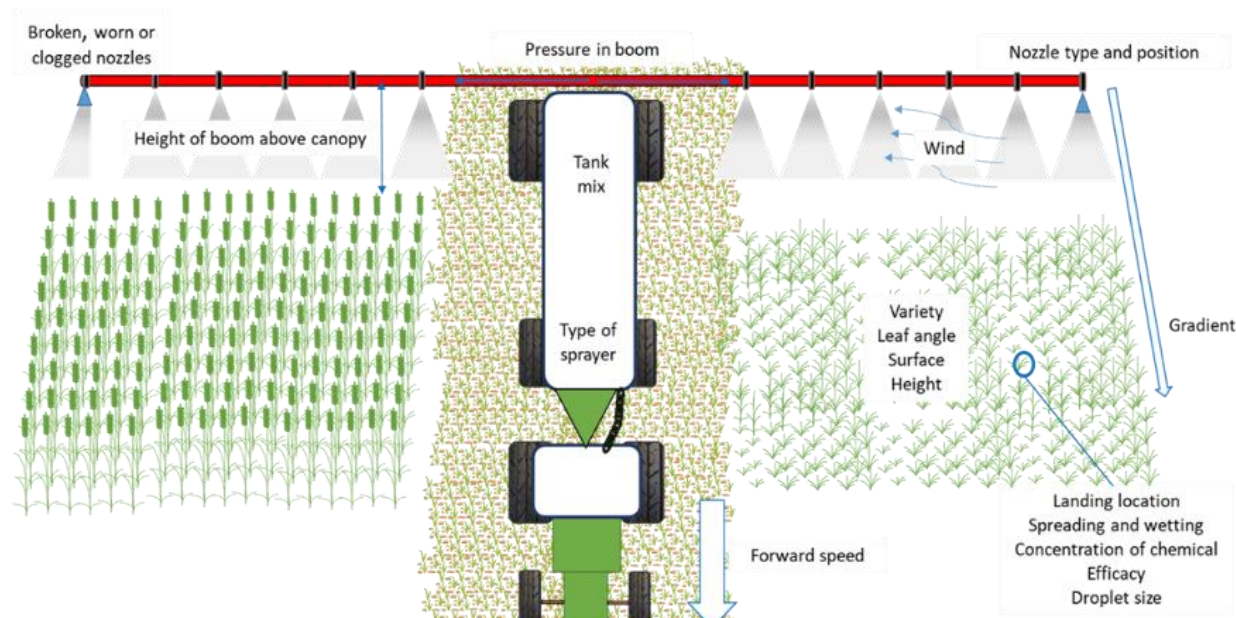


**Figure 2-2: Influencing factors on variation of spray deposition**

## 2.2 Methods

### 2.2.1 Dye selection

Several dyes have been used for spray deposition experiments (Wolters et al. 2008; Dekeyser et al. 2014; Derksen et al. 2012; Garcerá et al. 2017a; Wen et al. 2019). This study conducted preliminary investigations into suitable dyes for the destructive method and for research into a non-destructive method, not discussed in this paper. Candidate dyes were selected based on a set of criteria; stability (light fastness), solubility, quantification techniques available and reduced risk for both operator and environment, with a range of excitation and emission wavelengths ( $\lambda$ ) Table 2-1.

Green S is a blue non-fluorescent dye, and commonly used when testing agriculture spray nozzles as it biodegrades easily (Moozyckine and Davies 2002; Butler-Ellis and Lane 2014). Brilliant Sulfoflavine is a yellow dye used as an industry standard for leaf deposition sampling (Vollmer et al. 2014). Acid Red 52 is a pink, semi-fluorescent food colour with similar colours used in previous forestry studies (Brown et al. 2003). Uranine is a yellow fluorescent dye, chosen at the recommendation of the dye manufacturer and from the discussions of previous unpublished commercial research conducted at Silsoe Spray Applications (personal communication).

Testing each of the dyes was required to establish the optimal instrumental parameters for quantification of dye (e.g.,  $\lambda_{\max}$ , emission/absorption). Dyes were individually spiked into a known quantity of water (Acid Red 52, Green S and Brilliant Sulfoflavine) or NaOH (Uranine), and the same quantity was spiked onto white disks to establish recovery percentage. A Spectrophotometer (Acid Red 52, Green S and Brilliant Sulfoflavine) or Spectrofluorometer (Uranine) were used to determine quantity of a tracer in a solution. Through knowing the  $\lambda_{\max}$  of the tracer, concentration can be calculated. By setting up a range of solutions with known quantities of tank spray liquid, the quantity of sample deposited on the target, relative to the tank sample can be obtained.

**Table 2-1: Dye specifications for deposition testing**

| <i>Tracer</i>                           | <i>Supplier</i>                | <i>Buffer<br/>Required</i> | <i><math>\lambda_{max}</math><br/>(nm)</i> | <i><math>\lambda_{excitation}</math><br/>(nm)</i> | <i><math>\lambda_{emission}</math><br/>(nm)</i> |
|-----------------------------------------|--------------------------------|----------------------------|--------------------------------------------|---------------------------------------------------|-------------------------------------------------|
| <i>Green S<br/>(E142)</i>               | Honeywell<br>and Stein Ltd     | De-ionised<br>water        | 634                                        | 382                                               | 381, 750                                        |
| <i>BSF (Brilliant<br/>Sulfoflavine)</i> | Chroma<br>Color<br>Corporation | De-ionised<br>water        | 454                                        | 283                                               | 620                                             |
| <i>Acid Red 52<br/>(rhodamine B)</i>    | Sensient<br>Colors Group       | De-ionised<br>water        | 564                                        | 450                                               | 590                                             |
| <i>Uranine<br/>(fluorescein)</i>        | Sensient<br>Colors Group       | NaOH                       | 490                                        | 480                                               | 520                                             |
|                                         |                                |                            |                                            |                                                   |                                                 |

Dyes were selected to avoid persistence on the subsequent sampling and the ability to be detected when in a mixture without interference Figure 2-3, and Figure 2-4. Despite having a lower recovery rate, Acid Red 52 was selected due to its non-persistence, and suitability for the simultaneous work on non-destructive sampling which is not presented in this thesis but can be found in Appendix A. A full methodology to combine these two workstreams is given in Appendix B.

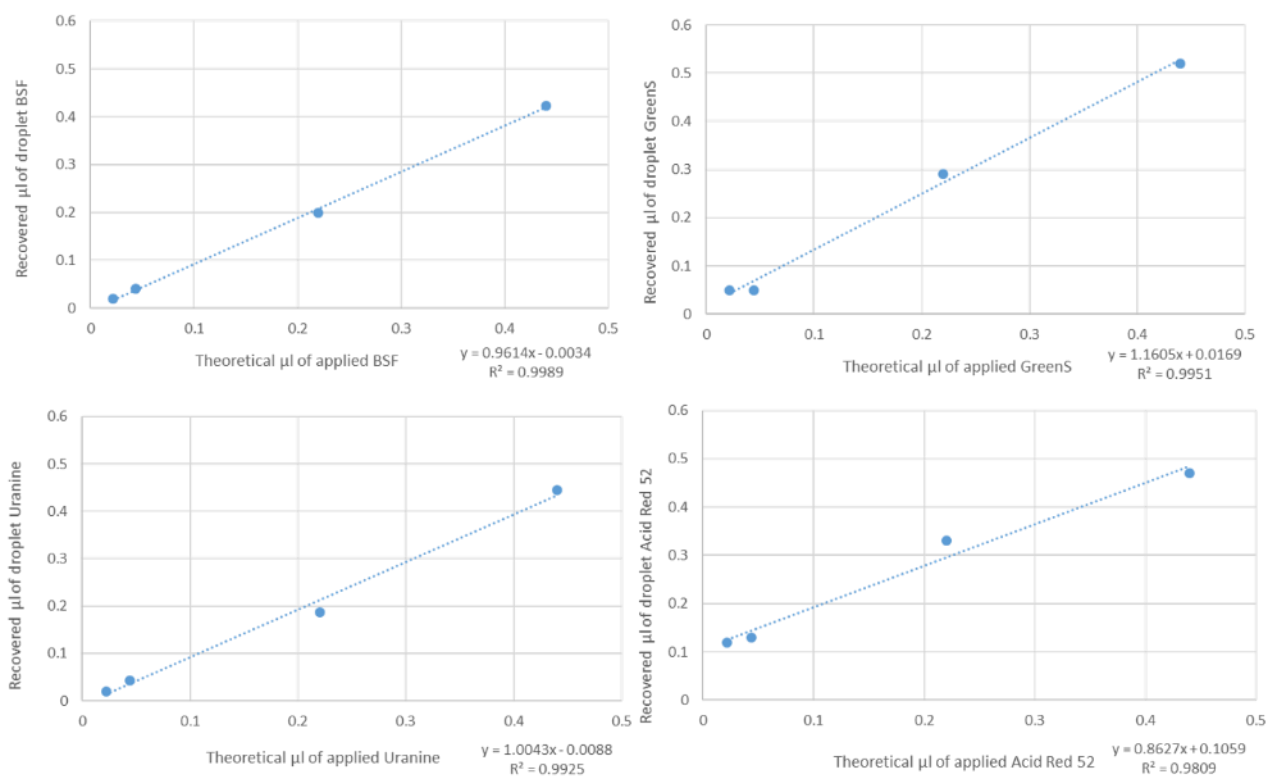


Figure 2-3: Detectability of known quantities of dyes.



Figure 2-4: Light Fastness testing for Acid Red 52.

### **2.2.2 Spray deposition**

WW was grown in 5L pots in John Innes no. 2 at a high seed rate and thinned to 15 seeds per pot after establishment in glasshouse conditions (Watson et al. 2018) at Cranfield University, Bedfordshire, in 2018. Pots were arranged in a randomised plot design with destructive sampling times randomly assigned to pots of each variety. Two varieties of wheat were selected for differing growth habits to determine if deposition differed between them, Skyfall (erect) and Claire (prostrate).

Samples were taken at approximate growth stages for T0, T1, T2 and T3 following a recommended fungicide application programme. At each of these key timings, pots were transported to Silsoe Spray Application Unit Ltd, Bedfordshire to use their spray facilities. To simulate standard practice of tractor spraying as recommended by Silsoe Spray Applications, a tracked boom with forward speed of 10 km/h and 110 degrees 03 standard commercially available flat fan nozzle at 3 bar, spraying a volume equivalent to 144 l/ha was used in a controlled environment, Figure 2-5. The pots were arranged in a row facing the direction of the boom and sprayed with one pass 0.5m above the canopy of 2% Acid Red 52, adjuvant Tween 20 at 0.1% in deionised water. High concentrations of dye were used for a stronger colour (Brown et al. 2003).

### **2.2.3 Sample handling**

Once dried, the wheat plant was cut at the base, placed into bags, and weighed, then 20 ml of deionised water was added to the bag and agitated to remove the deposited dye, Figure 2-6. The rinsate was then poured into test tubes and analysed with a spectrophotometer to determine the quantity of spray liquid recovered (Butler Ellis and Lane 2014). Height, fresh - weight and number of tillers were also recorded for each plant.

### **2.2.4 Statistics**

Statistical analysis was conducted using JMP, (SAS Institute Inc 2021). Boxplots and linear models were used to describe the impact of time of the variation of dye deposition. Edge effects were accounted for by removing the outer rows of samples from each pot before the statistical analysis was conducted.



**Figure 2-5: Pots of Winter Wheat under the track sprayer at Silsoe Spray Application Unit Ltds, Bedfordshire.**



**Figure 2-6: Samples bagged with 20 ml of deionised water before the rinsate was analysis in spectrophotometer**

## **2.3 . Results**

The spray solution recovered is referred to as spray liquid recovered ( $\mu\text{l}$ ). The quantity of dose received was highly variable within individual spray timings, and across the timings, independent of variety. Throughout the whole season, plant height ranged from 236 to 552mm, fresh weight ranged from 0.144 to 38.4g, and dye spray liquid recovered ranged from 2.31  $\mu\text{l}$  to 302  $\mu\text{l}$ . Microlitres of dye dose per gram of biomass ranged from 3.57  $\mu\text{l/g}$  to 16.1 $\mu\text{l/g}$ .

Spray liquid ( $\mu\text{l}$ ) recovered for the height (mm) and weight (g) is shown in Figure 2-8 and Figure 2-7. Dye recovery was lowest in WW plants at early growth stages. There was an increase in dye deposited as the canopy grew in height and weight, with later growth stage WW plants receiving more dye. Figure 2-8 shows height indicated spray liquid recovered,  $R^2 = 0.49$ , RMSE at 41.6 $\mu\text{l}$ . Figure 2-7 shows weight as a good indicator of spray liquid recovered, with an  $R^2$  of 0.89 and a RMSE of 19.2 $\mu\text{l}$ .

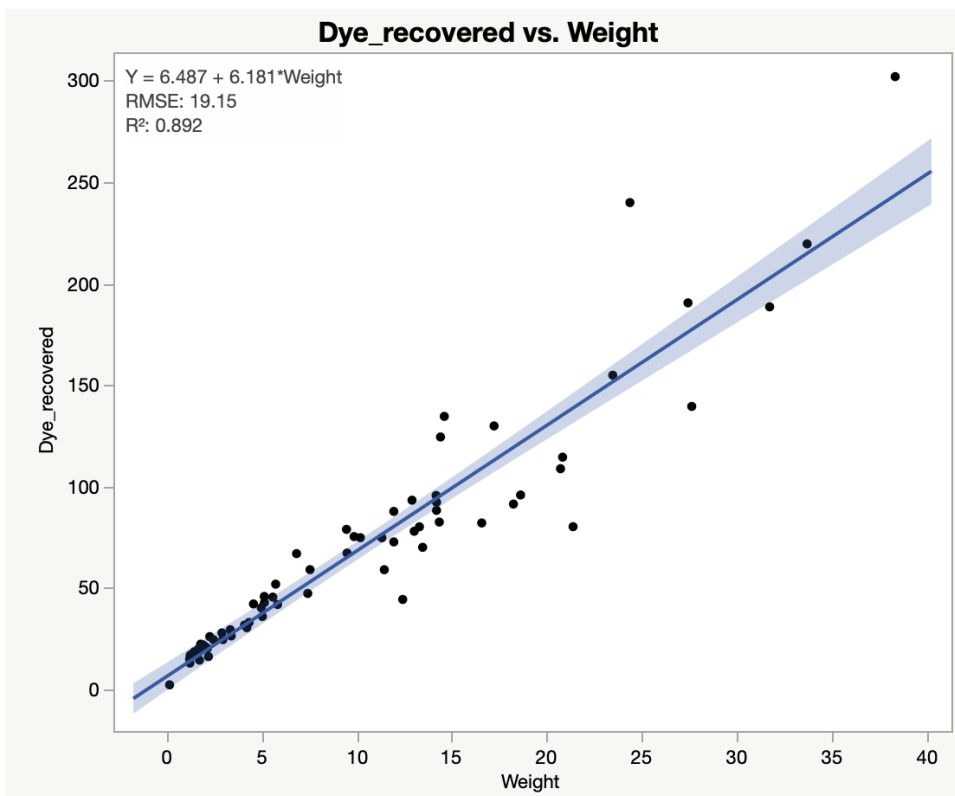


Figure 2-7: Spray liquid recovered (μl) vs weight (g) of winter wheat

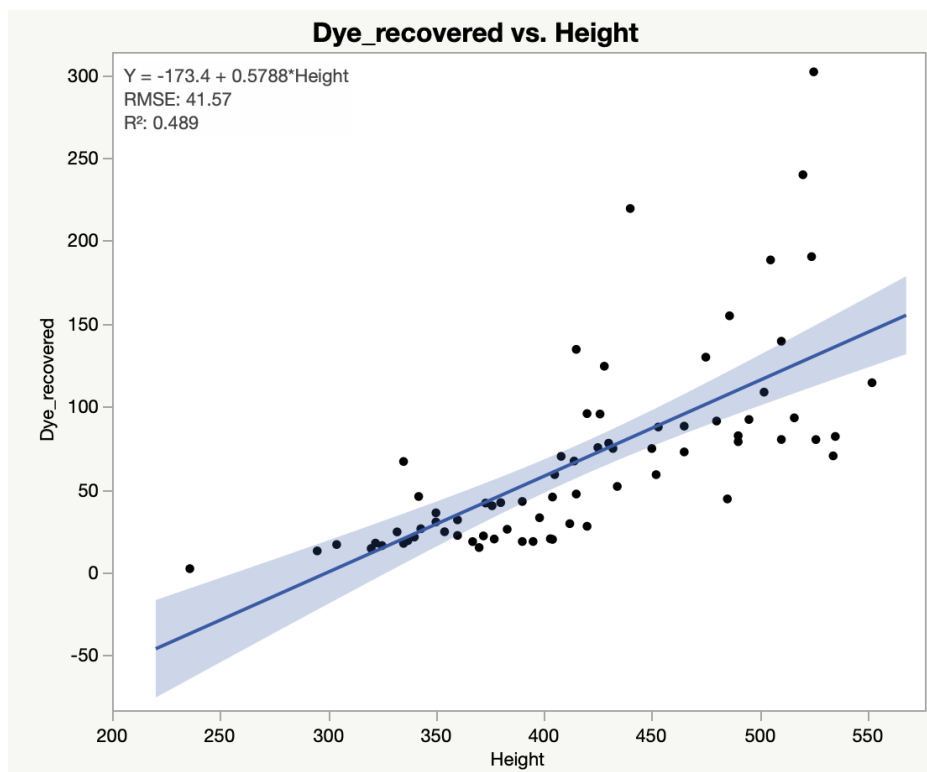


Figure 2-8: Spray liquid (dye) recovered (μl) vs height (mm) of winter wheat.

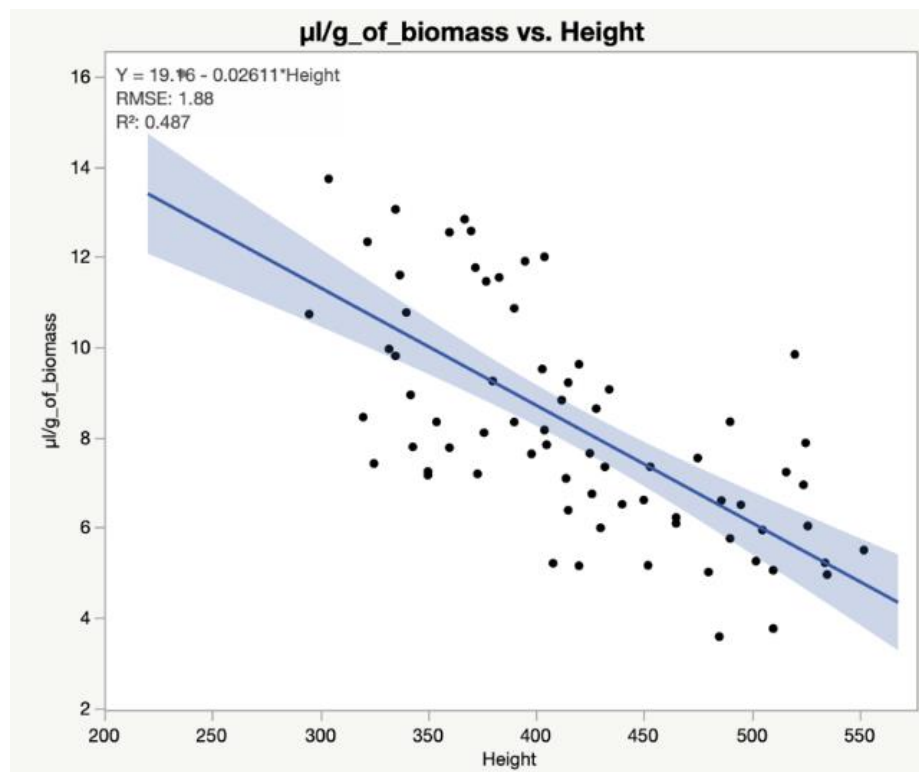


**Figure 2-9: µl of dye deposited per gram of biomass (g) vs height (mm)**

Figure 2-9 shows the µl deposited per gram of weight as height of the canopy increased. This figure shows the dye captured by the plant per gram was significantly higher on shorter WW plants and the amount of dye that the plant catches for its height decreases as the plant size increases.

The boxplots in Figure 2-10 show the interquartile ranges for spray timings and the impact of this on the size of the plant, spray liquid recovered and µl/g.

Figure 2-10a shows the weight (g) vs spray timing. Median values are in different locations, showing impact of time of dye recovery. The interquartile ranges for T0 are very compact with minimal variation in dye recovery. T1 shows slightly more range but a similar size to T2 but T3 has a much larger range. The skewedness was similar across all four box plots. There are a few outliers across the graph but T2 shows three. This demonstrates there was high variability of weight at later growth stages compared with earlier growth stages.

Figure 2-10b shows the height (mm) vs spray timing, median values for T0 & T1 are distinct but close, a difference of 25mm. Median values for T2 & T3 are higher than earlier spray timings. The interquartile ranges are similar in size. The skewedness was similar for T0 & T1, however T2 shows an upper skew and T3 shows a lower skew. There are no outliers. This shows the height remained at a similar level of variation throughout canopy growth.

Figure 2-10c spray liquid recovered vs spray timing; the median values increase through the time series. The interquartile ranges differ significantly between T0 and T4, with T0 being very compact, T1 and T2 being similar in size and T4 being a very widespread. The range overlaps significantly. The medians are central for T0 and T1, however there was an upper skewedness in T2 and T3. There was one outlier in T0 and three in T2. This boxplot shows that there was an increase in spray liquid recovered as the canopy grew, and that there is an increasing variability of dye recovery throughout canopy growth.

Figure 2-10d, shows the dye recovery vs spray timing, split by variety. This shows different patterns in recovery at different spray timings. The median values increase with the time series and are very similar at T0 and T2 for Claire and Skyfall. T1 Claire has a lower median range than Skyfall but has a significantly higher median range at T3. The interquartile range overlaps some of the boxplots. T0 and T1 in both varieties are compact, T2 from both Claire and Skyfall are of similar size as it T3 from Skyfall. Claire T3 has the widest distribution of boxplot, followed by Skyfall T2. There was some upper skewedness, in Claire T1, Skyfall T2 and T3. There was one outlier in T0 Claire, one in each T1 and T2 Skyfall. This boxplot demonstrates the same as Figure 2-10c but shows the difference between varieties, in that Claire had significantly higher levels of variation at T3 than Skyfall.

Figure 2-10e describes  $\mu\text{l}$  of dye deposited per gram of biomass. The median values decrease with the time series and are distinct between T0, T1 but T2 and T3 are very similar, with T2 having a slightly higher median value than T3. The interquartile ranges are all a very similar size with T0 and T1 being the same and

T2 and T3 having a slightly wider range. There was a very slight lower skewedness in T0 and T3 and a very slight upper skewedness in T4. This boxplot has one outlier in T0. This boxplot indicates that  $\mu\text{l/g}$  decreases as the canopy grows, but the range of variation is consistent.

Figure 2-10f describes the  $\mu\text{l}$  of dye deposited per gram of biomass split by variety. The median values decrease through time, but both T2 and T3 in each variety are very similar. The interquartile ranges are variable. Both varieties T0 and T1 are similar in size, T2 Claire and T3 Skyfall have a similar interquartile range and T3 Claire and T2 Skyfall have a similar range. There was an upper skewedness in Claire T0 and T1 and Skyfall T1, T2, and T3. There was a very slight lower skew in Claire T3. This boxplot highlights the difference between the varieties, the only similarity being range of variation at T1.

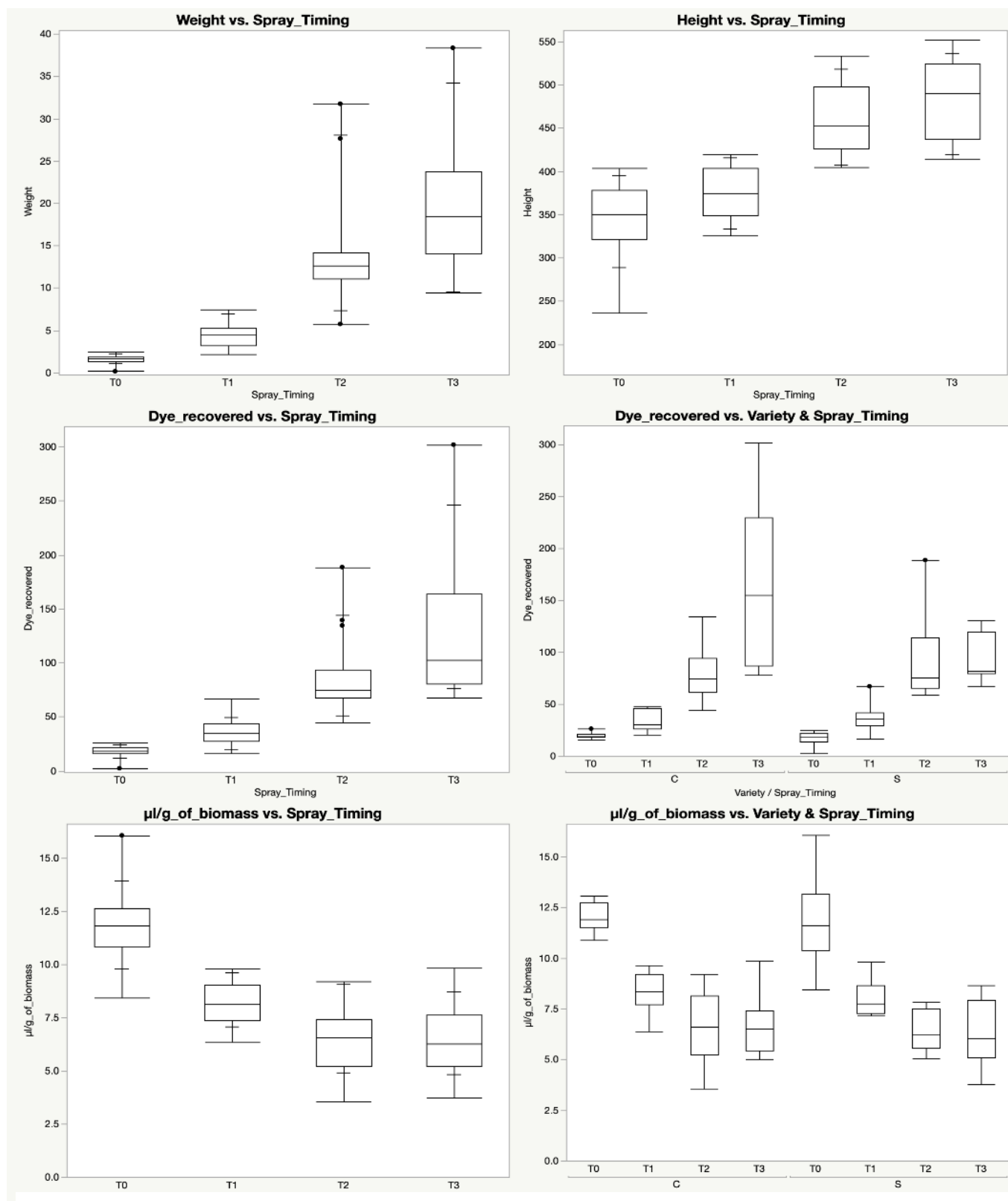


Figure 2-10: left to right, top to bottom. Time series, spray timings, T0, T1, T2, T3. a) Weight (g). b) Height (mm). c) spray liquid (dye) recovered (μl). d) spray liquid (dye) recovered (μl), split by varieties (C = Claire and S = Skyfall). e) spray liquid (dye) recovered (μl), per gram of biomass. f) spray liquid (dye) recovered (μl), per gram split by varieties.

