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Student Report 56

Variable rate application of fungicides on winter wheat

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CONTENTS

1. Industry Summary

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 (Figure 1). At a fixed application rate, smaller plants will receive relatively higher dose rate, than larger ones. With VRA, there is potential to match dose rates to plant growth and development.

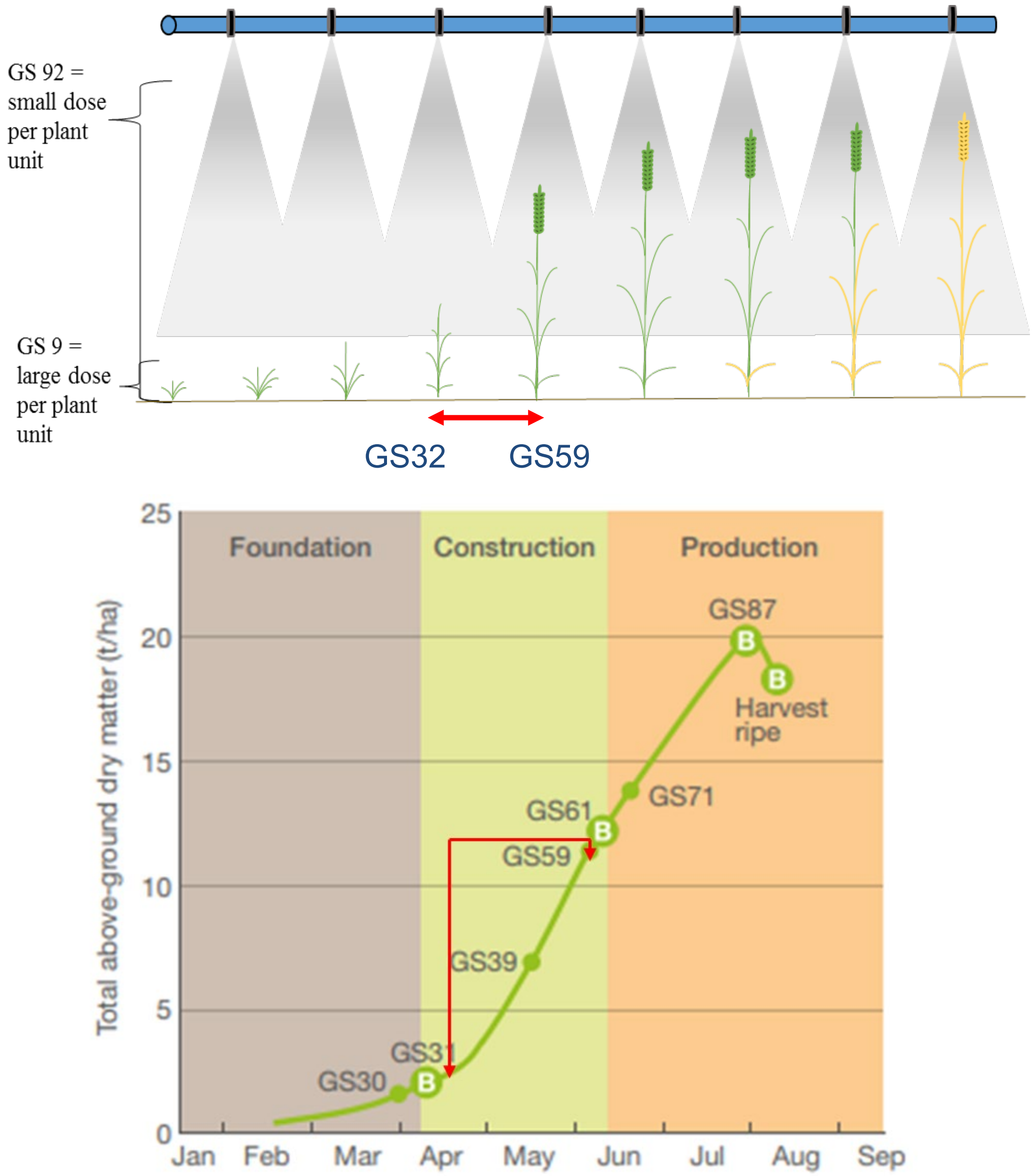

Figure 1. A typical fungicide recommendation is a fixed dose rate across growth stage 32-59 (Top). This corresponds to almost 10t/ha variation in crop biomass (Bottom, modified from AHBD wheat growth guide). Smaller plants will receive a larger dose per unit plant area or biomass, compared to larger plants.

VRA could reduce fungicide costs, help slow 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 active ingredients, the future of fungicide application is to determine the most appropriate dose and reducing over-spraying where possible.

The primary aim of this research 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 through June, a field study was conducted over two farms to measure the spatial and temporal variation in volumetric biomass and determine if normalized difference vegetation index (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.

2. Introduction

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. 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.

2.1. Research Gaps

When creating a VRA system, consideration of these key factors is paramount; for adjustment there are a range of nozzle technologies 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 the 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.

The review of the literature highlighted several areas of study within VRA and 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.

2.2. Aim:

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

2.3. 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?

This report summarises the key findings of each objective within the 5 subsections within the methods, results, discussion sections, with overall recommendations at the end.

3. Materials and methods

3.1. 'State of the art' in dose adjustment – summary of PhD review

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. 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).