## 2.4 Discussion

Determining the optimal timing for adjusting application rates and the basis, whether it be biomass or GS, would give precise control of fungicides, preventing resistance, stopping further environmental damage and economising fungicide spend. Winter wheat GSs are based on biophysical changes to the canopy such as tillering, gaps between nodes or ear emergence and these changes will directly influence the canopy biomass. By using biomass as the decision basis for fungicide application, a known quantity per gram of plant material is applied or can be applied.

Labels for protectant fungicides have a single recommended maximum dose rate to cover a wide range of growth stages but do not always mention specific timings or percentage of leaf. Furthermore, fungicide labels do not discuss how to adjust the rate to suit the GS or visible leaf nor how adjustments affect efficacy. However, since using the max dose for the range of GSs is excessive and expensive, farmers and agronomists choose a percentage of the recommended rate to apply. Their decision is not based on an individual GS requiring a specific dose per gram of biomass and is leaving farmers at risk of yield lost due to disease if under-spraying or to financial loss if over-spraying.

The results of this experiment show that as the plant size increases, the quantity of dye deposited is greater. The change in deposition between early application timings, T0 and T1, and later applications, T2 and T3, was significant in the amount of dye deposited per gram of biomass. The increase in dye deposited however, is not proportional to the biomass as  $\mu\text{l/g}$  decreases as the canopy grows. This is a crucial factor for determining the quantity of fungicide to apply. The level of active in the fungicide will be greatly affected by this. Fungicide deposition quantity should be based on the age of the canopy, increasing the quantity as the canopy grows. However, this does not mean that rates should increase, as increasing spray volume does not improve penetration of the canopy. Determining rates to apply requires careful consideration of other factors, such as nozzles and water quantity (Butler Ellis and Lane 2014).

In current field practice the optimal timings of fungicide applications are difficult to determine. Timings T0-T3 are used to bracket when fungicides should be applied, but there is conflicting advice on whether the decision of when to apply be based on leaf emergence or a GS. Further still, there is diverging advice on the percentage of the visible leaf or which GS should be present for application. Spraying with the current manufacturer recommended rates leads to high doses of fungicide on early WW and a lower dose on later WW. This suggests potentially significant wastage under current manufacturers' recommendation, where it is not tailored to the canopy biomass.

The two varieties selected have different canopy structures. Claire is open and prostrate, and Skyfall is close and erect. This had some effect on dye recovery, but only significantly at T3, with Claire being extremely variable. There was no consistent variation in microlitres of dose per gram between the two varieties.

The impact of tillering capability will influence deposition due to the resultant increase in canopy biomass, increasing the surface area for fungicide landing and adding biomass which will require more fungicide to achieve a constant dose. Other factors such as variety, nutrient availability and plant growth regulation application will also change the biomass by affecting the health, height, and habit.

The dose rate deposited in this trial is difficult to relate to agronomy suggestions as the figures do not show number of plants or biomass in a square metre figure. Taken from the AHDB Wheat Growth Guide (2018), the benchmark number of plants established from Sept-Oct sowing is 260/m<sup>2</sup>. The average dye deposited at T0 was 18.27µl, equating to 47.5l/ha deposited on 260 plants. At T1 the dye deposited was 36.5µl making a dose rate of 94.9l/ha. Using this comparison T2 and T3 has dose rates over the 144l/ha used in this trial therefore is not a suitable comparison. T0 and T1 dose rates are significantly under the 144l/ha dose rate used in this trial. Further trials looking at depositions within square metre canopies would provide more reliable data to compare to agronomy suggestions in l/ha.

Deposition of fungicides is understood by using tracer dyes, but current methods used across industry differ and, few that have investigated WW canopies, do not

examine growth stages beyond GS 31. This is problematic as comparison of fungicide spray deposition through dyes is challenging and therefore building upon previous work is difficult. The ability of a soluble dye to represent fungicide deposition is limited but necessary. Representative dyes are combined with adjuvants to best replicate the sum of the properties. This trial used Tween 20 to mimic some of the properties of a fungicide and developed a protocol for dye deposition. Its use within further industry would give more consistency with wider testing of chemical dosage on growth stages and the defined units of output would follow on with microlitres of dose per gram of biomass, Appendix B. The use of  $\mu\text{l/g}$  (fresh - weight) in this trial was suggested by Silsoe Spray Applications, Bedfordshire, as it follows their protocol and allowed for understanding of deposition within the canopies relative to plant size.

Some studies conduct deposition analysis by growing WW in shallow trays at a high seed rate. These investigations focus on early growth stages and do not go beyond GS 31 (Butler Ellis, et al. 2012). For improved understanding of spray deposition at all growth stages, later growth was required. Deposition is investigated with a tracer dye combined with active ingredients (Brown et al. 2003; Pergher et al. 2013; Garcerá, et al. 2017b) or without (Stajenko et al. 2012; Ferguson et al. 2016). The use of an adjuvant does not affect the dye recovery (Cai and Stark 1997).

This chapter moves a step towards determining optimal timing and justifies the importance of further testing to understand deposition and how deposition changes over time as related to crop GS. Significant work is required to fully determine the optimal timing and the dose rate specific to the size of the winter wheat plants. Scaling up from this further to field studies would give a better understanding of how external factors influence the variation in deposition.

## **2.5 Conclusions**

This chapter demonstrates the increase in variation as the canopy grows and variation in deposition of dye. It also shows that variability in plant parameters will impact variation in dye deposition and dye deposition relative to biomass with canopy age. There was a high level of variability in plant parameters in this experiment, despite being grown under controlled conditions. There are multiple factors influencing variation that require further investigation to move forward with determining appropriate fungicide dose rates. The most suitable dye to analyse spray deposition within WW canopies was Acid Red 52 and a standard operating procedure was developed for this, Appendix B. Further determination of deposition relationships would also encourage the best recommendations for dose adjustments to achieve a consistent microlitres of dose per gram for all fungicide application timings and provide the basis dose rate for variable rate application.

## **3 Investigating the variation in winter wheat fields**

### **3.1 Introduction**

A uniform winter wheat (WW) canopy is the ideal basis for fungicide applications, which the current approach to spraying is based on. However, this is not the reality of crop canopies as there are several influencing factors which cause variation in germination, tillering, biomass, height, and ear formation (Gooding and Davis 1997). The recommended uniform approach to applications of fungicides ensures a base level of protection from yield-reducing diseases. However, the excess chemistry leads to resistance, environmental damage and is a high variable cost to farmers (Pimentel 1995; van den Bosch et al. 2011; Department for Environment Food and Rural Affairs 2021; Wainwright 1978). To avoid further environmental impact, resistance, and excessive cost, the alternative is to use variable rate applications (VRAs) of fungicides. VRA requires a comprehensive understanding of the variation in crop canopies, which in turn, requires a rapid measuring system for observing them. There are more incidences of Unmanned Aerial Vehicles (UAVs) being used to conduct spraying. However, there are several issues such as spray direction and control, battery life, weight of the tank, which all require investigation before they can be utilised for spraying PPPs. The expense and the complexity of using UAVs as a basis for rapid ground measuring currently limit their use for many farmers. This study will evaluate the ability of Normalised Difference Vegetation Index (NDVI) satellite imagery to understand canopy biomass using ground observations as a basis for VRA.

At present, applications of fungicides have a constant dose rate. The dose rate derives from manufacturer recommendations and varietal resistance and is adjusted for the field by farmers and agronomists. Application rates are calculated as a percentage of the recommended dose rate from the manufacturer, mixed with water and additives such as adjuvants, (Crop Smart 2018; AHDB 2018). Crop walking observations are performed monthly when not in the growth phase and then bimonthly during the growing season to qualitatively assess the pest, disease and weed pressures, leaf visibility (emergence) and the growth stage of

the crop. These are then used to determine the optimum uniform applications of fungicides, with respect to manufacturer recommended rates published on the product label. This dose rate does not suit areas of variation in growth stage and leaf visibility (indicators of canopy biomass), resulting in under- and over-dosing. Chapter 2 investigates appropriate dose rates and concludes that variation increases as the canopy grows and the deposition of dose relative to biomass increases.

Farm variability should inform fungicide application decisions, but both spatial and temporal variation should be considered. Spatial variation refers to in-field variation at each of these application times, whereas temporal variation refers to the change in variation seen between these spray times. In practice a crop may have both different size plants at one growth stage, and different growth stages, making application timings a compromise. The optimal timings (T) used to determine fungicide spray applications, based on growth stage, are shown in Figure 2-1. The fungicides timings are T1-3, but there is an optional T0 to alleviate early disease pressure which is becoming more popular as a preventative option e.g., the product is applied pre-emptively, see chapter 0. The application timings sit within windows of 1 week where much of the canopy is suitable for the uniform spray. This is a short period of time which farmers may miss due to adverse weather, wind, and field conditions. Missing this window will then contribute to higher levels of variation as diseases dominate and start to impact growth and later, yield.

Spatial and temporal variation within WW fields is caused by many factors. Soil type, subsoil type, soil surface characteristics, field gradient, aspect, water availability, fertiliser application, plant growth regulator (PGR) application, pest and disease infection, crop protection application, seed rate and field history are all influencing factors for crop growth, (Godwin and Miller 2003a) Figure 3-1. Variation may also come from seed rate, missed drilling, or areas of the field which do not germinate and may require a high seed rate, or if the seed rate is too high and individual plants do not produce a high number of tillers (Gooding and Davis 1997; Wood et al. 2003). Farmers strive to have a high enough seed

rate to ensure germination whilst encouraging tillering and keeping the cost as low as possible. The timing of applications such as N, PGRs and PPPs also influences the canopy variation. For example, missing spray windows of

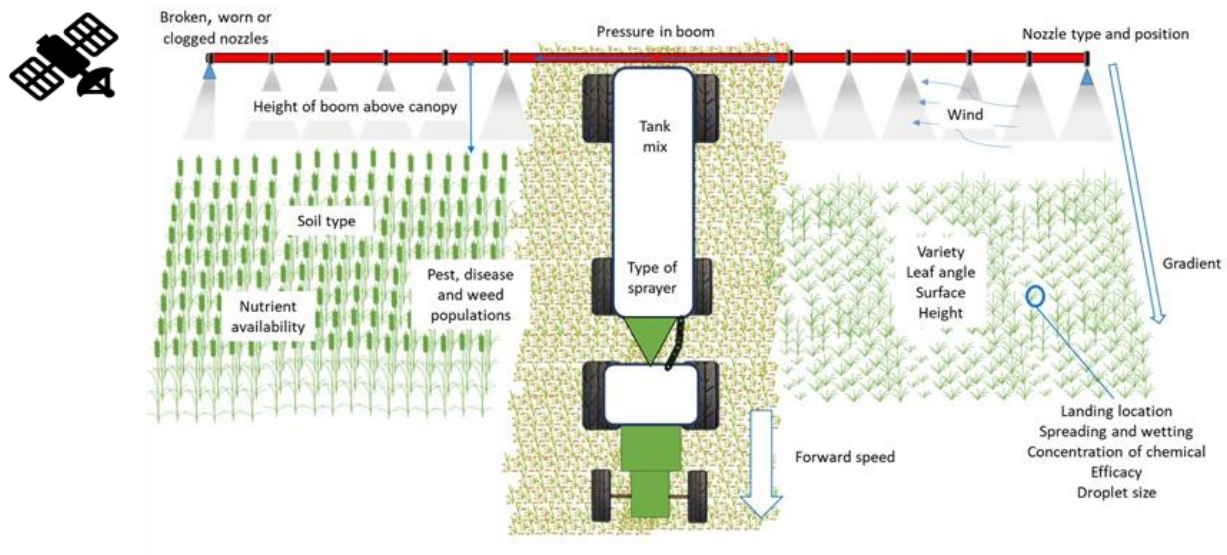


**Figure 3-1: Causes of within-field variation of winter wheat growth.**

protectant fungicide applications due to high wind weather, results in yield-contributing leaves being left unprotected and susceptible to disease (Allen-Stevens 2017).

There are two different types of fungicides: protectant/contact and systemic. Protectants remain on the outside of the plant, killing spores and hyphae on contact. Systemics are absorbed by the plant tissue, also killing spores or where hyphae have penetrated the plant surface. A systemic fungicide can move through the plant and treat the target pathogen in post-infection plants. This makes it suitable for disease detection methods that target the dose rate as required (Whetton et al. 2018). This thesis focuses on protectants applications through VRA which match the dose rate to the size of the plants seen in the field, whilst maintaining efficacy of protection.

Agricultural land covers 71.8% of the UK 2018, and areas of food production encompass a high proportion of biodiversity (Department for Environment Food and Rural Affairs 2021) which is also unable to survive intense agricultural systems (Tscharntke et al. 2012). Bystander spray, surface water run-off and chemicals leaching into the water system have the potential to cause

environmental pollution and have detrimental impacts on the health of organisms (Pimentel 1995). These impacts on biodiversity have increased the pressure from the public and policy to reduce their inputs on farms, (Coe and Finlay 2020).

Due to this environmental pressure, there is a depleting list of active chemistry, (The Anderson Centre 2014). Even with the few actives available, some are ineffective due to resistance from 'overuse,' (Keulemans et al. 2019). The reduction in effective active chemistry is challenging to farmers as it risks greatly reducing yields. Using a variable rate system has the potential to reduce the chemistry applied but could justify the use of stronger dose rates in smaller areas where there is an intense infection, which would reduce resistance risk.

Crop protection is the highest variable cost to farmers in WW production, averaging £216 per ha, 2019, (Department for Environment Food and Rural Affairs 2020a). Depending on the crop, the cost for fungicide application could range from £68 to £168 (Collins and Phelan 2020). A reduction in this cost would be significant for farmers as the cost of fungicides is only expected to increase, (Coe and Finlay 2020), but changing the way crop protection products are applied could reduce the active quantity required. Matching dose rates to suit variability requires an understanding of the canopy and the factors influencing the canopy. The dose rate and application method should consider the biomass and the WW variety. Chapter 0 showed that the difference in deposition per gram of biomass was significant between growth stages T0/T1 and T2/T3 and the increase in deposition was not proportional to the biomass. The assumption from this is that the efficacy will have decreased as the distribution across the plant will be lower.

### **3.1.1 Image-based approach**

Performing fungicide applications based on spatiotemporal field variation improves efficiency, protects the efficacy of the limited products available and reduces the highest variable cost to farmers per ha. When making decisions for applications, farmers and agronomists must process a significant number of factors that influence a large amount of heterogeneous data and make swift decisions based on these data for field applications. Using technology could reduce the resources required for these decisions and improve accuracy.

Remote sensing is an increasingly popular method in agricultural systems as it offers alternatives to manual and time-consuming observations. These sensing methods include tractor mounted, airborne, and satellite, sensing, and ground-based multispectral imaging systems (Ferguson 2019). The most widely known and used spectral method for assessing crop canopy or photosynthetically active vegetation is NDVI which uses a combination of near infrared (NIR) and red (R) reflectance,  $NDVI = (NIR - R) / (NIR + R)$ , to infer plant properties (Jones and Vaughan 2010). Despite a huge improvement in technology, there is a financial barrier for farmers and the upfront costs of some services and machinery can be prohibitive. From talking to companies selling this technology there is also a risk that the service provided is not effective at understanding variation, meaning that farmers could end up applying ineffectual, low, or excessive, high, dose rates.

The most researched remote sensing-based application method is Variable Rate N. The assumption for these systems is that other stressors in the field will have little to no impact on the N requirements. Further development work in water stress has been conducted along with the option of using other spectral reflectance to create alternative vegetation indexes (Ferguson 2019). There are fewer studies conducted into spatial resolution required for pesticides or fungicide application (Miller 2019a), suggesting the variation is not well understood.

Tackenburg et al, (2016b) uses a real-time sensor based (Leaf Area Index) LAI and NDVI to adjust fungicide dose. Their method requires an initial pass to determine min and max canopy variation and the farmer sets the min and max of the application based on these findings. This method increases a farm's workload as an extra pass is required for each field and each application timing, however it is in real time. The imaging equipment is also prohibitive to some farmers due to cost. Yue et al., (2018) conducted a comparison study of multiple crop parameters measured from a UAV mounted hyperspectral sensor and high-definition digital camera to ground spectrometer data. The study found height was a crucial factor in the best method for predicting Volumetric Above Ground Biomass (VAGB). Height was estimated in  $m^3$  but used in combination with vegetation indices, random forest regression and partial least squares

regression. Modelling options do exist with WW canopy biomass estimations, but they are time consuming, involve numerous inputs and struggle with uncertainties and model structure, (Sui et al. 2018).

Using remote sensing methods to monitor WW fields across the UK could provide insight into areas of high and low variability, enabling a full understanding of the potential for the reduction in fungicides that VRA could provide. Expounding this information to farmers could reduce the risk of disease if under-spraying or financial loss if over-spraying. Investigating the variation detection ability of satellite NDVI imagery used by the VRA sprayers on the market would give farmers better information to make optimal crop decisions.

Determining how much the biomass varies spatially and temporally on a farm using remote sensing could support farmers struggling with the upfront cost of variable rate technology by allowing them to make an informed decision as to whether the amount of variation justifies the initial cost of the technology or a subscription service. The idea of variable rate fungicide application is not new. However, an in-depth understanding of field variation using remote sensing methods is crucial to unlocking the future of variable rate spraying.

This chapter aims to answer Question 3 from the introduction: Are NDVI estimates of biophysical parameters suitable for determining temporal and spatial variability of biomass for fungicide applications?

## **3.2 Methods**

Observing variation within WW fields through manual measurements and comparing the results to remote sensing data demonstrates the comparability of the measurements and how accurate the variability is represented by the remote sensing approaches. This study establishes the accuracy of remote sensing methods for predicting variation in WW fields from measuring commercial fields and uses the best relationship found within the data to calculate variation differences across all WW fields in a region of the UK.

### **3.2.1 Commercial field study**

Field measurements were conducted in Bedfordshire, UK, during one growing season, 2019. Two commercial farms, 20 miles apart, Figure 3-2, employing standard agricultural practice were selected for measurements with all except one field, having uniform applications of fertiliser and fungicides. Three fields from each farm were selected as group 1 WW, with all fields growing Skyfall, apart from one growing Zyatt. 'Great Dole,' 'Lavendon' and 'Home Field,' are situated in Olney, Buckinghamshire, Figure 3-3, whereas 'Avenue,' 'Ivy Ground' and 'Near Warden,' are in Silsoe, Bedfordshire, Figure 3-4.

Table 3-1 describes the field information such as size, variety, and application.



**Figure 3-2: Satellite imagery of commercial field sites, Olney, Buckinghamshire and Silsoe, Bedfordshire in England**

**Table 3-1: Site, field name, size, variety of winter wheat grown and fungicide application method for commercial fields.**

| <i>Site</i> | <i>Field Name</i> | <i>Size (ha)</i> | <i>Variety</i> | <i>Application</i> |
|-------------|-------------------|------------------|----------------|--------------------|
| Olney, UK   | Great Dole (GD)   | 32.2             | Skyfall        | Trial              |
|             | Lavendon (L)      | 14.2             | Skyfall        | Uniform            |
|             | Home Field (HF)   | 9.5              | Zyatt          | Uniform            |
| Silsoe, UK  | Avenue (A)        | 8.1              | Skyfall        | Uniform            |
|             | Ivy Ground (IG)   | 7.7              | Skyfall        | Uniform            |
|             | Near Warden (NW)  | 5.7              | Skyfall        | Uniform            |



**Figure 3-3: Satellite imagery taken from Google maps, of Olney, Buckinghamshire, UK with fields Great Dole, Lavendon and Home Field**



**Figure 3-4: Satellite imagery of commercial field Silsoe, Bedfordshire, UK with fields Avenue, Ivy Ground and Near Warden.**

Crop growth stages were determined by regular crop walking between February and June 2018. Table 3-2Table 3-2 shows the timing of the measurements against the NDVI values downloaded from Sentinel 2 and selected for non-cloudy images using visual inspection. The expectation is that NDVI is at its highest when the canopy is fully closed, just prior to ear formation. Table 3-2 shows the required leaf visibility and growth stage for the optimal timing of fungicide application, the date of infield measurements collected, the date of the satellite imagery taken, the observed growth stage at the time of sampling and a comment on this growth stage as to the suitability of the application timing.

Calibration sites were required for field observations of satellite imagery. Sites were selected in February 2019, this was during the tillering phase for WW but prior to the main growth period, which showed inherent field variability. Imagery provided by SOYL, Frontier Agriculture, based on Planet satellite data (Planet Team) was used to determine ground calibration sites. Images were stratified into eight NDVI values and a point in each range was selected, see Figure 3-5 (Wood et al. 2003). Data points were navigated to using a Trimble Geo7x handheld device and marked with a fibreglass cane. At each data point, three 0.25 m<sup>2</sup> quadrats were positioned in an arrow formation, 2m apart, in the direction of drilling, following the rapid calibration method proposed by (Wood et al. 2003) and used by Waine et al (2014). During all measurements, GPS points were taken for each quadrat, using the Trimble with an accuracy of 0.2m.

**Table 3-2: Dates of imaging, sampling and range of growth stage observed, 2019.**  
No data was available for Olney T0, Silsoe T0 & T1.

| <i>Fungicide Application</i> | <i>Image date</i> | <i>Field sampling date</i> | <i>Required growth stage</i> | <i>Range of observed growth stage</i> | <i>Comment on application timing</i> |
|------------------------------|-------------------|----------------------------|------------------------------|---------------------------------------|--------------------------------------|
| <b><i>Olney</i></b>          |                   |                            |                              |                                       |                                      |
| T0                           | 5th April         | NA                         | GS29                         | NA                                    |                                      |
| T1                           | 10th April        | 15th April                 | GS30-31 (Leaf 3 emergence)   | 30-32                                 | Ideal                                |
| T2                           | 16th May          | 16th May                   | GS39 (Flag leaf emergence)   | 33-39                                 | Early to ideal                       |
| T3                           | 1st June          | 6th June                   | GS59 (Ear emergence)         | 59-65                                 | Ideal to late                        |
| <b><i>Silsoe</i></b>         |                   |                            |                              |                                       |                                      |
| T0                           | 5th April         | 4th April                  | GS29                         | NA                                    |                                      |
| T1                           | 18th April        | 18th April                 | GS30-31                      | NA                                    |                                      |
| T2                           | 10th May          | 13th May                   | GS39                         | 32-39                                 | Early to ideal                       |
| T3                           | 1st June          | 12th June                  | GS59                         | 59-65                                 | Ideal to late                        |

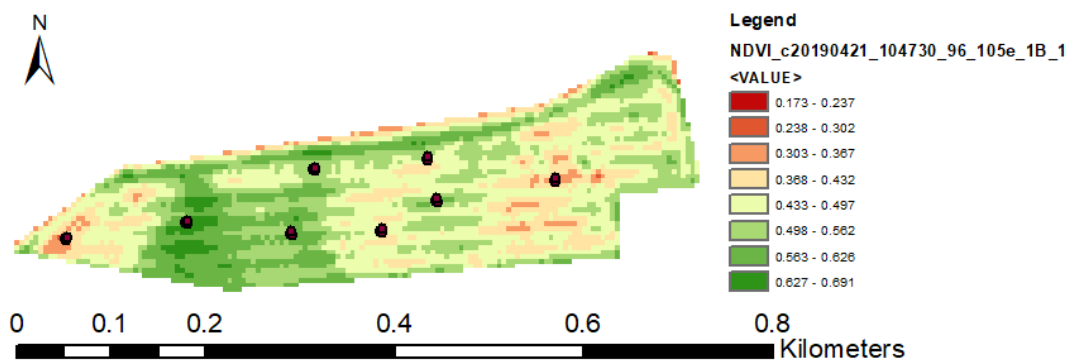


**Figure 3-5: Stratified NDVI values in Avenue, Silsoe showing selected ground measurement sites**

Destructive sampling was only used for growth stage analysis to minimise damage to the commercial crop. Non-destructive measurements were then recorded for each quadrat to understand the spatial and temporal changes; growth stage, leaf number, number of plants, canopy height, and mean number of tillers (T0-T1), shoots (T2), and ears (T3). No data was available for GS and Leaf Emergence (LE) at Olney T0 or Silsoe T0, and T1. Number of weeds and any pest or disease damage were also measured. An average value for each data point was collected from the three quadrats which created the equivalent value for the NDVI pixel (3m x 3m). The GPS data point for each quadrat was then taken and a digital photograph was captured at a height of 1.8m for later visual inspection and comparison. As measurements conducted were non-destructive, volumetric above ground biomass (VAGB) per metres cubed (m<sup>3</sup>) was calculated using two equations. Equation 1 was used for T0-T2 where *a* is number of shoots, *b* is number of plants, *c* is the height in metres and *d* is VAGB.

**Equation 3-1: Calculation of volumetric above ground biomass (VAGB) for T0-T2, where *a* = number of shoots per plant, *b* = number of plants per quadrat, *c* = height (m) and *d* = VAGB**

$$4(abc) = d$$

The study by Yue et al., 2018 presents the calculation for VAGB using dry weight samples. This was not possible in this study so VAGB here is presented as fresh weight biomass calculation. Equation 2 was used for T3, where *x* is ear number, *y* is height in m and *z* = VAGB:

**Equation 3-2: Calculation of volumetric above ground biomass (VAGB) used for T3, where *x* = ear number per quadrat, *y* = height (m) and *z* = VAGB**

$$4(xy) = z$$

Multispectral imagery was supplied by SOYL, collected from the Planet constellation, (Planet Team, n.d.). Selected for its high spatial resolution with (3 m by 3m pixels) and daily revisit time which allowed for selection of images with less than 15% cloud cover. These were pre-processed with top of atmosphere correction by Planet. NDVI images were created in ArcGIS for each key spray

timing. NDVI values for each of the ground sample locations at each date were extracted using a GIS, to provide the data to model the canopy variation.

Statistics were performed using JMP (SAS Institute Inc 2021). Data were normally distributed so multi-factor analysis and the post-hoc Tukey test used to determine fields and spray timings of significant difference, ( $p < 0.05$ ). A variability gauge chart was used for determining farm fields outside of the normal range of variability. Boxplots were used to study range of variation. NDVI was plotted against VAGB and an equation, RMSE. The  $r^2$  was extracted to determine the suitability of NDVI as an indicator for VAGB and the spatial and temporal variation.

### **3.2.2 Assigning a dose rate to NDVI values**

Applications of fungicide are decided by agronomists and are decided as a percentage of the manufacturers recommended dose rate. Tackenberg et al. (2017) used a camera-based system to decide dose rates for fungicide application on WW, adjusting the L/ha dose to match crop canopy coverage. Using a similar method, NDVI values were assigned a dose rate based on the applications recommended by an agronomist for Olney farm.

### 3.3 Results

This study aims to understand variation in volumetric biomass during a season, by monitoring the canopy for consistent areas of variation seasonally and determining if NDVI is an appropriate measure of VAGB.

Observations showed that within the farms there was highly variable VAGB spatially, even across distances of 100m. Temporally this was the case at each fungicide application time, displaying a broad range of growth GS and LE, Table 3-2: Dates of imaging, sampling and range of growth stage observed, 2019. No data was available for Olney T0, Silsoe T0 & T1. Table 3-2, Appendix D. For Silsoe T3, the image date is 11 days before the field sampling date, this was due to the availability of non – cloudy imagery. The implication of this is that it is not the most accurate representation of the status of the canopy however, by T3 application timing the ear will have emerged (GS61) and the canopy is complete, (AHDB 2018). Each spray timing saw a range of GS that either were the required growth stage or, in the case of T2 were either the required GS or six GSs below. In the case of T3, GSs were either the required or up to six GSs ahead, meaning the window for application will have passed as the desired target leaf may have fully emerged.

Considering volumetric VAGB, Near Warden was the only field with a significantly higher mean than the others. Variation across fields was normally distributed. T3 was the only spray timing with a significantly higher mean VAGB than the others. Using heterogeneity of variance tests for height (m), VAGB ( $m^3$ ) and NDVI, showed that Avenue field had above average of variation in height at T3, and for NDVI, Near Warden field had a higher mean and below the levels of variation seen in other fields in this study in at T3.

#### 3.3.1 Height

Variation of height (m) at each application time is shown in Figure 3-6 as boxplot separated by field. Great Dole had consistent variation in height throughout the season as the interquartile ranges are a similar size. Home Field and Lavendon were similar, with a medium interquartile range at T1, very small range at T2, but

the largest range in height at T3. Avenue shows the highest interquartile range of variability, with variability in height at its lowest at T1. Ivy Ground had the least range of variation spatially, and only a slight temporal variation at T1. The range of variation at Near Warden remains consistent throughout the season.

### **3.3.1 Volumetric Above Ground Biomass**

Variation of VAGB at application times at field level is shown in Figure 3-7. From the farm at Olney, Great Dole had similar levels of variation in VAGB at T1 and T2 but greater variation at T3. The interquartile skewedness moves chronologically between each as lower, upper and the lower again. The range slightly overlaps as VAGB increases between all the spray timings but more between T2 and T3. Home Field had significant changes in variation, T1 had high interquartile range and a very slight, lower skewedness. T2 had a smaller range than T1 but larger lower skewedness, and one outlier. It also shows a slight decrease in VAGB. T3 has much greater variation and had a large upper skewedness. Lavendon had similar size ranges in T1 and T2, but it had a hugely variable VAGB at T3. T1 and T3 have upper skewedness and T2 had lower skewedness, and their ranges overlap slightly but were distinctly different showing the increase in biomass overtime.

From the Silsoe based farm, Avenue had very similar T0 and T1 boxplots in size and range, and T2 and T3 were similar length but T3 shows the increase in VAGB. The median values were different with T0, T2 and T3 having an upper skewedness and T1 having a lower skewedness. Ivy Ground has T0 & T2 similar in size and range but T1 was bigger with a smaller range. T3 has the widest range and size of variation of VAGB. T0 showed a lower skewedness as did T1, T2 showed a central median but T3 showed an upper skew. T0 had one outlier. Near Warden showed similar levels of variation throughout the season, with all the boxplots being of similar size and range. The skewedness did change from no skewedness at T0 to an upper skew at T1, slight lower skew at T2 and then a lower skewedness at T3. These VAGB boxplots show Avenue was the most variable field throughout all the growth stages but Lavendon, Home Field and Ivy Ground also had high variability at T3.

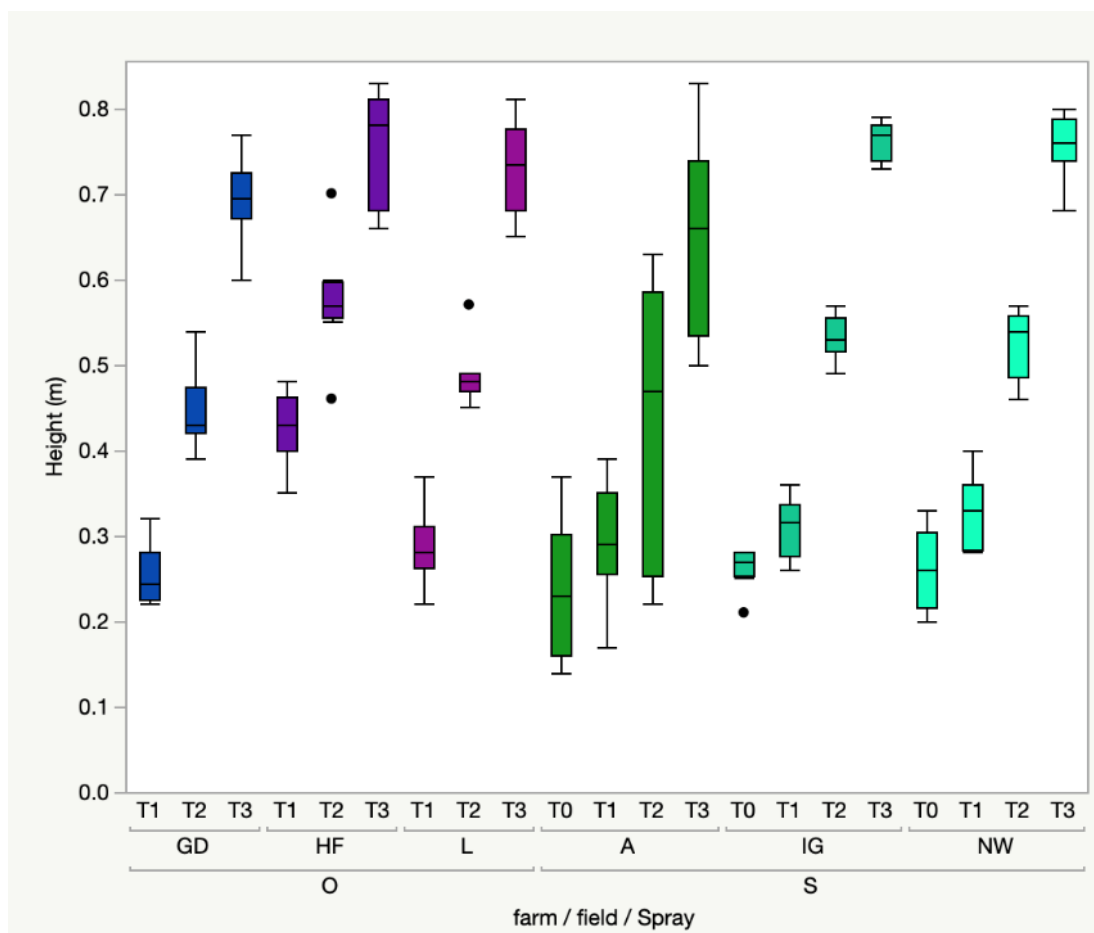


**Figure 3-6: Boxplot of the in-field plant height (m) variation split by fungicide application timing, field, and farm, (T0-T3 fungicide timings, A - Avenue, IG - Ivy Ground, NW - Near Warden, GD - Great Dole, L - Lavendon, HF - Home Field, O- Olney, S-Silsoe). Boxplot shows interquartile range, and the whiskers show extent of the range of variation. No data is available for Olney T0.**

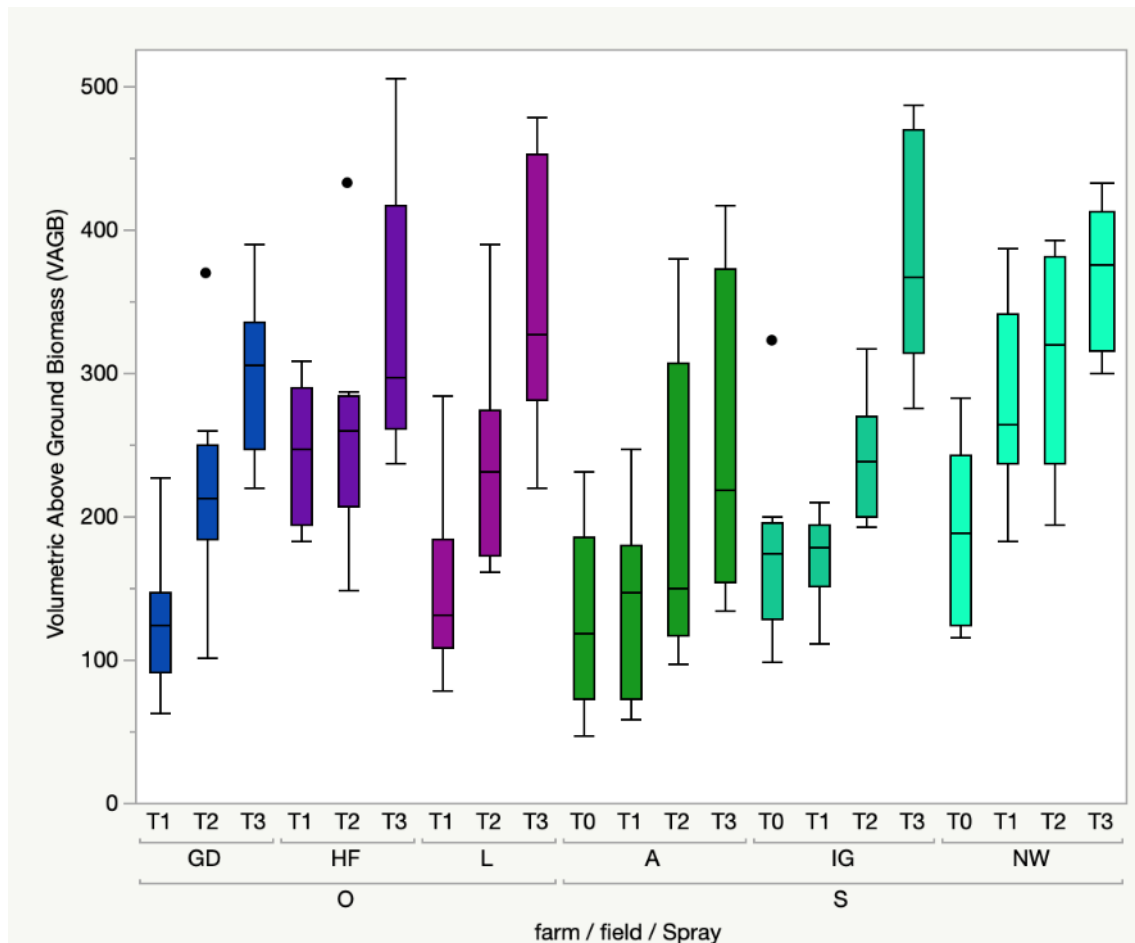


**Figure 3-7: Boxplot of Volumetric estimation of Above Ground Biomass (m<sup>3</sup>) split by fungicide timing, field, and farm. (T0-T3 – fungicide timings; Fields: A - Avenue, IG - Ivy Ground, NW - Near Warden, GD - Great Dole, L - Lavendon, HF - Home Field; Farms: O-Olney, S-Silsoe). Boxplot shows interquartile range, and the whiskers show extent of the range of variation. No data is available for Olney T0.**

Figure 3-8 shows the ground photography taken at T1, of point 1 and 2 in Avenue, the most variable field, within 100 m of each other, mapped onto satellite imagery from Planet scope. Visual inspection shows there is a significant difference in biomass inside the quadrat as the soil can still be seen at point 1. Figure 3-9 compares points 1 and 2 at each of the spray application timings. The biomass difference is significant in this case. Figure 3-10 shows the ground photography and stratified NDVI in Near Warden for comparison as it was the least variable field.

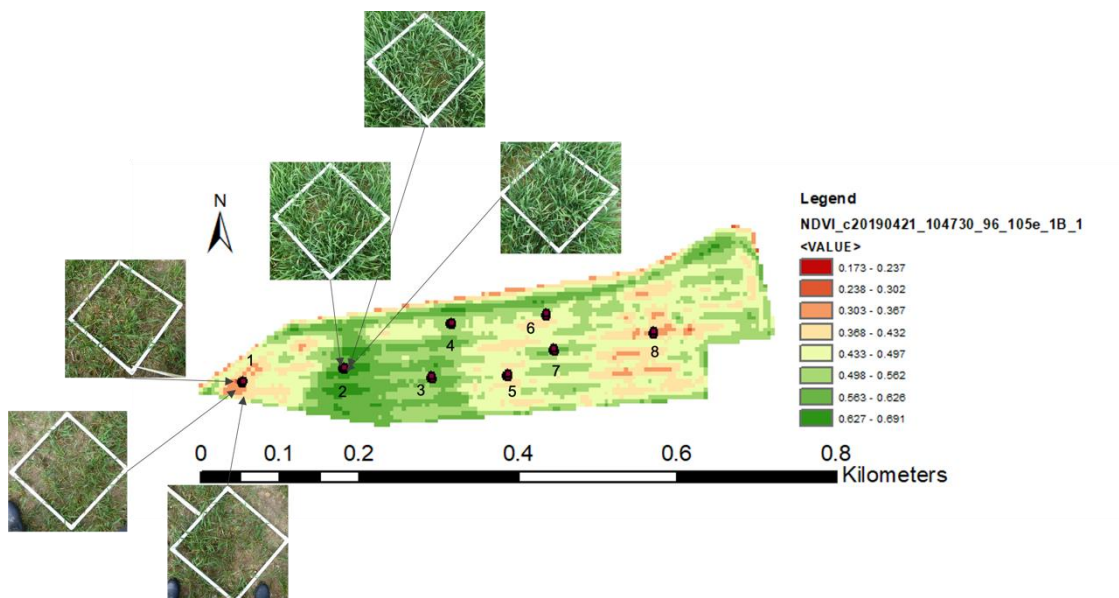


**Figure 3-8: Avenue, Silsoe, taken at T1 from Planet scope basic scene product image, 21/04/2019, showing variation between quadrats of points 1 and 2.**

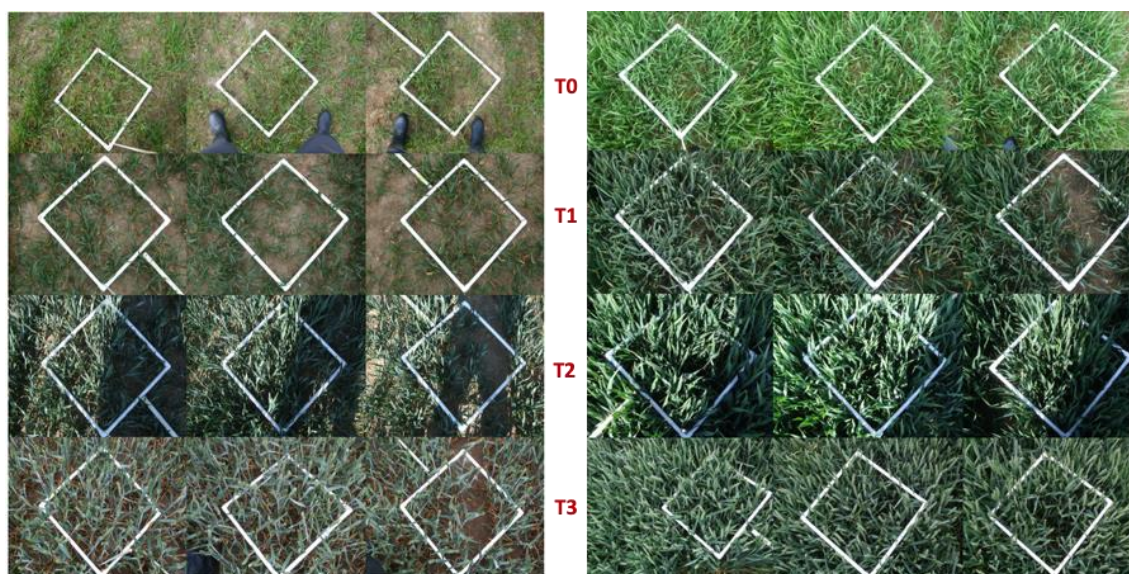


**Figure 3-9: Ground photographs of sample quadrats (0.25 m²) in Avenue field, Silsoe, points 1 and 2, showing crop variation at the key fungicide application timings**

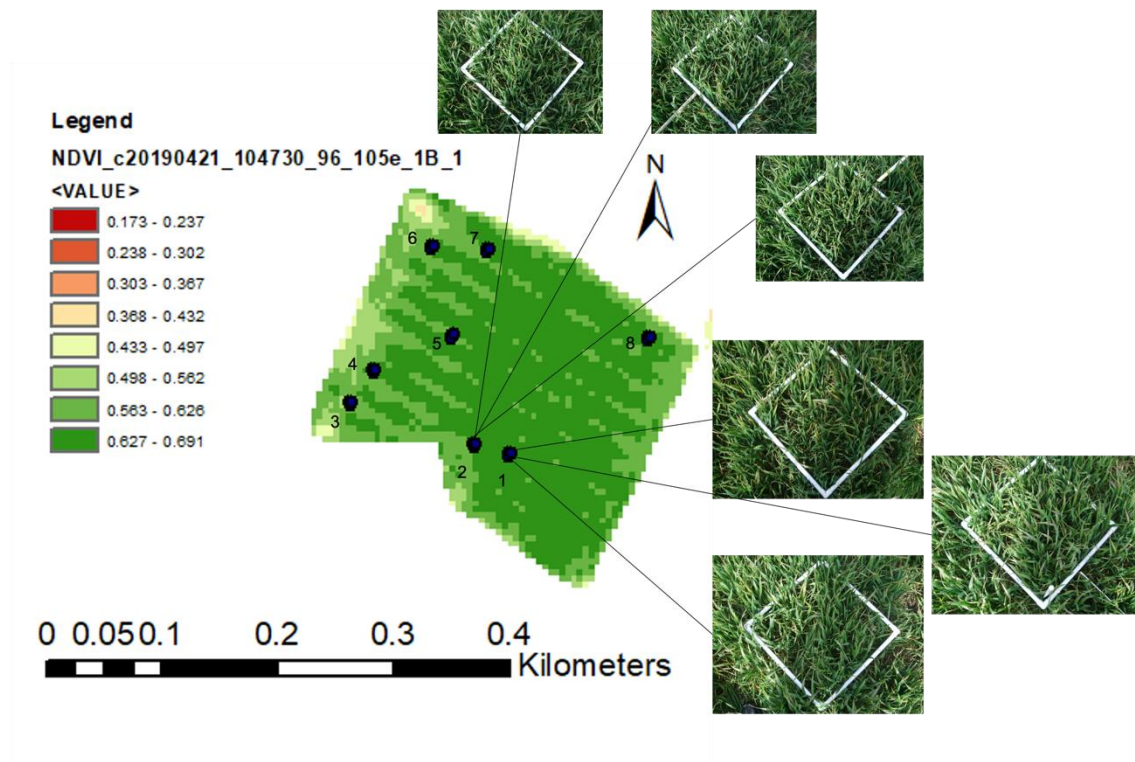


**Figure 3-10: Near Warden, Silsoe, taken at T1 from Planet scope basic scene product image, 21/04/2019, showing variation between quadrats of points 1 and 2.**

### 3.3.2 NDVI

NDVI variation is shown in Figure 3-11. From Olney, T0 was not recorded. At Great Dole overall variation through time was high with only a slight overlap of boxplot between T2 and T3. T1 showed its largest range of variation, with a slight upper skewedness. T2 and T3 showed NDVI variation was similar in size and range, T2 also showed an upper skew and T3 shows slight lower skewedness. Home Field overall variation was less than Great Dole or Lavendon, but the boxplots do not overlap which highlights the temporal variation. T1 of Home Field had a similar size variation to Great Dole T1 with a slight lower skewedness. T2 and T3 both show upper skews and similar size boxplots. Lavendon overall NDVI variation had a wide range through time with none of the boxplots overlapping. T1 variation had a wide range of variation with a strong upper skew, T2 had a shorter range of variation, and a central median line. T2 had one outlier. T3 showed a similar range of variation to T2.

The variation across the Silsoe farm in NDVI image was larger than at Olney. Avenue was very different to all other fields, it showed significant spatial variation which was decreased temporally. T0 and T1 were of similar size but T2 and T3 decrease in size significantly. T0 showed a lower skew, T1-T3 had central median lines and no outliers. Ivy Ground had some spatial variation which varied temporally but the values of NDVI decreased overtime. T0 and T2 showed an upper skew but the other timings had a central median line. Near Warden NDVI variation overall showed a wide range of variation spatially with very short boxplots at T1 and T2. Temporally the value of NDVI decreased after T1. T3 shows the most variation. T1 had an upper skew. Variation in NDVI did not show a similar level of variation to VAGB after T1. The widest variation was shown at T0 and T1 application time, which is consistent with the canopy being closed after this time.

### **3.3.3 VAGB vs NDVI**

Variation at each spray timing of VAGB (left) and NDVI (right) is shown in Figure 3-12 as a boxplot graph for all fields combined. The graph shows the pattern of VAGB variation, highlighting that there is little overall difference in the range of variation at the different spray times. It also shows that VAGB increases over time, but the ranges overlap significantly. There were only slight changes to box size, T1 and T3 were slightly larger, and a movement of the median line with T0 and T2 having slight lower skewedness, T1 having even skewedness and, T3 having upper skewedness. NDVI does not follow the same pattern of increase over time or similarity of variation. T0 had a medium size range, lower skewedness and two outliers. T1 overall increases in NDVI value but shows a range of variation with a central median line. T2 is higher again in NDVI value but smaller range than T0 or T1, there is a lower skew and five outliers. T3 is lower than T2 but had a similar median line to T1. The range at T3 is the smallest but had an upper skewedness and one outlier. This boxplot shows the NDVI does not reflect canopy variation across both farms temporally after T2, which implies this method cannot be used once the canopy is saturated.

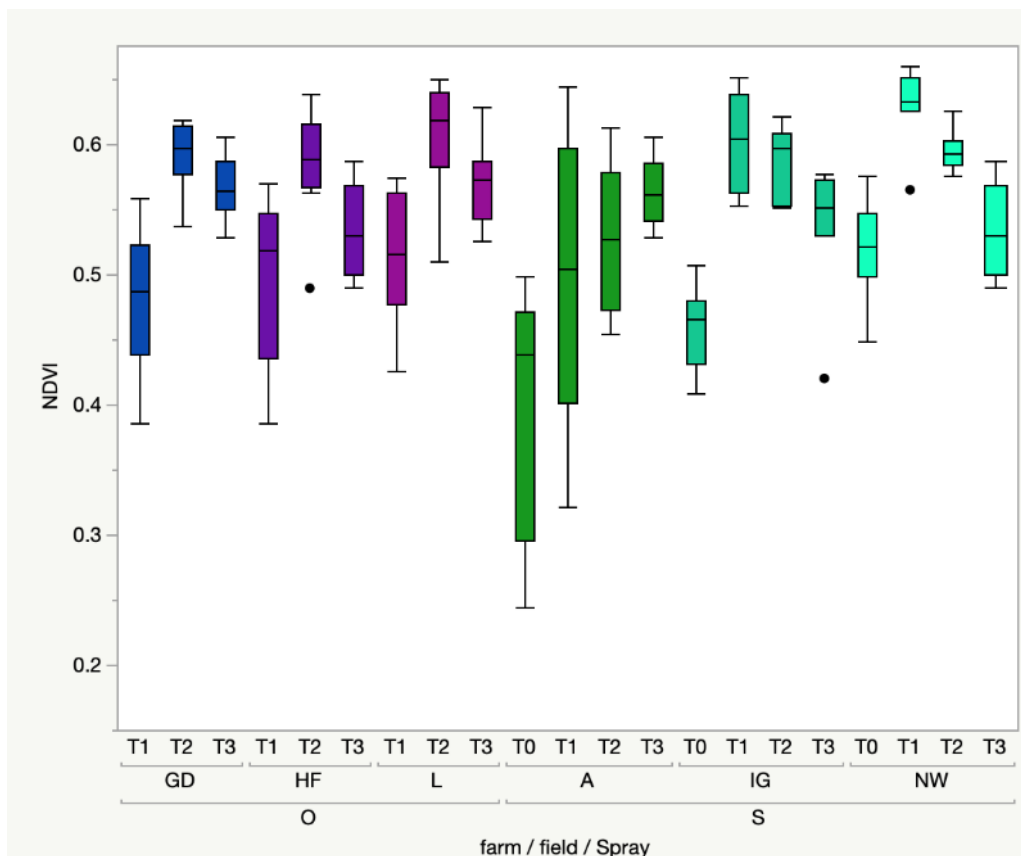


**Figure 3-11: Boxplot of NDVI split by fungicide timing, field, and farm. (A - Avenue, IG - Ivy Ground, NW - Near Warden, GD - Great Dole, L - Lavendon, HF - Home Field, T0-T3 – spray timings). No data is available for Olney T0.**

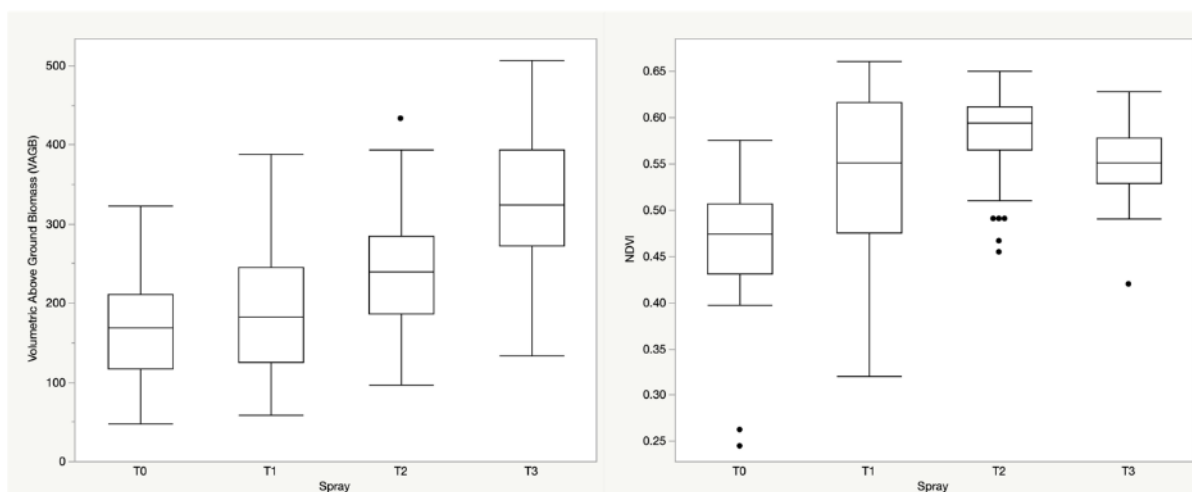


**Figure 3-12: Boxplot of (left) variation in VAGB (m³) and (right) NDVI at fungicide timings for all fields combined.**

### **3.3.4 Predicting VAGB with NDVI**

To understand whether the measured VAGB and the NDVI reflect one another to the extent that the NDVI is useful metric to predict spray timing, a comparison of linear fits for each fungicide application time was performed, Figure 3-13. T0 only had the data from the Silsoe farm but shows the best relationship with an  $r^2 = 0.585$  and RMSE = 44.28. RMSE were used to give a quantitative indication of error in units of VAGB. Best performance value is zero. T1 had a lower  $r^2 = 0.368$ , with an RMSE = 63.24. At T2 the relationship between NDVI and VAGB had lowered to  $r^2 = 0.207$  and a higher RMSE = 74.18. T3 had the lowest  $r^2 = 0.008$  but had the highest RMSE, 90.48, which shows a poor relationship. The relationship between NDVI and VAGB on a farm level showed that Olney had a  $r^2 = 0.215$ , RMSE of 88.93 and Silsoe had a similar  $r^2 = 0.219$  and a higher RMSE, 94.30, Figure 3-14.

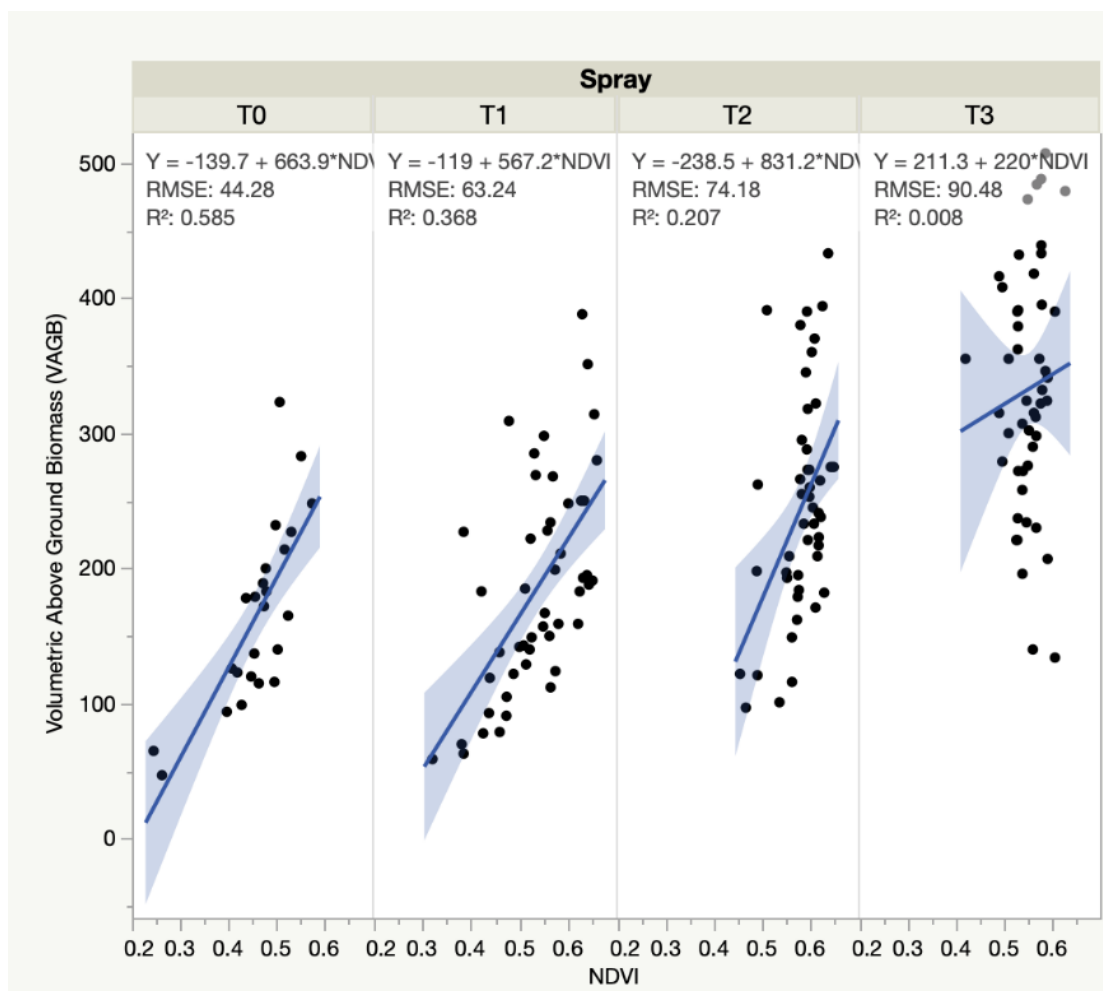


**Figure 3-13: Linear fit of NDVI to predict Volumetric estimation of Above Ground Biomass (m³), split by spray timing. No data is available for Olney T0.**

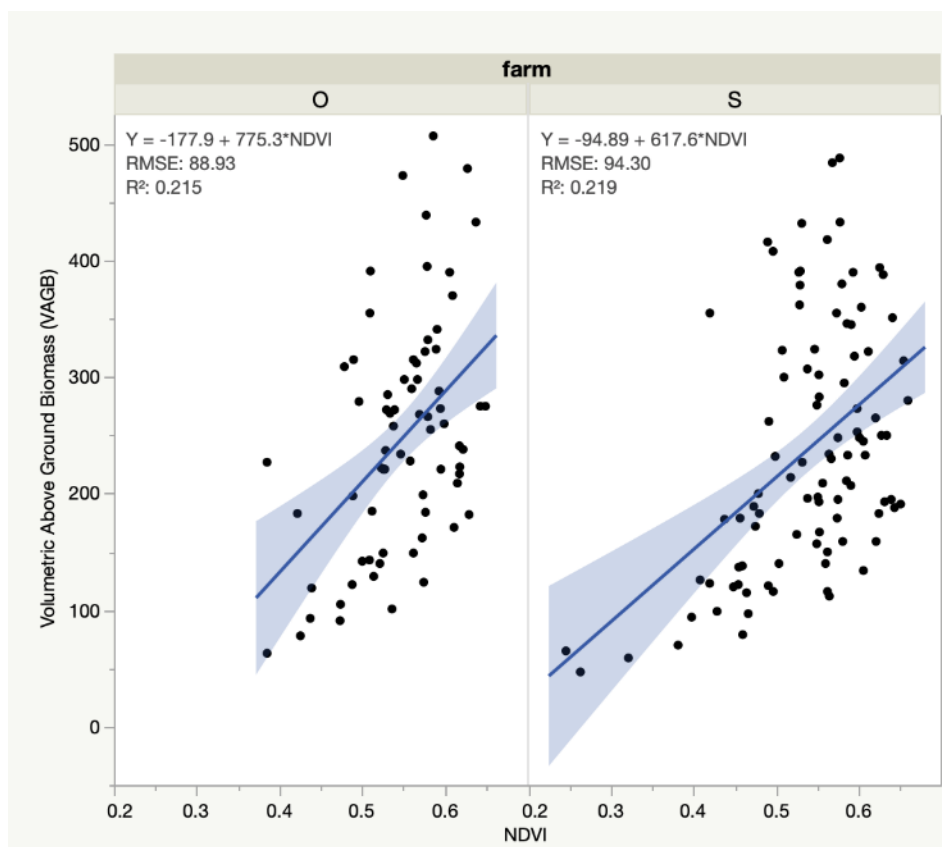


**Figure 3-14: Linear fit of NDVI to predict Volumetric estimation of Above Ground Biomass (m<sup>3</sup>), split by farm, O= Olney, S = Silsoe. No data is available for Olney T0.**

### 3.3.5 Assigning dose rate values to NDVI

The agronomist for the farm at Olney recommended a 50% dose rate of a 2L/ha application of Bravo, (protectant fungicide). Assigning different dose rates to NDVI values throughout the season would not be appropriate as the NDVI ranges do not differ distinctly between the growth stages. Selecting one application timing, T1, and assigning fungicide dose rates based on minimum and maximum NDVI values, the recommended dose rate is shown in Table 3-3**Error! Reference source not found.**, (Tackenberg et al. 2017). These values are used in chapter 5 to calculate spray rates. The Active L/ha are a percentage of the recommended manufacturers max dose rate of 2L/ha for Bravo at T1 (GS30-32), (Onley Farm Agronomist).

**Table 3-3: Application rates L/ha for crop canopy percentage and NDVI value, where rates for application were the linear relationship between min and max NDVI T1 values.**

| <b><i>NDVI Value</i></b> | <b><i>Crop Canopy Cover (%)</i></b> | <b><i>Active L/ha</i></b> |
|--------------------------|-------------------------------------|---------------------------|
| 0.7                      | 95                                  | 1.9                       |
| 0.6                      | 80                                  | 1.6                       |
| 0.5                      | 65                                  | 1.3                       |
| 0.4                      | 50                                  | 1                         |
| 0.3                      | 30                                  | 0.6                       |

### 3.4 Discussion

This chapter investigated WW biophysical parameters through ground measurement and satellite images and showed the range of variation spatially and temporally across six separate fields in 2019. The nature of variability in WW fields can be seasonal, annual, or inherent depending on the climatic, soil and disease pressure conditions and the field itself. Variability in growth stages, plant height, VAGB and NDVI were monitored.

Growth stage was used in this study to determine appropriate spray and measurement timings. There were significant levels of GS variation in this trial with some fields six growth stages ahead and others behind. In this case the growth stages measured were close to the required growth stage for the fungicide application, but physical variation was seen in the lack of emergence (flag leaf at T2) or being beyond full emergence (ear emergence at T3). The effect of a spray timing being too early or too late for the required emergence would mean that the area required would not be adequately protected. T2 in this trial would have been sprayed too soon for full flag leaf coverage, and T3 would have been sprayed too late for protection of the ear. Yield variation, grain number, is influenced by region, soil type and early crop management whereas severe disease can significantly affect grain size, reducing the yield and financial gains from the season (AHDB 2018). GSs are fundamental to best practice use of protectant fungicide spray, therefore VRAs based solely on growth stages would mean multiple passes during a short window to ensure all the leaves are caught. This is impractical as farmers already struggle with time and multiple passes may lead to compaction. Timing the application to catch all the target leaves is important but applying a dose which does not suit the size of plant may lead to resistance, financial, and chemical wastage.

Measuring crop canopies using height gives an indicator of the above ground biomass (Dammer et al. 2015c). This was useful in this study as destructive biomass calculations were not appropriate for the farms. It would have also meant selecting new locations for quadrats for each sampling round. In future this would prove a useful training technique to compare the sampling methods. In this study,

plant height was highly variable in some fields with Avenue being the most variable. The range of height at each spray timing went from < 5cm in Lavendon T2 and Ivy Ground T0 and > 40cm in Avenue at T2. The range of variation in height over time changes significantly in Home Field, Lavendon and Avenue, which may be due to factors listed in the introduction and shown in Figure 3-1. This change in variation indicates that canopy biomass does not even out as the season grows in every field, supporting the use of appropriate variable rate application.

Using height to create an estimate VAGB value combined with plant number and tiller number, or the number of ears was an effective way of showing the levels of variation in the field in this study. Variability of VAGB was greater in some fields than in others, with Avenue being the most variable. It is likely some of the variation is caused by mechanical damage on the headlands and access to and from the field as points 1 & 8. The variation could also be influenced by the bordering hedges, animal damage.

Soil type and topography is also an influencing factor. Avenue has two soil types, Evesham 3 (411c) and Bearsted 1 (541A). Evesham 3 is described as, highly fertile, a slowly permeable calcareous clayey, and fine loamy over clayey soil. Bearsted 1 is described as, low in fertility, a well-drained coarse loamy and sandy soils over sand or sandstone, in places ferruginous. The distribution of these soils is Evesham 3 covers points 3, 4, 5, 6, and 7, and Bearsted 1 at 1, 2 and 8, (Cranfield University 2022) . The soil type alone, does not account for all the variation as site 2 had high VAGB so it is likely to be influenced by other factors listed above. Near Warden was the least variable and has a single soil series, Evesham 3, (Cranfield University 2022). Understanding soil variability in conjunction with NDVI or plant height variation would be interesting further research as it could be a strong decision basis for VRA.

Avenue and Near Warden are part of the same farm, Silsoe, and therefore would all be sprayed the same uniform dose. At the farm, Near Warden had the highest VAGB through the season, which if applied with the same dose as Avenue would either lead to an ineffective treatment in Near Warden or would mean Avenue

was being overdosed. Variability was greatest at T3, when the ears are out and when the canopy is closed and no longer growing.

Finding an accessible, rapid method of understanding variation in fields for fungicide applications would remove the barriers to wide-scale use of variable rate application. The use of satellite imagery to monitor biomass variation using NDVI is rapid and more accessible than UAV mapping and sensing methodologies. NDVI variation showed similar ranges of variation to that shown in the plant height and VAGB only up to T1. The range of values for NDVI decreased after T1 which is consistent with canopy closure and NDVI saturation at T2 and crop ripening at T3, (Dong et al. 2020). Values could have fluctuated due to cloud cover as there is currently no perfect solution to removing cloud. However, the images selected were visually inspected to ensure the lowest level of cloud cover. Future systems involving NDVI should account for cloud cover issues as when a year has heavy cloud cover from end of March – end of April, there will be few images to choose from. Using UAV technology would overcome this, however there would be limits from the climate conditions (wind, rain etc).

Linear fit of NDVI using different spray timings was not effective with only T0 having an  $r^2 = 0.585$  for Silsoe Farm, T1 having an  $r^2 = 0.368$ , and all other timings having  $r^2 < 0.3$ . This would mean that NDVI imagery taken close to T0 was the optimal timing to base the VRA on. T0 in this case was measured for Silsoe only, but the relationship for NDVI and VAGB for each farm had very similar values, so the assumption is that T0 in Olney would also show a better NDVI and VAGB relationship. Further research into when the canopy is best represented by NDVI would be beneficial. Measuring WW canopies from 1<sup>st</sup> March – 30<sup>th</sup> April may provide better relationships than the ones found for latter spray timings.

T0 is an optional spray, with farmers only recently using it in areas of high disease pressure. T1 is the best spray timing to capture variation in VAGB for applications from this study and the equation produced for this is piloted in a quick method for understanding the range of variation in WW fields in 2018 for the East of England using Google Earth Engine. Equation 3-3 shows the prediction equation extracted from T1 for these farms

**Equation 3-3: T1 prediction equation for VAGB (m<sup>3</sup>), using NDVI for T1 values, where x = NDVI and Y = VAGB**

$$y = 567.2x - 119$$

Creating a system where farmers or agronomists can see areas of variation using initial imagery, and then assess the height variation and feed this back into the NDVI and prediction tool, would be the next move forward with this application technique, until a base level of understanding for each field was achieved. This could then be used to justify the use of VRA in fields if there is enough variation seen and would be a cost-effective modelling approach for VRA fungicides.

### 3.5 Conclusion

Understanding the variation in WW fields spatially and temporally is increasingly important for accurate estimation of yields and precision application of inputs. This chapter focused on one main research question, how does VAGB vary across time and space? This was broken down into two further questions. Do the areas of variation remain variable throughout the season i.e., is the temporal variation consistent? This chapter found that volumetric biomass variation is not limited to either spatial or temporal changes. Throughout the season the levels of spatial variation remained variable. The second question this chapter addressed was: are NDVI predicted estimates of plant height and VAGB suitable for determining spatial variability of biomass for fungicide applications? This study found that NDVI was a suitable indicator of biomass variation, however, the best timing for NDVI measurements to indicate variation was at T0 when the canopy is still open. Later NDVI measurements lead to lower levels of variation in NDVI which did not reflect the VAGB well. The scope of this study was to understand where the variation occurred not the reason for the variation but has speculated some factors in this specific study. This chapter has monitored the variation within a WW crop canopy throughout the fungicide application period and determined the most appropriate timing for NDVI imaging of this variation. Cloud cover is still a major concern and pixel size is important to understand the full extent of variation. Current spray technology can adjust over 0.5m so the smaller the pixel the more accurate the application, (Miller 2019a). Further work from this chapter would be, to upscale the monitoring to the same fields and more with a VAGB method and compare them to NDVI with the aim to create a machine learning algorithm, which would determine future variation. Future work should focus on the reasons behind the variation and include soil mapping in conjunction with plant parameters variation as a basis for VRA. The feasibility of using UAVs to overcome the cloud cover should also be considered for further work.

## **4 Rapid methodology for understanding the regional range of variation**

### **4.1 Introduction**

Assessments of variation in winter wheat (WW) fields can be time consuming and expensive. This is a barrier to many farmers as margins are growing increasingly tight, with the average business income for 2019/2020 at £46,000 (Department for Environment Food and Rural Affairs 2020b). The time taken for UAV flights on good weather days and online tractor sensor measurements can be long (Ferguson 2019). Whilst the cost of the UAV, tractor with mounted sensor or subscription service might not be justifiable by a small farm or a farm with only a small area of WW production.

One step forward to making variable rate applications (VRA) within reach of most farmers would be to use accessible, and therefore cheaper data to drive decisions such as NDVI satellite imagery. The data may be less accurate due to the pixel size of the imagery or timing of the sensing; however, it could provide access to VRA which was prohibitive before, leading to a more suitable use of fungicide applications.

Annual recommendations for fungicide applications are made by bodies such as farming press, agronomists, chemical companies such as Syngenta and Bayer, and levy boards (AHDB), based on the conditions the season has already seen and any disease forecasting. This chapter pilots a method which could produce maps of variation across the UK, which would provide a full understanding of how variation changes through seasons, regions, and fields. Understanding how the regions vary from each other unlocks data for more informed use of applications. Regionally, crops reach the desired growth stages and leaf visibility at different times following the weather. Predicting variation across a whole region through imagery will influence the media recommendations and therefore the decisions made by agronomists and farmers for crop protection applications. The scope of this chapter focuses on one region.

The previous chapter studied the use of NDVI to reflect the biophysical parameters measured in six wheat fields. Chapter 3 used Planet imagery for determining variation as the resolution is high with 3 by 3 m pixels as it was shown to be critical in accounting for variability, (Skakun et al. 2021) . This chapter uses Sentinel 2 (Copernicus 2019b) with 10 by 10 m pixels due to the ease of processing in Google Earth Engine, (Gorelick et al. 2017) which was crucial to rapid data extraction. A comparison of the standard deviation from Planet constellation (Planet Team, n.d.) to Sentinel 2 was conducted to determine the similarity in variation values. Using the NDVI values determined from the regional extraction of min and max and standard deviation, the range of volumetric biomass for each field at T1 was calculated using the equation extracted for NDVI and VAGB ( $\text{m}^3$ ) at T1 from chapter 3. The distribution of the range could be used in conjunction with spray deposition relating to biomass from chapter 2 to determine where VRA use is justified due to the variation seen in the canopy.

This chapter addresses the following objective (4): What is the range of NDVI variation in winter wheat canopies in the East of England at T1?

## **4.2 Methods**

### **4.2.1 Comparison of the satellite imagery**

Sentinel 2 NDVI values were extracted for the dates closest to the application timings with the least cloud cover, for the six fields in this study. They were extracted using the EO browser and plotted against planet constellation satellite imagery from chapter 3. Sentinel 2 data was selected for comparison as it could be used in the rapid estimation of variation from Google Earth Engine. Standard deviation was plotted as it expresses the variation seen compared to the mean.

### **4.2.2 Google Earth Regional study**

UKCEH Land Cover® plus: crops, (CEH 2018) map, gathers crop information from field parcels greater than 2 ha in the UK using a combination of Sentinel-1 C-band Synthetic Aperture Radar (SAR) and Sentinel-2 optical data, (Copernicus 2019b; 2019a). WW fields, including oats, were isolated from the imagery using ArcPRO (ESRI 2017) and assigned a region using the intersect tool. Regional data sets were then imported as csv files into Google Earth Engine (GEE). The number of WW fields per region are displayed in Table 4-1. East of England was selected for having the greatest number of WW fields in England, 43,675 fields. GEE was used to process satellite imagery from Sentinel-2 for T1.

Visual pre-inspection of satellite imagery revealed the optimal days nearest T1, for minimal cloud cover. The image selection was then refined further using local cloud masking through the sentinel 2 QA band, (Beale, 2021). The standard deviation of NDVI was extracted from Sentinel 2 for the East of England, T1, and distributed as a frequency. Data points were removed where the image was too cloudy to retrieve NDVI min and max NDVI range data were normally distributed. The fields were split into categories of variability using the standard deviation and shown in a heat map of variation using ArcGIS.

**Table 4-1: Number of fields for each region in England**

| <i><b>Region</b></i>     | <i><b>Number of fields</b></i> |
|--------------------------|--------------------------------|
| East Midlands            | 30855                          |
| East of England          | 43675                          |
| London                   | 205                            |
| North East               | 8718                           |
| North West               | 2844                           |
| South East               | 18677                          |
| South West               | 15885                          |
| West Midlands            | 17972                          |
| Yorkshire and the Humber | 22771                          |

## **4.3 Results**

### **4.3.1 Comparison of imagery**

The standard deviations for T1 from the NDVI imagery extracted from the planet constellation and Sentinel 2 imagery are plotted in Figure 4-1. The satellites have a good relationship with  $r^2 = 0.95$ . On this, the assumption of Sentinel 2 as a similar representation of in-field variation can be made as like that of the planet constellation.

### **4.3.2 Google Earth Regional study**

The standard deviations of NDVI of all fields from the UKCEH Land Cover® plus in East of England in 2018 at T1 were extracted using Google Earth Engine and Sentinel 2 imagery. There were just under 36000 successful extractions from the 19<sup>th</sup> April 2018, and are shown in Figure 4-2. The data was normally distributed. The most frequent standard deviation was 0.06-0.07 with just over 3000 fields. There were a significant number of fields with a standard deviation  $>0.12$ . Table 4-2 lists the standard deviation of the NDVI values from the planet data in chapter 3, Figure 4-3 shows the comparison of these data. The variation seen in the five of the six fields is below the most frequent standard deviation but Avenue field sits above the most frequent variation.

Figure 4-4 shows the range of variation in the East of England. Areas of highest variability are seen on the coast and in the western most part of the region. The blank areas show Thetford Forest and Norwich. A diagonal line from Southwest of the region to the Northeast splits the main areas of high and low variability.

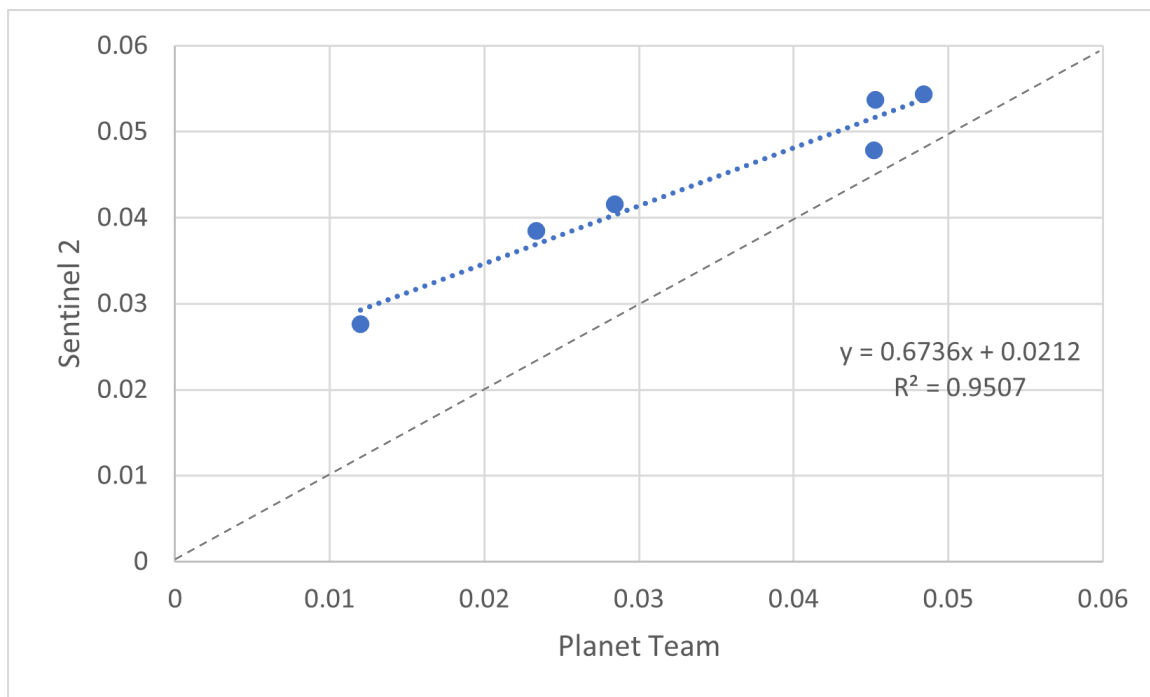


**Figure 4-1: Standard deviation of NDVI at fungicide application timing T1 extracted from Planet constellation, used for field study, and Sentinel 2, used for quick estimation method in regional analysis.**

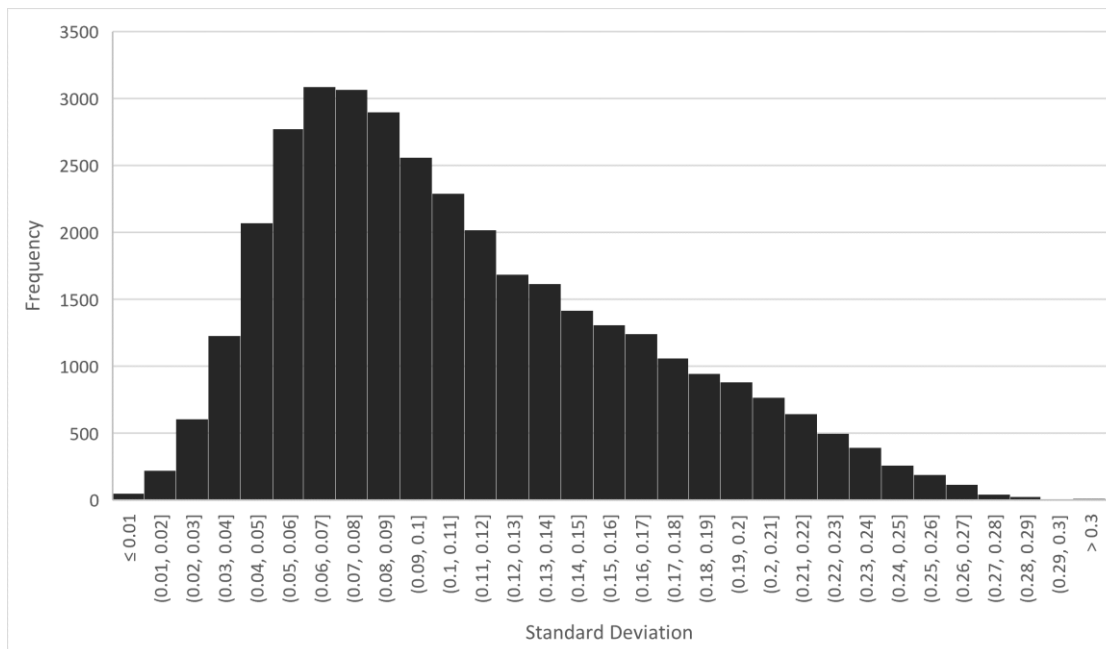


**Figure 4-2: Histogram of standard deviation of NDVI extracted Sentinel 2 imagery of all fields in East of England in 2018 at T1, 19<sup>th</sup> April 2018, CEH Landcover + and Google Earth Engine.**

**Table 4-2: Standard deviation of NDVI from the fields trials in chapter 3.**

| <i>Farm</i>   | <i>Field</i> | <i>Standard Deviation of NDVI range</i> |
|---------------|--------------|-----------------------------------------|
| <i>Silsoe</i> | Avenue       | 0.111327                                |
|               | Ivy Ground   | 0.039271                                |
|               | Near Warden  | 0.029342                                |
| <i>Olney</i>  | Great Dole   | 0.026843                                |
|               | Lavendon     | 0.045369                                |
|               | Home Field   | 0.044854                                |

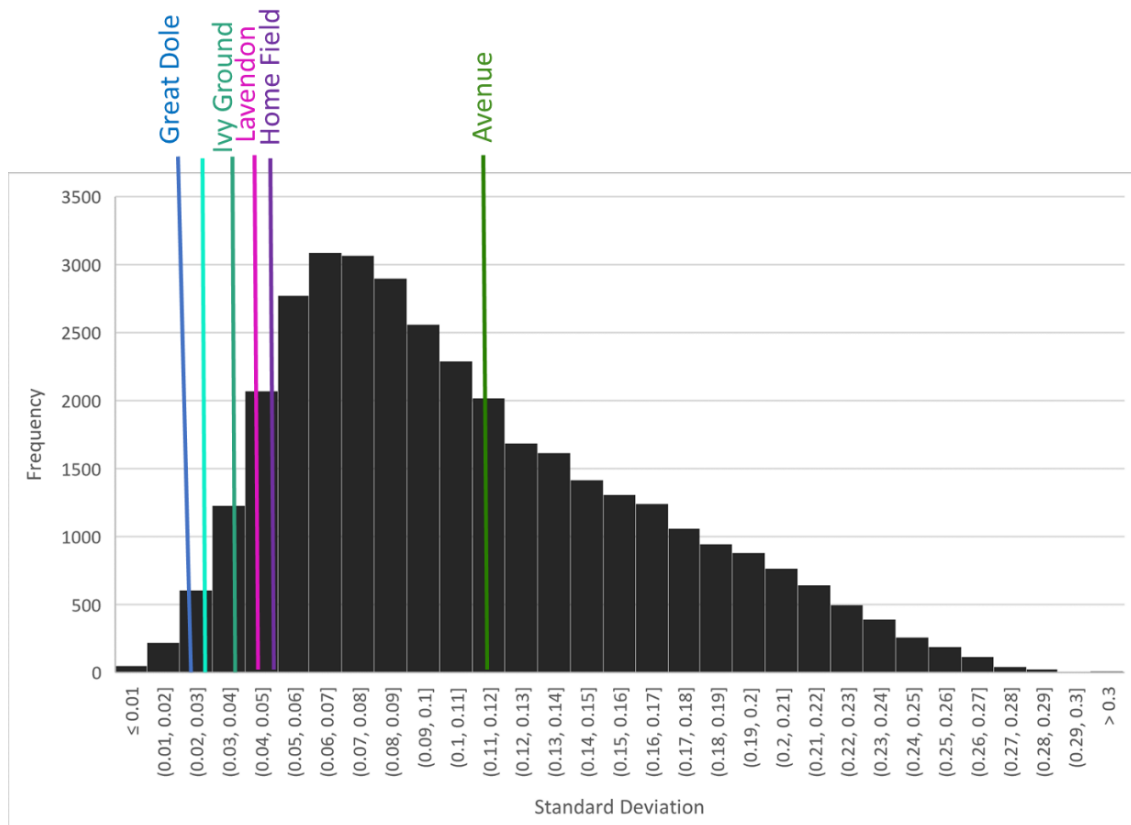


**Figure 4-3: Standard deviation of NDVI from the field trials mapped on to the histogram of standard deviation of NDVI extracted Sentinel 2 imagery of all fields in East of England in 2018 at T1, 19th April 2018, CEH Landcover + and Google Earth Engine**

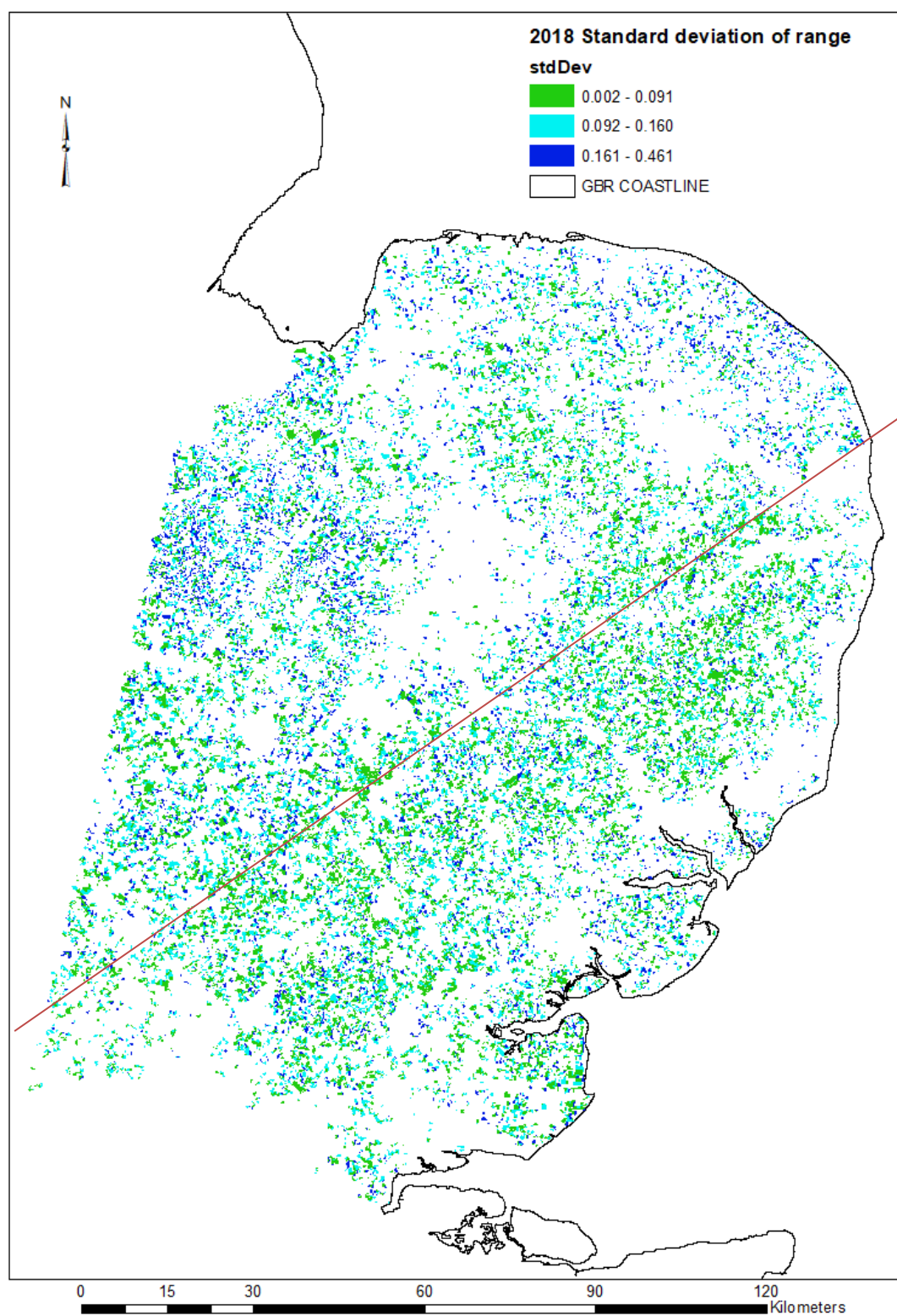


**Figure 4-4: Map of standard deviation of NDVI at T1 for each winter wheat field grown in East of England in 2018.**

## 4.4 Discussion and Conclusion

Determining regional biomass variation using satellite imagery is a cost-effective forecasting method and justifies the use of wide-scale VRA by highlighting the potential for savings. Other modelling systems are available but require significantly more time, processing power and technical ability to determine variation, (Sui et al. 2018). In addition to the influences of variation outlined in chapter 3, regional variation within WW fields may also be influenced by cloud cover, (AHDB 2018).

Imagery was difficult to extract during the season due to cloud cover, which is a major issue for remote sensing of crop monitoring (Oerke 2019). Despite improved cloud masking, cloudy pixels will still cause bias in data.

Using the combination of Google Earth Engine and UKCEH Land Cover® plus, the method was successful at extracting regional NDVI imagery that highlight variation for 43,675 fields in the East of England. The standard deviation showed the range of variation was great in many fields, which justifies the importance of future use of VRA in the region. Comparing the trial data with all of the variation in the East of England shows the field trial data were typical.

The range of variability seen in the east of England is largely split by a diagonal line as show in Figure 4-4. The reasons for such variability could include, planting dates, range of varieties, topography, weather patterns, soils, and the effect of disease. Planting dates, variety ranges and disease prevention as recommended by AHDB are only regionalised into the East region which covers the whole of the study area and therefore unlikely to variation locally. Referring to the Soil Survey of England and Wales, (Cranfield National Soil Resources Institute (NSRI) 1983), the South-eastern area of low variability largely coincides with soils from the 711 group. Remainder of the region which has low variability also has some coincidence 411 soils. This is the Evesham group, which in the study conducted in chapter 3 shows areas of high variability. Although there is a broad coincidence of the low variability region with soil types, this is not the full story, as shown by a more localised study (see section 3.4). Studying the topography of the region, the areas of low-lying land in the Northwest of the area show high variability,

(Topographic-map.com 2022). Finally, the area of high variability in the Northeast is coincident with the driest part of the region, (Met Office 2018). Although these environmental factors coincide with the regions of high and low variability, the mechanisms to account for them are currently unclear and require further work.

Further work also should be done to determine the range of variation across the UK and the percentage of variation within fields should be extracted to determine exact savings per field. This study is limited by the minimum and maximum values as the proportion of them is unknown. To justify exactly where the VRA becomes of cost benefit to the farmer, the proportion of variability should be identified.

Creating a system where farmers or agronomists can see areas of variation using initial imagery, and then assessing the height variation and feeding this back into the NDVI and prediction tool would be the next move forward with this application technique. Once a base level of understanding of variation for each field is achieved, this could then be used to justify the use of VRA in fields where enough variation is seen, providing a cost-effective modelling approach for VRA fungicides.

This chapter answers the following research question from objective 4: What is the range of NDVI variation in winter wheat canopies in the East of England at T1? The chapter looked at a range of spatial variation in one region of WW fields to answer this question. It found that there is significant range in NDVI and therefore VAGB, Height and Spray deposition that warrants the use of widescale VRA with only a small number of fields having low levels of variation. This study contributes the new technique for extracting NDVI data on a mass scale to determine the minimum and maximum variation in WW fields. This is a cost effective and simple method to determine suitability of VRA on farms. The limitations of this study are the relationships to determine each crop parameter, the ability of NDVI to predict crop VAGB at T1 and unobtainable data from cloud cover. However, this is a proposed model and will need further work to extract the best data. Future studies would include using the optimal relationship for VAGB from further studies recommended in chapter 3, and determining the variability threshold for switching from standard spraying to VRA.

## **5 Evaluating Variable Rate Application of fungicides on Winter Wheat**

### **5.1 Introduction**

Fungicides are expensive and cost is increasingly important to farmers with margins getting tighter every year to keep the price of a loaf low. Variability from fields influences the yield (t/ha), which drives price and the market. Overuse of fungicidal chemistry has led to soil deterioration and resistance of targets to the chemistry which required higher dose rates, thus increasing costs to farmers. Furthermore, since fungicides are known to contaminate non-target areas, the environmental cost of their use must be considered. By modifying application methods, to increase specificity of fungicide application, monetary and environmental costs can be reduced.

In 2019 the UK was the 6th highest producer of cereals in the EU. Cereals accounted for 52% of the croppable areas in the UK, with 1.44 million ha of treated wheat. The average cost of crop protection for WW fields in 2019 was £216 per ha. This means approximately £311 million (to the nearest million) was spent on crop protection in the UK in 2019. At least 50% of crop protection budgets for wheat are spent on fungicides, making them the highest variable cost to farmers. This equals at least £155 million on fungicides for wheat every year (Department for Environment Food & Rural Affairs 2020).

A way to reduce these variable costs would be to adapt the spraying system to VRA, as the change in rate over the field to match the dose rate should result in a reduction of spray. However, VRA is not commonplace for fungicides, likely due to the expense of technology, time taken to retrain on new systems for farm staff, time taken to map the field, or lack of trust in the method. Actively reducing the rates is a perceived risk to farmers, if the spray rate is wrong the crop could be at risk (Tscharntke et al. 2012).

Fungicide environmental effects research only accounted for 13% of crop protection studies between 1991 and 2013. Fungicides can pollute aquatic ecosystems, from surface water runoff, and cause harm to a wide range of

nontarget organisms. Reducing the rates of fungicides and ensuring the dose rate is appropriate will lessen the environmental impact of fungicide exposure. Resistance is also an important consideration when calculating dose rate since fungal pathogens can develop resistance to exposure of fungicides within a few years (Zubrod et al. 2019). Preventing resistance requires a mix of fungicides and modes of action (AHDB 2020). Making the dose rate the most appropriate will prevent resistance from overuse or inappropriate use.

A barrier to using VRA is the cost of a new system. New tractors are ever increasing in their capabilities, with many now having GPS navigation and section control. However, the cost of a new towed or self-propelled sprayer with these additions will be out of budget for some farmers. Some companies offer a retroactive fit of a device which will perform VRA, which is a more affordable option. To justify purchase of VRA equipment, the time taken to save money from reduced fungicide (and other crop protection) applications must be before the requirement of a new purchase of equipment, (Mowbray 2021).

This chapter addresses the final research question: what and where is the economic benefit of VRA compared to a uniform dose rate? This will be done by performing a cost benefit analysis of a standard fungicide application programme and a VRA programme using a pulse width modulation system with inputs derived from satellite imaging methods used in chapter 3.

## **5.2 Methods**

To determine the cost benefits associated with VRA, two scenarios were compared. Scenario 1 was based on a uniform application rate and scenario 2 was based on a VRA system using a pulse width modulation tractor programmed with satellite imagery to determine the dose rate applied. Machinery costing sheets from Markham and Chapman (1998) were used to calculate cost per ha that informed fixed costs. All costings for tractor cost, running and maintenance, labour, and fuel, were extracted from Redman (2021).

### **5.2.1 Assumptions**

This methodology for comparison is based on six assumptions:

1. There is no major disease outbreak in the season
2. The sprayer in scenario 1 is not equipped for VRA
3. T1 calculation for VAGB from NDVI from chapter 3 is a reasonable representation of variation in the field
4. NDVI value (0.3-0.7) represents canopy crop cover
5. The dose rate required to suit biomass increases in a linear fashion
6. There were no yield deficits as consequences of these applications

### **5.2.2 Cost benefit analysis**

#### **5.2.2.1 Scenario 1 – Uniform application**

This scenario was based on the Farms from chapter 3. The fungicides selected were what was used at T1 as part of a mix sprayed at Olney, in 2019. The farm chose an application rate of 80% recommended manufacturer dose rate of Aviator 235 Xpro as it is recommended for a wide range of diseases with actives, bixafen and prothioconazole (Bayer). The cost of the Aviator 235 Pro was £291.67/10L, (Olney Farm, 2021). These decisions were made based on an agronomist assessment and recommendation. The application speed was 200L/ha. Agronomy information was not available for Silsoe Farm so

recommendations for Olney was used, this has limitation but the understanding a cost difference for Silsoe is still useful for this study. The cost of fungicide for each field was calculated for 2019. **Table 5-1** shows the breakdown of fixed costs of spraying taken from Markham and Chapman (1998) and Redman (2021).

**Table 5-1: The breakdown of fixed costs for a uniform spray application, based on a template from Markham and Chapman (1998) with input figures from Redman (2021).**

| Uniform Application Fixed Costs       |   |       |                              | Cost           | Label          |
|---------------------------------------|---|-------|------------------------------|----------------|----------------|
| Sprayer purchase price after discount |   |       |                              | £207,380.00    | A              |
| Selling price after                   | 8 | years | B                            | £58,066.40     | C              |
| Average value                         |   |       | $A+C/2$                      | £132,723.20    | D              |
| Interest (HP)                         |   |       | $Dx$ (bank lending rate)     | £1,327.23      | E              |
| Depreciation                          |   |       | $A-C/B$ years                | £18,664.20     | F              |
| Insurance                             |   |       | $Dx(£15 \text{ per } £1000)$ | £1,990.85      | G              |
| Annual fixed costs                    |   |       | $E+F+G$                      | £21,982.28     | H              |
| Hours worked annually                 |   |       |                              | 200            | I              |
| Fixed cost per hour                   |   |       |                              | £109.91        | J              |
| <b>Operating cost per hour</b>        |   |       |                              |                |                |
| Labour per hour                       |   |       |                              | £11.20         | K              |
| Fuel per hour                         |   |       |                              | £6.18          | L              |
| Spares & repairs as % of new price    |   |       |                              | 1.5%           | M              |
| Spares & repairs cost                 |   |       | $A*M/I$                      | £15.55         | N              |
| <b>Cost per hour</b>                  |   |       |                              | <b>£142.84</b> | <b>J+K+L+N</b> |
| <b>ha per hour</b>                    |   |       |                              | <b>10</b>      |                |
| <b>Cost per ha</b>                    |   |       |                              | <b>£14.28</b>  |                |
| <b>Total Annual Cost</b>              |   |       |                              | <b>£28,569</b> |                |

#### **5.2.2.1 Scenario 2 - VRA**

This scenario used a satellite basis for variation monitoring, and a pulse width modulation system for the VRA system. Appropriate quantities of fungicides were calculated using the percentage of pixel NDVI values, from Planet Satellite imagery from the 19<sup>th</sup> April 2019. NDVI pixel values were extracted from all pixels within the fields, Figure 5-1 and Figure 5-2. These pixels were then grouped into bands of 0.1 width. Each band was matched with a dose rate of L/ha based on those from Tackenberg et al. (2018), where canopy had a 95% coverage, 100% of the 80% application rate decided by the agronomist, NDVI value 0.7, was applied and where canopy had 30% coverage, then 25% of the application rate was applied (NDVI value is 0.3), Table 5-2. The farm equipment was costed at £25,700 for a John Deere PWM ExactApply to be used in conjunction with a sprayer (Mowbray 2021). Table 5-3 shows the breakdown of fixed costs for the variable rate application method. The sprayer price includes the cost of the ExactApply from John Deere. The labour cost is higher due to the more complex skill set required for application. The use of precision agriculture to monitor crop canopies is sold as a subscription service for VRA N at £2/ha, (Redman 2021). The overall cost of fungicides was calculated for each field and compared to the standard system costs. The price of the VRA system was then considered and used to calculate the take to pay for the upfront cost of the system.

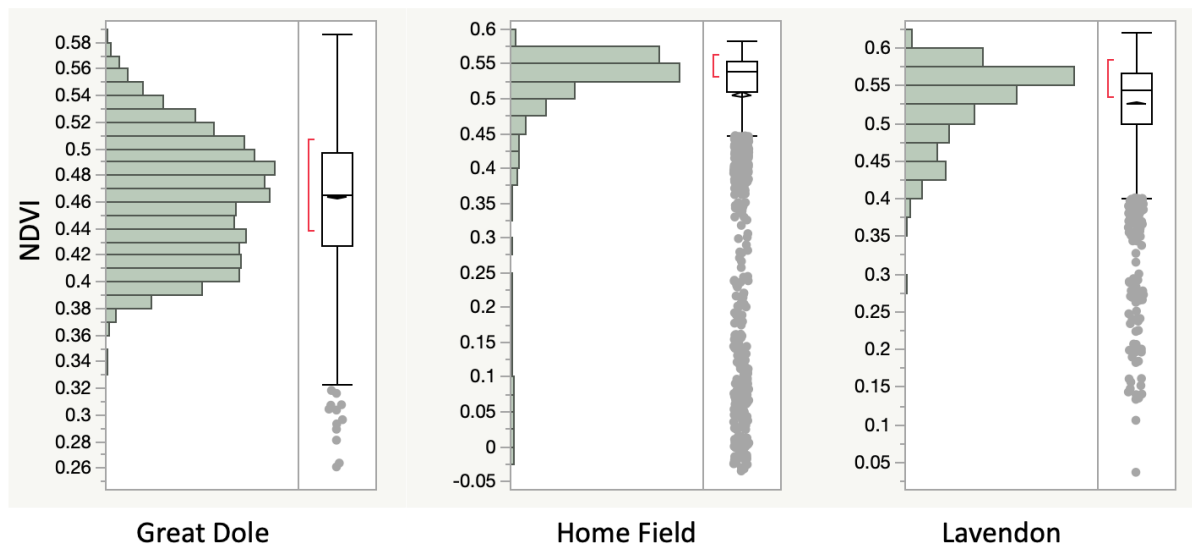


**Figure 5-1: Distribution of NDVI pixel values for each field from the Olney farm at T1.**

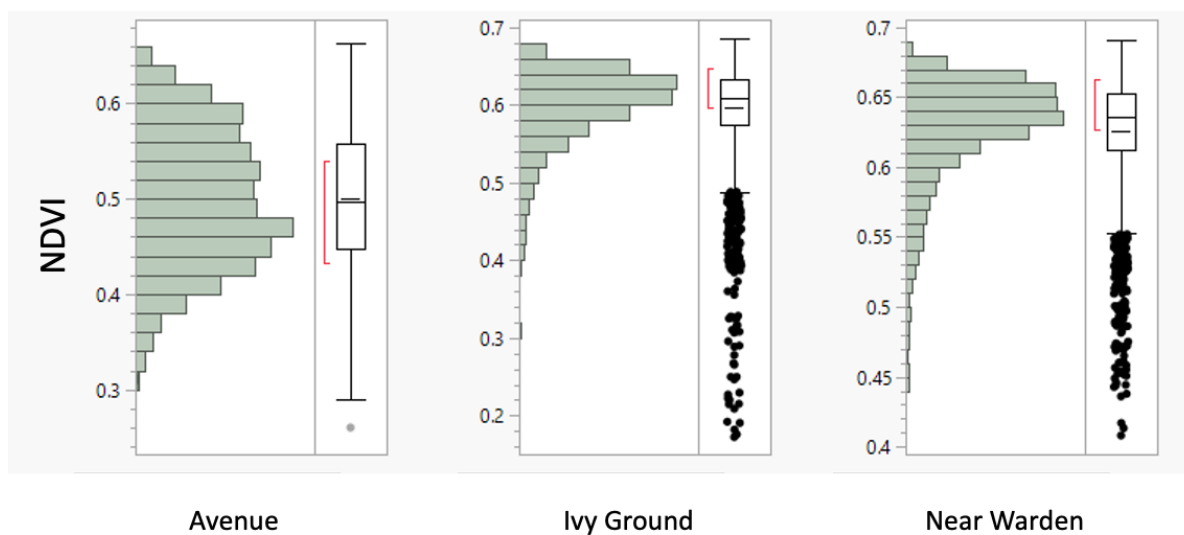


**Figure 5-2: Distribution of NDVI pixel values for each field from the Silsoe farm at T1.**

**Table 5-2: Application rates for crop canopy percentage and NDVI value, where rates were the linear relationship for application rate was taken from Tackenberg et al. 2017 and NDVI min and max values were taken from min and max NDVI seen in chapter 3 at T1.**

| <i><b>NDVI<br/>Value</b></i> | <i><b>Crop<br/>Canopy<br/>Cover<br/>(%)</b></i> | <i><b>Application<br/>Rate (L/ha)</b></i> |
|------------------------------|-------------------------------------------------|-------------------------------------------|
| 0.7                          | 95                                              | 200                                       |
| 0.6                          | 80                                              | 166                                       |
| 0.5                          | 65                                              | 131                                       |
| 0.4                          | 50                                              | 97                                        |
| 0.3                          | 30                                              | 50                                        |

**Table 5-3: The breakdown of fixed costs for a variable rate application method, based on a template from Markham and Chapman (1998) with input figures from Redman (2021).**

| Variable Rate Application Fixed Costs |   |       |                              | Cost              | Label          |
|---------------------------------------|---|-------|------------------------------|-------------------|----------------|
| Sprayer purchase price after discount |   |       |                              | £233,080.00       | A              |
| Selling price after                   | 8 | years | B                            | £65,262.40        | C              |
| Average value                         |   |       | $A+C/2$                      | £149,171.20       | D              |
| Interest (HP)                         |   |       | $Dx$ (bank lending rate)     | £1,491.71         | E              |
| Depreciation                          |   |       | $A-C/B$ years                | £20,977.20        | F              |
| Insurance                             |   |       | $Dx(£15 \text{ per } £1000)$ | £2,237.57         | G              |
| Annual fixed costs                    |   |       | $E+F+G$                      | £24,706.48        | H              |
| Hours worked annually                 |   |       |                              | 200               | I              |
| Fixed cost per hour                   |   |       |                              | £123.53           | J              |
| Labour per hour                       |   |       |                              | £14.13            | K              |
| Fuel per hour                         |   |       |                              | £6.18             | L              |
| Spares & repairs as % of new price    |   |       |                              | 0.015             | M              |
| Spares & repairs cost                 |   |       | $A*M/I$                      | £15.55            | N              |
| <b>Cost per hour</b>                  |   |       |                              | <b>£159.40</b>    | <b>J+K+L+N</b> |
| <b>ha per hour</b>                    |   |       |                              | 10                |                |
| <b>Mapping service cost per ha</b>    |   |       |                              | 2                 |                |
| <b>Cost per ha</b>                    |   |       |                              | <b>£15.94</b>     |                |
| <b>Total Annual Cost</b>              |   |       |                              | <b>£31,879.18</b> |                |

### 5.3 Results and Discussion

Using VRA instead of uniform application a saving of £747.72 was found for the three fields across the Olney Farm at one application timing (T1) and for one of the chemicals, Table 5-4. This was calculated at £13.82 per ha saved from a dose rate based on canopy cover. There are 3 application timings and an optional T0 every year. These applications have a mix of chemicals so there may be further savings available for more targeted applications of individual actives. In the case of Olney using VRA at T0, T2, and T3 an overall saving would be made of £55.28/ha. Annually this equates to £2990.90 just across those 3 fields. A saving of £195.12 was found at Silsoe at T1 application timing. This becomes £9.08 per ha. Further savings across the season and other sprays, T0, T2, and T3 would be £36.30/ha and annually £780.48. Avenue was the most variable field in chapter 3 and savings comparison between the different scenarios were £105.55. Near-warden was the least variable field and VRA saved £35.16. If a farm had fields with the same level of variation as Near-warden, then it would be difficult to justify the VRA method and upfront costs. Whereas if a farm had fields with variation that was similar to Avenue, then the fiscal rewards of VRA would be realised sooner.

**Table 5-4: Results of cost for each fungicide application scenario where scenario 1 is uniform application and scenario 2 is VRA on study farms Olney (top), Silsoe (bottom).**

| Scenario 1: Uniform application                    |                    |                             |                                     |                                |                     |                                 |                           |
|----------------------------------------------------|--------------------|-----------------------------|-------------------------------------|--------------------------------|---------------------|---------------------------------|---------------------------|
| Olney                                              | Size of field (ha) | Active Chemical @ 1L/ha (L) | Application per field @ 200L/ha (L) | Active Chemical Cost (£29.2/L) | Water @ 199L/ha (L) | Water Cost (0.1775 pence per L) | Fixed Cost per ha (14.28) |
| Great Dole Home Field<br>Lavendon<br>Total<br>Cost | 32.2               | 32.2                        | 6440                                | 939.18                         | 6408                | 1137                            | 459.82                    |
|                                                    | 12.4               | 12.4                        | 2840                                | 361.67                         | 2468                | 438                             | 177.07                    |
|                                                    | 9.5                | 9.5                         | 1900                                | 277.09                         | 1891                | 336                             | 135.66                    |
|                                                    | 54.1               | 54.1                        | 11180                               | £1,577.93                      | 10766               | 1911                            | 772.55                    |
|                                                    |                    |                             |                                     | £1,577.93                      |                     | £19.11                          |                           |
| Scenario 2: VRA                                    |                    |                             |                                     |                                |                     |                                 | Fixed Cost per ha (15.94) |
| Great Dole Home Field<br>Lavendon<br>Total<br>Cost | 32.2               | 14.2                        | 2840                                | 414.17                         | 2826                | 502                             | 513.27                    |
|                                                    | 12.4               | 4.13                        | 945                                 | 120.34                         | 940                 | 167                             | 197.66                    |
|                                                    | 9.5                | 7.4                         | 1479                                | 215.69                         | 1472                | 261                             | 151.43                    |
|                                                    | 54.1               | 25.72                       | 5264                                | £750.21                        | 5238                | 930                             | 862.35                    |
|                                                    |                    |                             |                                     | £750.21                        |                     | £9.30                           |                           |
| Scenario 1 total:                                  |                    |                             | £2,369.59                           | Scenario 2 total:              |                     | £1,621.86                       |                           |
| Saving                                             |                    |                             |                                     |                                |                     | £747.72                         |                           |
|                                                    |                    |                             |                                     |                                |                     |                                 |                           |
| Scenario 1: Uniform application                    |                    |                             |                                     |                                |                     |                                 |                           |
| Silsoe                                             | Size of field (ha) | Active Chemical @ 1L/ha (L) | Application per field @ 200L/ha (L) | Active Chemical Cost (£29.2/L) | Water @ 199L/ha (L) | Water Cost (0.1775 pence per L) | Fixed Cost per ha (14.28) |
| Avenue Ivy Ground Near Warden<br>Total<br>Cost     | 8.1                | 8.1                         | 1620                                | 237.33                         | 1612                | 189                             | 116.478                   |
|                                                    | 7.7                | 7.7                         | 1540                                | 225.61                         | 1532                | 180                             | 110.726                   |
|                                                    | 5.7                | 5.7                         | 1140                                | 167.01                         | 1134                | 133                             | 81.966                    |
|                                                    | 21.5               | 21.5                        | 4300                                | 629.95                         | 4279                | 503                             | 309.17                    |
|                                                    |                    |                             |                                     | £659.95                        |                     | £5.03                           |                           |
| Scenario 2: VRA                                    |                    |                             |                                     |                                |                     |                                 | Fixed Cost per ha (15.94) |
| Avenue Ivy Ground Near Warden<br>Total<br>Cost     | 8.1                | 4.5                         | 904                                 | 131.78                         | 899                 | 160                             | 129.114                   |
|                                                    | 7.7                | 5.7                         | 1148                                | 167.43                         | 1142                | 203                             | 122.738                   |
|                                                    | 5.7                | 4.5                         | 904                                 | 131.85                         | 899                 | 160                             | 90.858                    |
|                                                    | 21.5               | 14.8                        | 2955.6                              | 431.1                          | 2940.8              | 522.0                           | 342.71                    |
|                                                    |                    |                             |                                     | £431.10                        |                     | £5.22                           | 0                         |
| Scenario 1 total:                                  |                    |                             | £974.15                             | Scenario 2 total:              |                     | £779.03                         |                           |
| Saving                                             |                    |                             |                                     |                                |                     | £195.12                         |                           |

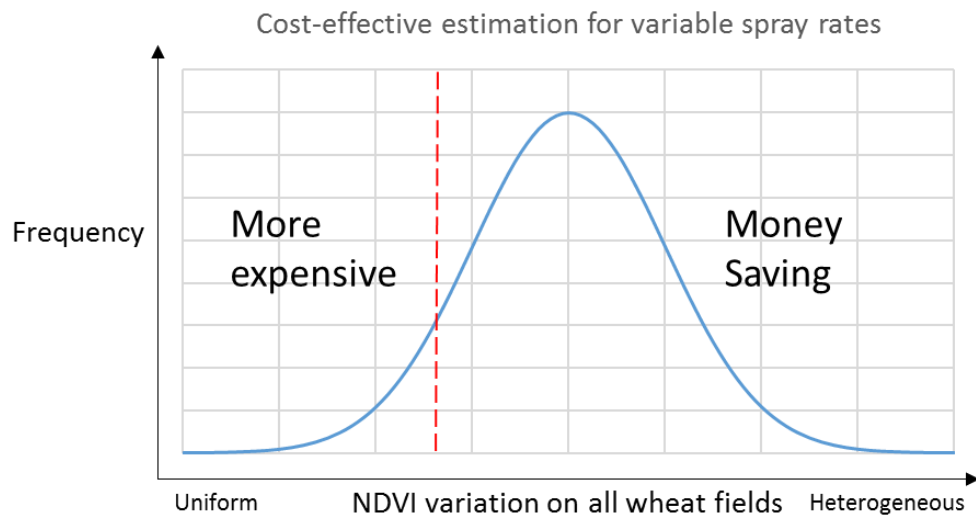


**Figure 5-3: Frequency distribution of uniform and heterogeneous fields. The red line symbolises a hypothetical line where VRA becomes cost effective, regardless of the variability.**

From the above it can be seen that it is possible to understand the savings using NDVI, considering the range of NDVI variation on all WW in the study region and depending on the frequency, theoretically there should be a boundary at which VRA becomes cost effective, Figure 5-3. To justify the initial purchase costs of VRA technology, a rapid assessment of NDVI variation is all that is necessary to understand the field is above or below this line.

The time taken for return on investment reduces if VRAs could be made across more crop protection applications such as PGRs, pesticides and other crops. Most new sprayers are now sold with a form of VRA equipment, (Mowbray 2021).

The limitations are from the use of NDVI mapping to make the association of crop canopy variation. As shown in chapter 3, NDVI to predict VAGB canopy variation had an  $r^2=0.386$  at T1. Using height to ground truth NDVI measurements may be a more reliable prediction system. Another limitation is the linear relationship between canopy crop cover percentage and dose rate. It is uncertain if the efficacy is as effective and further work following on from chapter 0 should investigate this.

## 5.4 Conclusions

This chapter performed a cost benefit analysis on the use of VRA in a scenario and compared it to the uniform application approach to determine where the economic benefits lie. The study found that savings of up to £13.80/ha on Olney Farm and £195.12 on Silsoe Farm could be made from just one fungicide application, T1. If a similar saving was made at T0, T2, and T3 an overall saving would be made of £55.28/ha on Olney, and £36.30/ha. This reduces the variable cost to farmers by a significant amount, with a saving of £2990.90 on Olney farm on or £780.48 on 3 fields at each farm.

This contributes to the VRA literature as it uses an alternative application rate to determine where savings could be made. The limitations of this study are within the linear NDVI dose rate relationship, the importance of retaining efficacy, and the ability of NDVI alone to determine canopy variation.

## 6 Discussion

The intention of this thesis was to deliver a comprehensive foundation for variable rate application of fungicides on winter wheat canopies. The chapters in this thesis study different areas of the VRA process, which collectively are a driving force for the future of VRA spraying. To achieve VRA of fungicides as commonplace in UK crop protection, 5 key questions were answered.

### *What is the current 'state of the art' technology for VRA of PPPs?*

The current 'state of the art' technology shows that there are many methods to conducting VRA of crop protection products. There is no one method which drives the market and there are issues in the deposition quantity and quality of the spray from these different systems. The systems in conjunction with the mapping technology are all built and sold to farmers without adequate research. The main areas of research behind VRA included: spray deposition, the efficacy of the changing rates, the environmental impact, the variability of a crop canopy and where and when this variability changes and, the mapping and modelling technology for understanding this variability. All the areas behind VRA should be considered to determine the most appropriate technology and mapping methodology for farmers moving forward. The technology is available to perform VRA spraying but requires studies to determine exact fungicide dose deposited and whether the variation determined by the mapping or modelling system reflects ground variation.

### *What is the variation in spray deposition in winter wheat canopies?*

Fungicide dose or spray dose, as was also researched in this thesis, varies at each spray application and between the applications. The study found that despite the increase in spray deposition as the canopy grows, the quantity of dye deposited decreases in relation to the size of the plant. To achieve a consistent quantity of fungicide relative to canopy biomass for protectant fungicides, further research should be conducted to confirm the spray rates that would achieve a consistent dose relative to plant biomass, which is proportional to the

manufacturer recommendations. This understanding of the dose required per canopy biomass would also work for systemic fungicide applications. In this pot trial, there was no significant difference between the two varieties studied. However, in a field study there is the potential for this to be a different case. Appendix B shows the pilot for a non-destructive method of sampling, further research into this in conjunction with work on using LiDAR to determine the canopy size would allow a canopy to be studied from seed to ear without being destroyed. The limitations of this study were the canopy size and that the plants did not represent an outdoor WW canopy and the representation of fungicide with dye. Outdoor conditions would have influenced the growth and therefore, variation.

***Are NDVI estimates of biophysical parameters suitable for determining temporal and spatial variability of biomass for fungicide applications?***

Chapter 3 investigated the spatial and temporal variability in six WW fields from two farms across the three fungicide application timings. This was to determine how variable the fields were when they are applied with a blanket dose rate and compare the variation through the season. The fields chosen were variable from each other: on one farm, Silsoe, Avenue had significantly higher levels of variation from all other fields and Near Warden had the lowest level of variation from all fields. This variation is likely to be caused by soil variation and environmental factors. These two fields are likely to have been sprayed with the same dose rate recommended by an agronomist.

***What is the range of NDVI variation in winter wheat canopies in the East of England at T1?***

This study found that there was a range of variability in NDVI of WW fields. The standard deviation showed a high number of fields with low levels of variability from the norm but with significant numbers of fields having high standard deviation. Using a heat map of the standard deviation of the range of each field in the East of England shows the wide range of variation and where the variation

lies. This justifies continued research and studies into the future of VRA in the UK.

### *What and where is the economic benefit of VRA?*

Chapter 5 studied the financial benefits of reducing the rates of application based on a fungicide linear relationship for one farm from chapter 3, (Tackenberg et al. 2018). There were potential savings of £13.82/ha at Olney and £9.08/ha at Silsoe. It is highly unlikely that VRA machinery would only be used in this case for the one application of fungicides. Therefore, the use of VRA could save significantly more and would be faster to pay off.

Overall VRA has many components which all need to work together to create a working system for wide-scale commercial use. There are many relating components in this study, Figure 6-1 shows the evolution of these relationships and the direction of travel for this study. Chapter 2 investigates Weight, Height and how this relates to canopy size and dose rate applications. Chapter 3 focuses on how these components relate to a precision agriculture method.

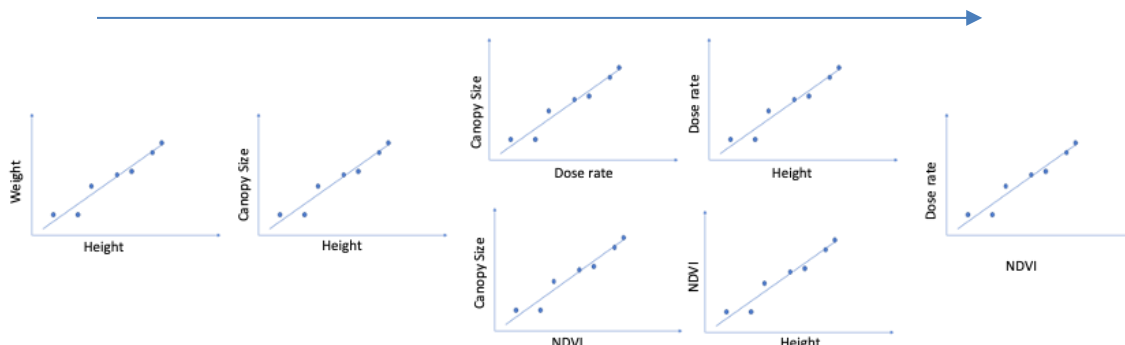


**Figure 6-1: Intermediate relationships between plant parameters for variable rate application used to determine dose rate applications from NDVI.**

The extent to which NDVI from Satellite imagery is suitable for precision applications of fungicides is hindered by the resolution of imagery and the unknown cloudy dates. NDVI from Satellite imagery was useful in this case to assess whether moving forward with VRA using precision systems is feasible. The limits of satellite imagery are overcome by the ever-increasing accuracy of the imagery and the frequency of the satellite passes however other precision agriculture methods including Unmanned Aerial Vehicles (UAVs) and tractor

mounted sensors. UAV imagery as the basis for VRA would be more accurate as assessing canopy biomass as the resolution is higher. UAVs do have limits with weather conditions and battery life but would be a rapid method of assessment which could be performed frequently. Camera mounted sprayers are also a more accurate assessment of canopy biomass and growth stage than compared with satellite imagery but would require a higher upfront cost and either an additional pass on the field or a slow driving speed, both of which take up more time and potentially lead to compaction.

There are limitations to this study in that it does not investigate the full extent of each discipline. Further investigation of these areas of VRA would enable a working approach and encourage wide-scale adoption by the industry.

## **6.1 Future studies and recommendations**

Ease of use, meeting real needs, future modification/evaluation plans, equipment and support are all factors which need to be considered before the application approach for VRA is encouraged for use. Mangold (1994) states that the best transferring of technological knowledge to an agricultural producer comes from another agricultural producer. Farmers want to see the process working elsewhere to get over the rejection reaction; the interaction with a live system gives confidence in trying it at home. Mangold (1994) also explains that technology is crucial to site-specific management, which causes a risk of rejection of the system. The amount of data gathered in a site-specific system may also be off putting, especially as factors such as weather, yield, soil types, performance of variety, PPPs, diseases, performance of equipment and others, will need to be stored in the form of raw data. Site-specific management could be used as a tool for pollution ownership, whereby farmers can monitor their own environmental impact, however the data collected as part of this could be harmful to farmers if in the hands of prosecutors (Castelnuovo 1994). To run a profitable, environmentally conscious business, these variables must be understood, annually. The information collated by the producers must be manageable and not onerous. However, the reliance of the farmer on others for decision-making and information would remove power from farmers. Farmers will not want to turnover but, will want to profit from the use of technology (Mangold 1994).

Economic analysis of VRA systems is key for convincing hesitant farmers. An up-to-date system should be developed so as the price and weather change, a real-time economic output can be understood, and strategies used so to not lose chemistry (Reetz and Fixen 1994). "The economic analysis should provide sufficient detail to evaluate the individual component practices of the technology package and show how each affects the costs and return per acre as well as per unit costs of production. As much as possible, the analysis should address not only the costs and returns on the field-by-field basis, but also the economic implications from an environmental impact basis." (Reetz Jr and Fixen, 1994).

Further studies should be conducted as to the nature of the variability and whether areas of low biomass are due to inherent conditions such as soil type, aspect, and gradient or are due to seasonal factors such as water availability, crop applications (fertilizer, PGR), seed rates, pest and disease infection, and cloud cover, (Wood, Taylor, and Godwin 2003; AHDB 2018; Godwin and Miller 2003).

Within the context of this limited study, there is a relationship between NDVI and crop biomass but only at early fungicide application timings before the canopy is closed. The variability mapping from NDVI at this stage could be done once to determine where the areas of high and low canopy biomass are and linked to other within field properties causing this variation e.g. soil characteristics. Application decisions can then be made based on the areas of variation identified in the season. If a farmer chose a system where they used more frequent and accurate mapping tools such as LAI or UAV NDVI then they could use satellite imagery to decide if their fields are variable enough to warrant the upfront cost of investment in VRA machinery.

Creating a readily accessible NDVI-based VRA map for all fields in the UK based on T1 variability would give the best chance of saving chemicals on a mass scale. This in conjunction with further work into determining the deposition in relationship to canopy biomass as it changed throughout the season would be the most appropriate use of protectant fungicides. The use of protectants in this way would complement the use of disease detection based VRA systems which use systemic fungicides to combat diseases. Growth stage detection for optimal timing should still be conducted in the traditional sense but where the canopy varies should be dictated by the NDVI mapping.

## 7 Conclusions

This thesis describes the effective and efficient VRA spraying of protectant fungicides in winter wheat canopies by investigating and uniting all aspects of VRA. The introduction evaluated the current 'state of the art' in technology of PPP applications, giving the foundations of where the industry is focused and where the improvements are to be made. Chapter 2 addresses the issue of the deposition of fungicide and the unknown relationship between the size of the WW plant and the dose received, and the efficacy. The study created a standardised system for measuring spray deposition which will provide a basis for future studies on dose rate and canopy size to be conducted. Chapter 3 determined NDVI was a good indicator of canopy biomass variation at T0 and was reasonable at T1. Satellite-derived NDVI was a rapid, cheap, and effective method for determining the levels of variation which should be made accessible to use in conjunction with an agronomist, to determine optimal timing and dose rate. Chapter 4 determined a method for rapid extraction of the range of NDVI from Google Earth satellite imagery and used this to produce a map showing the range of variation in the East of England. The value of this to VRA methodology is to use as a rapid assessment of potential fields and determine where VRA would be beneficial. Chapter 5 took the farms used in chapter 3 and determined the cost benefits to performing one spray with VRA, savings of £9.08 and £13.82/ha depending on the farm. Prior to this thesis, individual studies focused on one small aspect of VRA. Collating all the information together shows the full extent of the work left to do to effectively reduce costs, prevent further avoidable environmental damage and to stop resistance to chemistry. The shortcoming of this thesis is that it could not go far enough in depth in each area of research, leaving large gaps for future investigations. Future work includes: understanding the deposition of fungicides through different VRA systems; establishing the baseline of how PPPs relate to biomass, and determining non-destructive methods of sampling of dose deposition; determining the best timing for satellite imagery for understanding canopy variation; discovering the point where variability is great enough to warrant a VRA, over uniform dosing and using this to create recommendations for farmers based on their variability; conduct trials

of VRA on standard farms and compare the results and investigate whether the final yield was impacted; and finally, creating a programme for each farm based on satellite imagery and their ground truth studies, which farmers will use to perform the best method of spray to suit their variability and with this, reduce cost, avoid further environmental damage and prevent resistance to the chemistry.

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## **Appendix A Pilot method for non-destructive sampling of spray deposition in WW canopies.**

The aim of this section was to pilot a non-destructive method of sampling spray deposition in wheat crop canopies, including describing the relationship between weight and height for winter wheat canopies. The proposed non-destructive method uses pixel analysis to determine the quantity of dye deposited in a winter wheat crop canopy.

### **A.1 Method**

Changing the dye to suit both destructive and non-destructive sampling meant a single trial was needed, and recovery results could be compared. To quantify spray deposition using non-destructive sampling methods of a computer vision method was selected due to the available technology in glasshouse. Blobs in this context refer to small structures which are significantly different to the rest of the image, either darker or brighter, (Wang, Lopez-Molina, and Baets 2017). A simple blob detection method in python language, (Python Software Foundation, n.d.) was used in this case to determine if dropleted Acid Red 52 dye was detectable.

Multiple images of sprayed pots were taken. Different size droplets were used to test the ability of detection, depending on the nozzle selected the distribution of droplet sizes is known and if droplets over a certain size can be detected, the related smaller droplets can be predicted, giving a spray deposition quantity (Silsoe Spray Applications). Image capture tests were required for pixel analysis, replication n=3; solubility in water (e.g., 0.1%, 1%, 10%, 50%, 100%) and stability (light fastness) at a range of concentrations on white discs and on leaf segments (10-minute intervals for 2-3 hours),

#### **A.1.1 Initial results**

Figure A-1 shows the output from the python blob detection. The code was able to recognise 2 $\mu$ l droplets but only at high concentrations of Acid red. Further work is required to determine quantities of dye deposited.

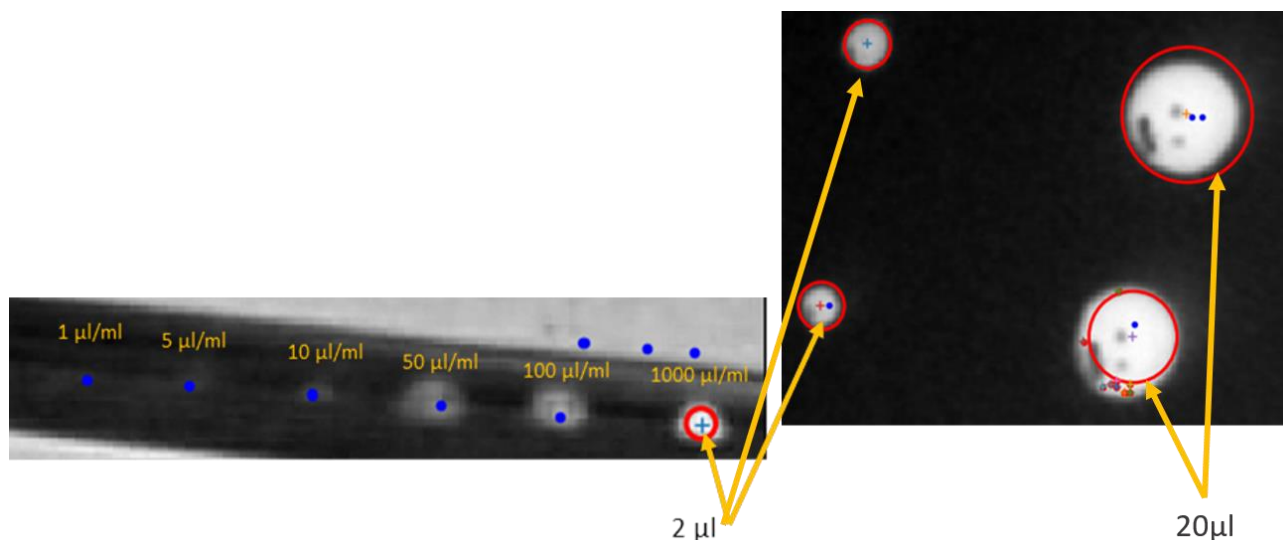


**Figure A-1: Droplet detection output from python program with marked known quantities,  $\mu\text{l}$**

Non-destructive sampling of spray deposition would allow continuous monitoring of a winter wheat canopy. It would also analyse specific deposition locations on winter wheat leaves along with the spread and shape of landed droplets. Access to this information gives precise understanding of deposition and could be used on remote sensing platforms to determine infield spray deposition. As precision spray technology use grows, this knowledge of deposition of spray should be used to inform fungicide application decisions. Further work into understanding specific quantities of dye deposited using the BLOB method is required as the results of detection were variable. Higher concentrations of dye were better for clarity of colour, but this may lead to staining which would impact later deposition. The length of time and the concentration of dye that may be left before influencing later deposition also requires investigation.

## **Appendix B Quantification of tracers by spectrofluorescence, fluorimetry and pixel analysis.**

### **B.1 Principle**

Four dyes were selected as test tracers for developing a new sampling technique: Acid Red 52, Green S, Brilliant Sulfoflavine and Uranine. A spectrophotometer is used for determining quantity of a tracer in a solution. By knowing the  $\lambda_{\text{max}}$  of the tracer, concentration of the tracer can be calculated. Image analysis techniques are being developed to quantify liquid deposits using pixel quantification. By setting up a range solution with known quantities of tank spray liquid, the quantity of sample deposited on the target relative to the tank sample can be obtained. This can be used to create machine learning algorithms to compare the number of pixels containing dye to known amount of tank liquid recovered. This aim being to develop a non-destructive quantification method.

### **B.2 Apparatus**

Visible spectrophotometer with Scan facilities, annually calibrated to manufacturers specification

Spectrofluorimeter Perkin Emer LS50B

Deionized Water (Lab-Grade)

Volumetric Flasks (Class B or above)

Calibrated pipettes (ID of pipettes recorded with data)

Plastic tripour beakers

Small 15ml sample tubes

Disposable cuvettes

SLR Camera set to one exposure setting

Non absorbent plastic discs (45 mm)

Camera stand set to 50cm height from sample

## **B.3 Reagents**

Reference to tracer guidelines found on the material safety data sheet relevant to each product. Details of dye wavelengths can be found in Table B-1. Use gloves and a lab coat to prevent contact with chemicals and dispose of excess tracer carefully and safely. Follow risk assessment.

1. Acid Red dye (Sensient Colors Group)
2. Green S dye (Honeywell & Stein Ltd)
3. Uranine U (Sensient Colors Group)
4. Brilliant Sulfoflavine (SSAU)

NB. Record (batch) number in lab book.

### **B.3.1 Sodium Hydroxide Buffer:**

#### **Stock Solution**

Mix 4g NaOH caustic pellets into 1 L of deionized water.

#### **Working buffer**

Mix up a 0.01M solution by adding 900 ml of Deionsied water and 100 ml of NaOH stock solution.

NB. Make fresh daily

## **B.4 Dye specification**

Determine the  $\lambda_{\text{max}}$ , nm,  $\lambda_{\text{excitation}}$ , nm and  $\lambda_{\text{emission}}$ , nm of each tracer using the scanning facilities on the spectrophotometer and spectrofluorimeter.

**Table B-1: Tracer dye information,  $\lambda_{max}$ ,  $\lambda_{excitation}$  and  $\lambda_{emission}$ .**

| <i>Tracer</i>                | <i><math>\lambda_{max}</math>, nm</i> | <i><math>\lambda_{excitation}</math>, nm</i> | <i><math>\lambda_{emission}</math>, nm</i> |
|------------------------------|---------------------------------------|----------------------------------------------|--------------------------------------------|
| Acid Red 52 (rhodamine B)    | 564                                   | 450                                          | 590                                        |
| Green S (E142)               | 634                                   | 382                                          | 381, 750                                   |
| BSF (brilliant sulfoflavine) | 454                                   | 283                                          | 620                                        |
| Uranine (fluorescein)        | 490                                   | 480                                          | 520                                        |

## **B.5 Quantification Procedure**

1. Mix up a standard 0.1% tank solution of 0.1grams of dye to 100ml of dilute into a volumetric flask. Dilute differs for each tracer; deionized water for Acid Red 52, Green S and BSF and NaOH working buffer for Uranine U. Also add adjuvant Tween 20 at 0.1% to represent spread of fungicides. Shake well to ensure all dye is dissolved. Stronger concentrations may be used if necessary. Results are reported as “ $\mu$ l of tank recovered.”
2. Set up a standard curve using this tank solution with at least 4 data points. Concentrations will vary but is based upon predicted concentration range. If unknown then a chosen concentration range of 0.5  $\mu$ l, 1.0  $\mu$ l, 5.0  $\mu$ l and 10  $\mu$ l of tank solution per 100 ml of dilute, which will obey Beer and Lamberts law with good linearity. Place into volumetric flasks and shake well to ensure all is mixed thoroughly. Gloves are worn throughout.
3. Tank sample is allowed to come to room temp
4. To understand if image analysis can distinguish between droplet size and volume, two different size droplets were considered. Place two droplets of 2  $\mu$ l and 20  $\mu$ l onto each filter disc making a total of 44  $\mu$ l per disc and repeat for each concentration. Replication was used to assess how repeatable each size droplet is by this technique.
5. Place the filter disc under the camera and photograph as soon as practical after spiking droplets. Then photograph every 30 mins until dry.

### **B.5.1 Visible spectrophotometry/destructive sampling:**

#### **Spectrophotometer measurements:**

6. When dry, place disk into conical beakers and agitate with 10ml of deionized water- Add further 10ml increments of deionized water if required noting the dilution factor. Further dilutions may be required if the concentration is not within the linear standard curve.
7. The spectrophotometer is set up, according to the manufacturers' instruction, with the auto-sampling facilities. Deionized water is used to zero the light path as a reference for all other standards. Placed at the beginning, after every ten samples or between different variations of samples and three at the end.
8. Check the samples for deposits and suspensions as this will interfere with the light path causing inaccurate sampling. Leave samples to settle if this is the case and centrifuge if the suspension persists.
9. Various analytical quality controls were put in place to ensure consistency in the instrument's performance throughout a run of samples (as detailed in 10).
10. When using spectrophotometer standards and samples are loaded into the auto-sampler and the software is started. Check the standard curve to ensure linearity and quality of fit line. (e.g.,  $0.995 < R^2 < 1.00$ ). Rerun standards if needed to provide a sound reference for subsequent data.
11. Once samples have finished running, check the data reading fits the visual appearance of the samples. Export the data to the excel file and adjust the data for dilutions ready for further analysis. Hard copy and network copies are kept for an agreed period. All samples capped and stored between 4-8°C.
12. Capture and dispose of waste appropriately.

### **Spectrofluorimeter measurements:**

13. When dry, place disk into tripour beakers and agitate with 10 ml of NaOH working buffer. Add further 10 ml increments if required noting the number of 10 ml increments used (note as dilution factor). Further dilutions may be required if the concentration is not within the linear standard curve or within machine sensitivity.
14. The spectrofluorimeter is set up, according to the manufacturers' instruction, and a sealed water cuvette is used to run the instruments validation tests. Provided the tests are passed, a printout of this System suitability test is filed with the sample results. NaOH working buffer is used to zero the light path as a reference for all other standards: placed at the beginning, after every ten samples or between different variations of samples and three at the end. Check the initial reading and take note of it as background noise: subtract either using the equipment's computer program or using excel once data is collected.
15. Check the samples for deposits and suspensions as this will interfere with the light path causing inaccurate sampling. Leave samples to settle if this is the case and centrifuge if the suspension persists.
16. Various analytical quality controls were put in place to ensure consistency in the instrument's performance throughout a run of samples.
17. When using spectrofluorimeter the software is started and the standards and samples are loaded into the machine individually, taking care to hold cuvettes on the edges and take the average reading from the output. Check the standard curve to ensure linearity and quality of fit line. (e.g.  $0.995 < R^2 < 1.00$ ). Rerun standards if needed to provide a sound reference for subsequent data.
18. Various analytical quality controls were put in place to ensure consistency in the instrument's performance throughout a run of samples (as detailed in 19).
19. Once samples have finished running, check the data reading fits the visual appearance of the samples. Export the data to the excel file and adjust the data for dilutions ready for further analysis. Hard copy and network copies

are kept for an agreed period. All samples capped and stored between 4-8°C.

20. Capture and dispose of waste appropriately.

#### **B.5.2 Pixel quantification/non-destructive sampling:**

21. Back up the images on three separate locations, to ensure secure storage of data. Organize the images according to timing or concentration, whichever suits the project.

22. Import the images into image analysis software.

23. Using a blob recognition program, isolate the pixels relating to dye and place data into relevant excel file. Use the pixel number to relate concentration/quantity of dye.

24. Take multiple training samples and compare with destructive data to train and test the program for robustness of sample quantification in future experiments.

### **B.6 Results**

The concentration relative to the standard curve can be read and multiplied by the dilution factor and extraction volume to gain the  $\mu\text{l}$  of sprayed liquid deposited on the target. Several reference samples may be taken during the experiment to monitor stability and changes in batches of dye. All samples are references against the tank mix from which they were generated.

## Appendix C – Chapter 0 spray deposition trial data

| Spray Timing | Variety | Pot | Dye recovered (µl) | Height (mm) | Weight (g) | Tiller | µl/g of biomass |
|--------------|---------|-----|--------------------|-------------|------------|--------|-----------------|
| T0           | C       | 1   | 26.07              | 383         | 2.258      | 4      | 11.5456156      |
| T0           | C       | 1   | 19.974             | 404         | 1.664      | 2      | 12.0036058      |
| T0           | C       | 1   | 18.64              | 367         | 1.452      | 2      | 12.8374656      |
| T0           | C       | 2   | 18.704             | 395         | 1.571      | 3      | 11.9057925      |
| T0           | C       | 2   | 20.212             | 377         | 1.764      | 3      | 11.4580499      |
| T0           | C       | 2   | 22.068             | 372         | 1.876      | 3      | 11.7633262      |
| T0           | C       | 3   | 17.562             | 335         | 1.345      | 2      | 13.0572491      |
| T0           | C       | 3   | 15.068             | 370         | 1.198      | 2      | 12.5776294      |
| T0           | C       | 3   | 18.702             | 390         | 1.722      | 2      | 10.8606272      |
| T0           | S       | 1   | 19.222             | 337         | 1.657      | 2      | 11.6004828      |
| T0           | S       | 1   | 24.504             | 332         | 2.461      | 5      | 9.95692808      |
| T0           | S       | 1   | 2.314              | 236         | 0.144      | 1      | 16.0694444      |
| T0           | S       | 2   | 13.038             | 295         | 1.215      | 2      | 10.7308642      |
| T0           | S       | 2   | 14.49              | 320         | 1.716      | 2      | 8.44405594      |
| T0           | S       | 2   | 21.384             | 340         | 1.986      | 3      | 10.7673716      |
| T0           | S       | 3   | 16.866             | 304         | 1.228      | 3      | 13.7345277      |
| T0           | S       | 3   | 22.35              | 360         | 1.781      | 3      | 12.5491297      |
| T0           | S       | 3   | 17.74              | 322         | 1.438      | 3      | 12.3365786      |
| T1           | C       | 1   | 45.856             | 342         | 5.13       | 6      | 8.93879142      |
| T1           | C       | 1   | 47.33              | 415         | 7.42       | 5      | 6.3787062       |
| T1           | C       | 1   | 42.844             | 390         | 5.14       | 4      | 8.33540856      |
| T1           | C       | 2   | 30.476             | 350         | 4.21       | 4      | 7.23895487      |
| T1           | C       | 2   | 24.596             | 354         | 2.95       | 3      | 8.33762712      |
| T1           | C       | 2   | 45.524             | 404         | 5.58       | 4      | 8.15842294      |
| T1           | C       | 3   | 29.466             | 412         | 3.34       | 3      | 8.82215569      |
| T1           | C       | 3   | 27.892             | 420         | 2.9        | 3      | 9.61793103      |
| T1           | C       | 3   | 20.356             | 403         | 2.14       | 3      | 9.51214953      |
| T1           | S       | 1   | 35.992             | 350         | 5.03       | 5      | 7.1554672       |
| T1           | S       | 1   | 41.89              | 373         | 5.83       | 4      | 7.18524871      |
| T1           | S       | 1   | 26.388             | 343         | 3.39       | 3      | 7.7840708       |
| T1           | S       | 2   | 40.25              | 376         | 4.97       | 4      | 8.09859155      |
| T1           | S       | 2   | 31.764             | 360         | 4.09       | 4      | 7.76625917      |
| T1           | S       | 2   | 42.162             | 380         | 4.56       | 4      | 9.24605263      |
| T1           | S       | 3   | 16.238             | 325         | 2.19       | 3      | 7.41461187      |
| T1           | S       | 3   | 33.032             | 398         | 4.33       | 4      | 7.62863741      |
| T1           | S       | 3   | 66.956             | 335         | 6.83       | 6      | 9.80322108      |

|    |   |   |         |     |        |    |            |
|----|---|---|---------|-----|--------|----|------------|
| T2 | C | 1 | 134.564 | 415 | 14.61  | 5  | 9.21040383 |
| T2 | C | 1 | 95.592  | 426 | 14.18  | 6  | 6.74132581 |
| T2 | C | 1 | 70.052  | 408 | 13.47  | 4  | 5.20059391 |
| T2 | C | 2 | 44.376  | 485 | 12.42  | 7  | 3.57294686 |
| T2 | C | 2 | 93.276  | 516 | 12.91  | 5  | 7.22509682 |
| T2 | C | 2 | 70.344  | 534 | 13.5   | 5  | 5.21066667 |
| T2 | C | 3 | 92.274  | 495 | 14.2   | 6  | 6.49816901 |
| T2 | C | 3 | 51.912  | 434 | 5.73   | 7  | 9.05968586 |
| T2 | C | 3 | 74.778  | 450 | 11.32  | 5  | 6.60583039 |
| T2 | S | 1 | 74.802  | 432 | 10.19  | 16 | 7.3407262  |
| T2 | S | 1 | 75.348  | 425 | 9.86   | 9  | 7.64178499 |
| T2 | S | 1 | 87.744  | 453 | 11.95  | 6  | 7.34259414 |
| T2 | S | 2 | 59.052  | 405 | 7.54   | 4  | 7.83183024 |
| T2 | S | 2 | 88.272  | 465 | 14.2   | 9  | 6.21633803 |
| T2 | S | 2 | 59.022  | 452 | 11.45  | 6  | 5.15475983 |
| T2 | S | 3 | 72.72   | 465 | 11.95  | 9  | 6.08535565 |
| T2 | S | 3 | 139.464 | 510 | 27.64  | 6  | 5.04573083 |
| T2 | S | 3 | 188.508 | 505 | 31.74  | 3  | 5.93913044 |
| T3 | C | 1 | 239.874 | 520 | 24.385 | 9  | 9.83694894 |
| T3 | C | 1 | 190.488 | 524 | 27.442 | 9  | 6.94147657 |
| T3 | C | 1 | 301.92  | 525 | 38.352 | 12 | 7.87234043 |
| T3 | C | 2 | 91.362  | 480 | 18.25  | 7  | 5.00613699 |
| T3 | C | 2 | 154.818 | 486 | 23.481 | 8  | 6.59333078 |
| T3 | C | 2 | 82.5    | 490 | 14.346 | 6  | 5.75073191 |
| T3 | C | 3 | 77.97   | 430 | 13.025 | 5  | 5.98618042 |
| T3 | C | 3 | 219.51  | 440 | 33.713 | 15 | 6.51113814 |
| T3 | C | 3 | 95.838  | 420 | 18.626 | 8  | 5.14538817 |
| T3 | S | 1 | 108.78  | 502 | 20.73  | 6  | 5.24746744 |
| T3 | S | 1 | 114.468 | 552 | 20.84  | 6  | 5.49270633 |
| T3 | S | 1 | 80.226  | 510 | 21.39  | 6  | 3.75063114 |
| T3 | S | 2 | 124.41  | 428 | 14.41  | 5  | 8.63358779 |
| T3 | S | 2 | 129.858 | 475 | 17.23  | 6  | 7.53673825 |
| T3 | S | 2 | 67.23   | 414 | 9.49   | 5  | 7.08429926 |
| T3 | S | 3 | 82.056  | 535 | 16.58  | 5  | 4.9490953  |
| T3 | S | 3 | 78.906  | 490 | 9.46   | 4  | 8.3410148  |
| T3 | S | 3 | 80.172  | 526 | 13.3   | 5  | 6.02796993 |

## Appendix D – Chapter 3 field variation trial data

| Date       | Spray | Farm | Field | Site | NDVI       | Plants per<br>quadrat | Plants per<br>square metre | Weeds per<br>quadrat | Weeds per<br>square metre | Average shoots<br>and tillers | Shoots or ears<br>per quadrat | Shoots or Ears<br>per square<br>metre | Growth stage | Height (m) | Volumetric<br>estimation of<br>Above Ground<br>Biomass<br>(VAGB) (m3) |
|------------|-------|------|-------|------|------------|-----------------------|----------------------------|----------------------|---------------------------|-------------------------------|-------------------------------|---------------------------------------|--------------|------------|-----------------------------------------------------------------------|
| 04/04/2019 | T0    | S    | A     | 1    | 0.24489633 | 44                    | 176                        | 0                    | 0                         | 36                            | 109                           | 436                                   |              | 0.15       | 65                                                                    |
| 04/04/2019 | T0    | S    | A     | 2    | 0.49909367 | 27                    | 107                        | 0                    | 0                         | 6                             | 160                           | 640                                   |              | 0.37       | 232                                                                   |
| 04/04/2019 | T0    | S    | A     | 3    | 0.473067   | 28                    | 113                        | 0                    | 0                         | 5                             | 153                           | 612                                   |              | 0.31       | 189                                                                   |
| 04/04/2019 | T0    | S    | A     | 4    | 0.45639267 | 44                    | 177                        | 0                    | 0                         | 4                             | 162                           | 647                                   |              | 0.28       | 179                                                                   |
| 04/04/2019 | T0    | S    | A     | 5    | 0.397549   | 38                    | 152                        | 0                    | 0                         | 3                             | 123                           | 491                                   |              | 0.19       | 94                                                                    |
| 04/04/2019 | T0    | S    | A     | 6    | 0.46433867 | 34                    | 136                        | 0                    | 0                         | 3                             | 117                           | 469                                   |              | 0.25       | 115                                                                   |
| 04/04/2019 | T0    | S    | A     | 7    | 0.41944833 | 33                    | 132                        | 1                    | 4                         | 4                             | 127                           | 509                                   |              | 0.21       | 123                                                                   |
| 04/04/2019 | T0    | S    | A     | 8    | 0.26248967 | 23                    | 91                         | 2                    | 7                         | 4                             | 82                            | 328                                   |              | 0.14       | 47                                                                    |
| 04/04/2019 | T0    | S    | IG    | 1    | 0.437512   | 45                    | 180                        | 1                    | 3                         | 4                             | 166                           | 663                                   |              | 0.27       | 178                                                                   |
| 04/04/2019 | T0    | S    | IG    | 2    | 0.507625   | 55                    | 220                        | 0                    | 1                         | 5                             | 292                           | 1169                                  |              | 0.28       | 323                                                                   |
| 04/04/2019 | T0    | S    | IG    | 3    | 0.42839433 | 25                    | 99                         | 0                    | 1                         | 4                             | 110                           | 439                                   |              | 0.21       | 99                                                                    |
| 04/04/2019 | T0    | S    | IG    | 4    | 0.47497233 | 34                    | 135                        | 1                    | 3                         | 5                             | 156                           | 624                                   |              | 0.27       | 172                                                                   |
| 04/04/2019 | T0    | S    | IG    | 5    | 0.479861   | 41                    | 164                        | 1                    | 3                         | 4                             | 164                           | 656                                   |              | 0.28       | 183                                                                   |
| 04/04/2019 | T0    | S    | IG    | 6    | 0.47857067 | 44                    | 177                        | 0                    | 0                         | 4                             | 191                           | 764                                   |              | 0.26       | 200                                                                   |
| 04/04/2019 | T0    | S    | IG    | 7    | 0.45487833 | 42                    | 168                        | 0                    | 1                         | 3                             | 140                           | 560                                   |              | 0.25       | 137                                                                   |
| 04/04/2019 | T0    | S    | IG    | 8    | 0.40787067 | 37                    | 148                        | 0                    | 1                         | 3                             | 111                           | 444                                   |              | 0.28       | 126                                                                   |
| 04/04/2019 | T0    | S    | NW    | 1    | 0.575194   | 42                    | 168                        | 6                    | 23                        | 5                             | 197                           | 787                                   |              | 0.31       | 248                                                                   |

|            |    |   |    |   |            |    |     |    |    |   |     |     |              |     |
|------------|----|---|----|---|------------|----|-----|----|----|---|-----|-----|--------------|-----|
| 04/04/2019 | T0 | S | NW | 2 | 0.552473   | 46 | 183 | 0  | 0  | 5 | 212 | 847 | 0.33         | 283 |
| 04/04/2019 | T0 | S | NW | 3 | 0.4483     | 40 | 160 | 0  | 0  | 4 | 146 | 585 | 0.2          | 120 |
| 04/04/2019 | T0 | S | NW | 4 | 0.53195233 | 46 | 184 | 5  | 21 | 4 | 200 | 799 | 0.28         | 227 |
| 04/04/2019 | T0 | S | NW | 5 | 0.52522333 | 37 | 148 | 12 | 48 | 5 | 175 | 699 | 0.24         | 165 |
| 04/04/2019 | T0 | S | NW | 6 | 0.503609   | 38 | 151 | 1  | 5  | 4 | 151 | 603 | 0.23         | 140 |
| 04/04/2019 | T0 | S | NW | 7 | 0.496685   | 35 | 141 | 1  | 4  | 4 | 141 | 565 | 0.21         | 116 |
| 04/04/2019 | T0 | S | NW | 8 | 0.517841   | 35 | 140 | 2  | 7  | 5 | 185 | 741 | 0.29         | 214 |
| 15/04/2019 | T1 | O | GD | 1 | 0.5585     | 44 | 176 | 0  | 0  | 4 | 176 | 704 | 31 0.32      | 228 |
| 15/04/2019 | T1 | O | GD | 2 | 0.5142     | 34 | 136 | 0  | 0  | 3 | 114 | 457 | 31 0.28      | 129 |
| 15/04/2019 | T1 | O | GD | 3 | 0.4735     | 32 | 127 | 0  | 0  | 3 | 95  | 380 | 30 0.24      | 91  |
| 15/04/2019 | T1 | O | GD | 4 | 0.3853     | 31 | 125 | 0  | 0  | 2 | 71  | 283 | 30 0.22      | 63  |
| 15/04/2019 | T1 | O | GD | 5 | 0.4392     | 35 | 141 | 0  | 0  | 3 | 118 | 472 | 30 0.25      | 119 |
| 15/04/2019 | T1 | O | GD | 6 | 0.4375     | 32 | 129 | 0  | 0  | 3 | 107 | 429 | 30 0.22      | 93  |
| 15/04/2019 | T1 | O | GD | 7 | 0.5004     | 34 | 137 | 1  | 4  | 4 | 142 | 569 | 30 0.24      | 142 |
| 15/04/2019 | T1 | O | GD | 8 | 0.5257     | 40 | 159 | 2  | 7  | 3 | 133 | 533 | 31 0.28      | 149 |
| 15/04/2019 | T1 | O | HF | 1 | 0.5696     | 23 | 93  | 0  | 0  | 6 | 140 | 560 | 32 0.48      | 268 |
| 15/04/2019 | T1 | O | HF | 2 | 0.5123     | 22 | 87  | 1  | 3  | 5 | 115 | 460 | 31 0.4       | 185 |
| 15/04/2019 | T1 | O | HF | 3 | 0.5235     | 30 | 120 | 0  | 0  | 5 | 140 | 560 | 31 0.4       | 222 |
| 15/04/2019 | T1 | O | HF | 4 | 0.534      | 26 | 105 | 0  | 1  | 6 | 158 | 632 | 32 0.43      | 269 |
| 15/04/2019 | T1 | O | HF | 5 | 0.5512     | 27 | 107 | 1  | 3  | 6 | 160 | 641 | 32 0.47      | 298 |
| 15/04/2019 | T1 | O | HF | 6 | 0.4788     | 28 | 111 | 1  | 5  | 6 | 174 | 697 | 31 0.44      | 309 |
| 15/04/2019 | T1 | O | HF | 7 | 0.422      | 15 | 61  | 0  | 0  | 8 | 129 | 515 | 31 0.35      | 183 |
| 15/04/2019 | T1 | O | HF | 8 | 0.3852     | 26 | 105 | 1  | 3  | 5 | 132 | 527 | 32 0.43      | 227 |
| 15/04/2019 | T1 | O | L  | 1 | 0.5312     | 43 | 173 | 0  | 0  | 5 | 217 | 867 | 31 Late 0.32 | 285 |
| 15/04/2019 | T1 | O | L  | 2 | 0.4883     | 29 | 117 | 0  | 0  | 4 | 117 | 469 | 30 0.26      | 122 |
| 15/04/2019 | T1 | O | L  | 3 | 0.5092     | 37 | 149 | 0  | 0  | 3 | 125 | 501 | 30 0.28      | 143 |

|            |    |   |    |   |            |    |     |    |    |   |     |     |    |      |     |
|------------|----|---|----|---|------------|----|-----|----|----|---|-----|-----|----|------|-----|
| 15/04/2019 | T1 | O | L  | 4 | 0.5217     | 27 | 109 | 0  | 0  | 4 | 118 | 473 | 32 | 0.29 | 140 |
| 15/04/2019 | T1 | O | L  | 5 | 0.4741     | 29 | 117 | 0  | 0  | 3 | 98  | 392 | 31 | 0.27 | 105 |
| 15/04/2019 | T1 | O | L  | 6 | 0.4257     | 22 | 89  | 0  | 0  | 4 | 89  | 357 | 30 | 0.22 | 78  |
| 15/04/2019 | T1 | O | L  | 7 | 0.5748     | 29 | 116 | 0  | 0  | 4 | 108 | 432 | 30 | 0.28 | 124 |
| 15/04/2019 | T1 | O | L  | 8 | 0.5739     | 31 | 125 | 0  | 0  | 4 | 135 | 541 | 32 | 0.37 | 199 |
| 18/04/2019 | T1 | S | A  | 1 | 0.32081967 | 29 | 116 | 0  | 0  | 3 | 87  | 348 | 30 | 0.17 | 59  |
| 18/04/2019 | T1 | S | A  | 2 | 0.64396833 | 19 | 76  | 0  | 1  | 7 | 130 | 520 | 31 | 0.36 | 188 |
| 18/04/2019 | T1 | S | A  | 3 | 0.601496   | 26 | 105 | 0  | 0  | 6 | 158 | 631 | 31 | 0.39 | 248 |
| 18/04/2019 | T1 | S | A  | 4 | 0.549517   | 34 | 135 | 0  | 0  | 4 | 122 | 489 | 31 | 0.32 | 157 |
| 18/04/2019 | T1 | S | A  | 5 | 0.459584   | 22 | 88  | 0  | 0  | 4 | 82  | 327 | 31 | 0.25 | 79  |
| 18/04/2019 | T1 | S | A  | 6 | 0.581045   | 28 | 113 | 0  | 0  | 4 | 131 | 525 | 31 | 0.28 | 159 |
| 18/04/2019 | T1 | S | A  | 7 | 0.45917933 | 27 | 108 | 1  | 5  | 4 | 114 | 457 | 30 | 0.3  | 138 |
| 18/04/2019 | T1 | S | A  | 8 | 0.381125   | 16 | 64  | 14 | 57 | 4 | 64  | 256 | 31 | 0.27 | 70  |
| 18/04/2019 | T1 | S | IG | 1 | 0.58567    | 31 | 124 | 0  | 0  | 5 | 145 | 580 | 32 | 0.36 | 211 |
| 18/04/2019 | T1 | S | IG | 2 | 0.651419   | 28 | 113 | 0  | 1  | 5 | 142 | 567 | 31 | 0.33 | 191 |
| 18/04/2019 | T1 | S | IG | 3 | 0.562471   | 23 | 92  | 2  | 8  | 6 | 138 | 552 | 31 | 0.27 | 150 |
| 18/04/2019 | T1 | S | IG | 4 | 0.639973   | 28 | 111 | 0  | 1  | 5 | 147 | 589 | 31 | 0.33 | 195 |
| 18/04/2019 | T1 | S | IG | 5 | 0.631972   | 29 | 115 | 0  | 0  | 5 | 144 | 576 | 31 | 0.34 | 193 |
| 18/04/2019 | T1 | S | IG | 6 | 0.621592   | 31 | 124 | 0  | 0  | 4 | 134 | 535 | 31 | 0.3  | 159 |
| 18/04/2019 | T1 | S | IG | 7 | 0.564824   | 36 | 143 | 0  | 1  | 3 | 107 | 428 | 31 | 0.26 | 112 |
| 18/04/2019 | T1 | S | IG | 8 | 0.552795   | 36 | 144 | 0  | 1  | 4 | 133 | 532 | 31 | 0.3  | 167 |
| 18/04/2019 | T1 | S | NW | 1 | 0.65510667 | 43 | 172 | 4  | 17 | 5 | 217 | 868 | 31 | 0.36 | 314 |
| 18/04/2019 | T1 | S | NW | 2 | 0.630202   | 43 | 171 | 1  | 3  | 6 | 243 | 972 | 31 | 0.4  | 388 |
| 18/04/2019 | T1 | S | NW | 3 | 0.564478   | 38 | 151 | 1  | 4  | 6 | 210 | 840 | 30 | 0.28 | 234 |
| 18/04/2019 | T1 | S | NW | 4 | 0.66033867 | 39 | 157 | 3  | 12 | 5 | 194 | 776 | 30 | 0.36 | 280 |
| 18/04/2019 | T1 | S | NW | 5 | 0.63451333 | 40 | 159 | 14 | 56 | 5 | 196 | 785 | 31 | 0.32 | 250 |

|            |    |   |    |   |            |    |     |   |   |   |     |      |       |      |     |
|------------|----|---|----|---|------------|----|-----|---|---|---|-----|------|-------|------|-----|
| 18/04/2019 | T1 | S | NW | 6 | 0.625025   | 31 | 124 | 1 | 4 | 5 | 161 | 645  | 30    | 0.28 | 183 |
| 18/04/2019 | T1 | S | NW | 7 | 0.628058   | 40 | 158 | 0 | 0 | 6 | 216 | 862  | 30    | 0.29 | 250 |
| 18/04/2019 | T1 | S | NW | 8 | 0.64156933 | 40 | 161 | 0 | 0 | 6 | 257 | 1028 | 31    | 0.34 | 351 |
| 15/05/2019 | T2 | O | GD | 1 | 0.60963667 | 21 | 85  | 0 | 0 | 8 | 172 | 688  | 37    | 0.54 | 370 |
| 15/05/2019 | T2 | O | GD | 2 | 0.59949067 | 25 | 99  | 0 | 0 | 6 | 140 | 560  | 37    | 0.46 | 260 |
| 15/05/2019 | T2 | O | GD | 3 | 0.595506   | 26 | 105 | 0 | 1 | 5 | 132 | 527  | 37    | 0.42 | 221 |
| 15/05/2019 | T2 | O | GD | 4 | 0.53637267 | 21 | 85  | 0 | 0 | 3 | 64  | 256  | 33-37 | 0.39 | 101 |
| 15/05/2019 | T2 | O | GD | 5 | 0.57691867 | 30 | 120 | 0 | 0 | 4 | 109 | 436  | 33-37 | 0.42 | 184 |
| 15/05/2019 | T2 | O | GD | 6 | 0.57691867 | 30 | 120 | 0 | 0 | 4 | 109 | 436  | 33-37 | 0.42 | 184 |
| 15/05/2019 | T2 | O | GD | 7 | 0.61554367 | 30 | 121 | 0 | 0 | 4 | 118 | 471  | 37    | 0.44 | 209 |
| 15/05/2019 | T2 | O | GD | 8 | 0.618087   | 30 | 121 | 1 | 3 | 4 | 113 | 452  | 37    | 0.48 | 217 |
| 15/05/2019 | T2 | O | HF | 1 | 0.63788233 | 24 | 97  | 0 | 0 | 6 | 155 | 619  | 37+   | 0.7  | 433 |
| 15/05/2019 | T2 | O | HF | 2 | 0.58294633 | 23 | 93  | 0 | 0 | 5 | 117 | 467  | 37+   | 0.55 | 255 |
| 15/05/2019 | T2 | O | HF | 3 | 0.59492933 | 29 | 115 | 0 | 1 | 4 | 120 | 480  | 37+   | 0.57 | 273 |
| 15/05/2019 | T2 | O | HF | 4 | 0.59333167 | 24 | 96  | 0 | 0 | 5 | 128 | 512  | 37+   | 0.57 | 288 |
| 15/05/2019 | T2 | O | HF | 5 | 0.62234833 | 22 | 89  | 1 | 4 | 5 | 105 | 421  | 33-37 | 0.57 | 238 |
| 15/05/2019 | T2 | O | HF | 6 | 0.57963733 | 20 | 79  | 1 | 5 | 6 | 112 | 447  | 37+   | 0.59 | 266 |
| 15/05/2019 | T2 | O | HF | 7 | 0.56230267 | 16 | 63  | 0 | 0 | 5 | 83  | 333  | 33-37 | 0.46 | 149 |
| 15/05/2019 | T2 | O | HF | 8 | 0.489007   | 17 | 69  | 0 | 0 | 5 | 83  | 331  | 39    | 0.6  | 198 |
| 15/05/2019 | T2 | O | L  | 1 | 0.61843067 | 31 | 123 | 0 | 0 | 4 | 113 | 453  | 33-37 | 0.49 | 223 |
| 15/05/2019 | T2 | O | L  | 2 | 0.61795833 | 28 | 112 | 0 | 0 | 5 | 128 | 511  | 33-37 | 0.47 | 241 |
| 15/05/2019 | T2 | O | L  | 3 | 0.6296     | 28 | 112 | 0 | 0 | 3 | 93  | 371  | 33-37 | 0.49 | 182 |
| 15/05/2019 | T2 | O | L  | 4 | 0.649453   | 34 | 136 | 0 | 0 | 4 | 145 | 579  | 37    | 0.47 | 275 |
| 15/05/2019 | T2 | O | L  | 5 | 0.61142567 | 34 | 136 | 0 | 0 | 3 | 89  | 355  | 33-37 | 0.48 | 171 |
| 15/05/2019 | T2 | O | L  | 6 | 0.572893   | 25 | 100 | 0 | 0 | 4 | 92  | 367  | 37    | 0.45 | 162 |
| 15/05/2019 | T2 | O | L  | 7 | 0.643203   | 39 | 157 | 0 | 0 | 4 | 144 | 577  | 33-37 | 0.48 | 275 |

|            |    |   |    |   |            |    |     |    |    |   |     |     |       |      |     |
|------------|----|---|----|---|------------|----|-----|----|----|---|-----|-----|-------|------|-----|
| 15/05/2019 | T2 | O | L  | 8 | 0.51029533 | 40 | 160 | 0  | 0  | 4 | 173 | 693 | 37    | 0.57 | 391 |
| 13/05/2019 | T2 | S | A  | 1 | 0.454329   | 29 | 117 | 0  | 0  | 4 | 107 | 427 | 32    | 0.29 | 122 |
| 13/05/2019 | T2 | S | A  | 2 | 0.612099   | 24 | 96  | 0  | 1  | 5 | 127 | 508 | 33-37 | 0.63 | 322 |
| 13/05/2019 | T2 | S | A  | 3 | 0.580082   | 33 | 133 | 0  | 0  | 5 | 159 | 636 | 33-37 | 0.6  | 380 |
| 13/05/2019 | T2 | S | A  | 4 | 0.56252767 | 37 | 147 | 0  | 0  | 3 | 122 | 488 | 33-37 | 0.24 | 116 |
| 13/05/2019 | T2 | S | A  | 5 | 0.46630733 | 30 | 119 | 0  | 0  | 4 | 109 | 437 | 30    | 0.22 | 97  |
| 13/05/2019 | T2 | S | A  | 6 | 0.57432267 | 28 | 112 | 0  | 0  | 3 | 91  | 364 | 39    | 0.49 | 179 |
| 13/05/2019 | T2 | S | A  | 7 | 0.49138    | 29 | 115 | 2  | 7  | 4 | 122 | 487 | 37    | 0.54 | 262 |
| 13/05/2019 | T2 | S | A  | 8 | 0.49066167 | 17 | 67  | 12 | 49 | 4 | 67  | 267 | 37    | 0.45 | 121 |
| 13/05/2019 | T2 | S | IG | 1 | 0.595318   | 30 | 119 | 0  | 0  | 5 | 148 | 593 | 37    | 0.54 | 318 |
| 13/05/2019 | T2 | S | IG | 2 | 0.620977   | 24 | 96  | 0  | 0  | 5 | 119 | 476 | 37    | 0.56 | 265 |
| 13/05/2019 | T2 | S | IG | 3 | 0.552201   | 21 | 85  | 1  | 4  | 4 | 90  | 359 | 37    | 0.53 | 193 |
| 13/05/2019 | T2 | S | IG | 4 | 0.598601   | 27 | 109 | 0  | 0  | 5 | 128 | 513 | 33-37 | 0.53 | 273 |
| 13/05/2019 | T2 | S | IG | 5 | 0.60615167 | 34 | 137 | 1  | 3  | 4 | 126 | 505 | 37    | 0.49 | 245 |
| 13/05/2019 | T2 | S | IG | 6 | 0.60834333 | 24 | 96  | 0  | 1  | 4 | 103 | 412 | 37    | 0.57 | 233 |
| 13/05/2019 | T2 | S | IG | 7 | 0.55083667 | 30 | 119 | 0  | 1  | 3 | 96  | 383 | 37    | 0.51 | 197 |
| 13/05/2019 | T2 | S | IG | 8 | 0.556716   | 25 | 101 | 0  | 0  | 4 | 98  | 393 | 37    | 0.53 | 209 |
| 13/05/2019 | T2 | S | NW | 1 | 0.598674   | 28 | 111 | 2  | 8  | 4 | 120 | 479 | 33-37 | 0.53 | 253 |
| 13/05/2019 | T2 | S | NW | 2 | 0.59142533 | 30 | 121 | 0  | 1  | 5 | 152 | 607 | 33-37 | 0.57 | 345 |
| 13/05/2019 | T2 | S | NW | 3 | 0.57525267 | 34 | 135 | 0  | 0  | 3 | 101 | 404 | 33-37 | 0.48 | 195 |
| 13/05/2019 | T2 | S | NW | 4 | 0.626046   | 36 | 143 | 1  | 4  | 5 | 178 | 713 | 37    | 0.55 | 394 |
| 13/05/2019 | T2 | S | NW | 5 | 0.59363867 | 37 | 147 | 6  | 23 | 5 | 173 | 693 | 37    | 0.56 | 390 |
| 13/05/2019 | T2 | S | NW | 6 | 0.587098   | 38 | 151 | 2  | 8  | 3 | 113 | 452 | 37    | 0.5  | 233 |
| 13/05/2019 | T2 | S | NW | 7 | 0.58295433 | 34 | 136 | 0  | 0  | 5 | 160 | 640 | 33-37 | 0.46 | 295 |
| 13/05/2019 | T2 | S | NW | 8 | 0.60365133 | 35 | 141 | 0  | 1  | 5 | 163 | 653 | 37    | 0.55 | 360 |
| 06/06/2019 | T3 | O | GD | 1 | 0.60618767 | 21 | 84  | 0  | 0  |   | 127 | 508 | 59    | 0.77 | 390 |

|            |    |   |    |   |            |    |     |     |     |     |     |    |      |     |
|------------|----|---|----|---|------------|----|-----|-----|-----|-----|-----|----|------|-----|
| 06/06/2019 | T3 | O | GD | 2 | 0.56231333 | 20 | 79  | 0   | 0   | 116 | 464 | 61 | 0.68 | 315 |
| 06/06/2019 | T3 | O | GD | 3 | 0.546923   | 25 | 100 | 0   | 0   | 98  | 393 | 65 | 0.6  | 234 |
| 06/06/2019 | T3 | O | GD | 4 | 0.527762   | 23 | 91  | 0   | 0   | 83  | 331 | 61 | 0.67 | 221 |
| 06/06/2019 | T3 | O | GD | 5 | 0.56019433 | 25 | 99  | 0   | 0   | 105 | 419 | 65 | 0.69 | 290 |
| 06/06/2019 | T3 | O | GD | 6 | 0.56717    | 22 | 89  | 0   | 0   | 104 | 417 | 59 | 0.71 | 298 |
| 06/06/2019 | T3 | O | GD | 7 | 0.57634667 | 21 | 84  | 0   | 0   | 115 | 460 | 65 | 0.7  | 322 |
| 06/06/2019 | T3 | O | GD | 8 | 0.590945   | 24 | 96  | 0   | 0   | 117 | 469 | 65 | 0.73 | 341 |
| 06/06/2019 | T3 | O | HF | 1 | 0.586302   | 35 | 139 | 0   | 0   | 153 | 613 | 59 | 0.83 | 507 |
| 06/06/2019 | T3 | O | HF | 2 | 0.528684   | 22 | 87  | 0.3 | 1.3 | 90  | 360 | 65 | 0.66 | 237 |
| 06/06/2019 | T3 | O | HF | 3 | 0.496454   | 24 | 97  | 0   | 0   | 104 | 415 | 59 | 0.67 | 279 |
| 06/06/2019 | T3 | O | HF | 4 | 0.52963467 | 15 | 61  | 0   | 0   | 95  | 380 | 61 | 0.71 | 272 |
| 06/06/2019 | T3 | O | HF | 5 | 0.577759   | 26 | 104 | 0   | 0   | 135 | 541 | 65 | 0.81 | 439 |
| 06/06/2019 | T3 | O | HF | 6 | 0.509688   | 24 | 97  | 0   | 0   | 117 | 469 | 65 | 0.76 | 355 |
| 06/06/2019 | T3 | O | HF | 7 | 0.538165   | 15 | 59  | 0   | 0   | 81  | 324 | 61 | 0.8  | 258 |
| 06/06/2019 | T3 | O | HF | 8 | 0.489883   | 22 | 87  | 0   | 0   | 97  | 387 | 65 | 0.81 | 315 |
| 06/06/2019 | T3 | O | L  | 1 | 0.57885233 | 24 | 97  | 0   | 0   | 127 | 507 | 61 | 0.78 | 395 |
| 06/06/2019 | T3 | O | L  | 2 | 0.565981   | 17 | 69  | 0   | 0   | 106 | 425 | 61 | 0.73 | 312 |
| 06/06/2019 | T3 | O | L  | 3 | 0.57973667 | 26 | 103 | 0   | 0   | 112 | 447 | 65 | 0.74 | 332 |
| 06/06/2019 | T3 | O | L  | 4 | 0.589744   | 27 | 108 | 0   | 0   | 114 | 456 | 59 | 0.71 | 324 |
| 06/06/2019 | T3 | O | L  | 5 | 0.539534   | 20 | 79  | 0   | 0   | 105 | 420 | 61 | 0.65 | 272 |
| 06/06/2019 | T3 | O | L  | 6 | 0.52566333 | 25 | 100 | 0   | 0   | 82  | 329 | 65 | 0.67 | 221 |
| 06/06/2019 | T3 | O | L  | 7 | 0.62771467 | 27 | 109 | 0   | 0   | 157 | 628 | 59 | 0.76 | 479 |
| 06/06/2019 | T3 | O | L  | 8 | 0.549471   | 31 | 124 | 0   | 0   | 147 | 587 | 65 | 0.81 | 473 |
| 12/06/2019 | T3 | S | A  | 1 | 0.60618767 | 23 | 93  | 0   | 0   | 65  | 261 | 59 | 0.5  | 134 |
| 12/06/2019 | T3 | S | A  | 2 | 0.56231333 | 22 | 87  | 0   | 0   | 125 | 501 | 65 | 0.83 | 418 |
| 12/06/2019 | T3 | S | A  | 3 | 0.546923   | 25 | 101 | 0   | 0   | 110 | 441 | 61 | 0.74 | 324 |

|            |    |   |    |   |            |    |     |   |   |     |     |    |      |     |
|------------|----|---|----|---|------------|----|-----|---|---|-----|-----|----|------|-----|
| 12/06/2019 | T3 | S | A  | 4 | 0.527762   | 29 | 116 | 0 | 0 | 132 | 529 | 65 | 0.74 | 390 |
| 12/06/2019 | T3 | S | A  | 5 | 0.56019433 | 19 | 75  | 0 | 0 | 66  | 265 | 61 | 0.53 | 140 |
| 12/06/2019 | T3 | S | A  | 6 | 0.538382   | 26 | 103 | 0 | 0 | 80  | 319 | 59 | 0.6  | 196 |
| 12/06/2019 | T3 | S | A  | 7 | 0.56717    | 22 | 89  | 0 | 0 | 80  | 319 | 65 | 0.72 | 230 |
| 12/06/2019 | T3 | S | A  | 8 | 0.590945   | 18 | 73  | 0 | 0 | 95  | 381 | 59 | 0.55 | 207 |
| 12/06/2019 | T3 | S | IG | 1 | 0.573647   | 29 | 117 | 0 | 0 | 120 | 481 | 59 | 0.74 | 355 |
| 12/06/2019 | T3 | S | IG | 2 | 0.568461   | 24 | 97  | 0 | 0 | 153 | 613 | 59 | 0.79 | 484 |
| 12/06/2019 | T3 | S | IG | 3 | 0.419702   | 33 | 131 | 0 | 0 | 120 | 481 | 61 | 0.74 | 355 |
| 12/06/2019 | T3 | S | IG | 4 | 0.529245   | 21 | 84  | 0 | 0 | 124 | 495 | 65 | 0.77 | 379 |
| 12/06/2019 | T3 | S | IG | 5 | 0.531294   | 25 | 101 | 0 | 0 | 139 | 556 | 61 | 0.78 | 432 |
| 12/06/2019 | T3 | S | IG | 6 | 0.57737867 | 30 | 121 | 0 | 0 | 158 | 631 | 59 | 0.77 | 488 |
| 12/06/2019 | T3 | S | IG | 7 | 0.55213067 | 25 | 101 | 0 | 0 | 98  | 391 | 65 | 0.78 | 302 |
| 12/06/2019 | T3 | S | IG | 8 | 0.549721   | 25 | 101 | 0 | 0 | 94  | 377 | 59 | 0.73 | 276 |
| 12/06/2019 | T3 | S | NW | 1 | 0.586302   | 32 | 129 | 0 | 0 | 114 | 455 | 61 | 0.76 | 346 |
| 12/06/2019 | T3 | S | NW | 2 | 0.528684   | 35 | 141 | 0 | 0 | 116 | 464 | 59 | 0.78 | 362 |
| 12/06/2019 | T3 | S | NW | 3 | 0.496454   | 41 | 165 | 0 | 0 | 137 | 549 | 59 | 0.74 | 408 |
| 12/06/2019 | T3 | S | NW | 4 | 0.52963467 | 31 | 125 | 0 | 0 | 124 | 495 | 61 | 0.79 | 391 |
| 12/06/2019 | T3 | S | NW | 5 | 0.577759   | 38 | 151 | 0 | 0 | 135 | 541 | 61 | 0.8  | 433 |
| 12/06/2019 | T3 | S | NW | 6 | 0.509688   | 31 | 125 | 0 | 0 | 102 | 408 | 61 | 0.74 | 300 |
| 12/06/2019 | T3 | S | NW | 7 | 0.538165   | 27 | 108 | 0 | 0 | 111 | 445 | 59 | 0.68 | 307 |
| 12/06/2019 | T3 | S | NW | 8 | 0.489883   | 33 | 131 | 0 | 0 | 136 | 544 | 59 | 0.76 | 416 |

## Appendix E - **Chapter 3 regional satellite data**

Data tables available at request, and shared on Cranfield Online Research Data hub (CORD), 372 pages.

## **Appendix F – Chapter 5 NDVI pixel values from Olney farm, Buckinghamshire**

Data tables available at request, and shared on Cranfield Online Research Data hub (CORD), 389 pages.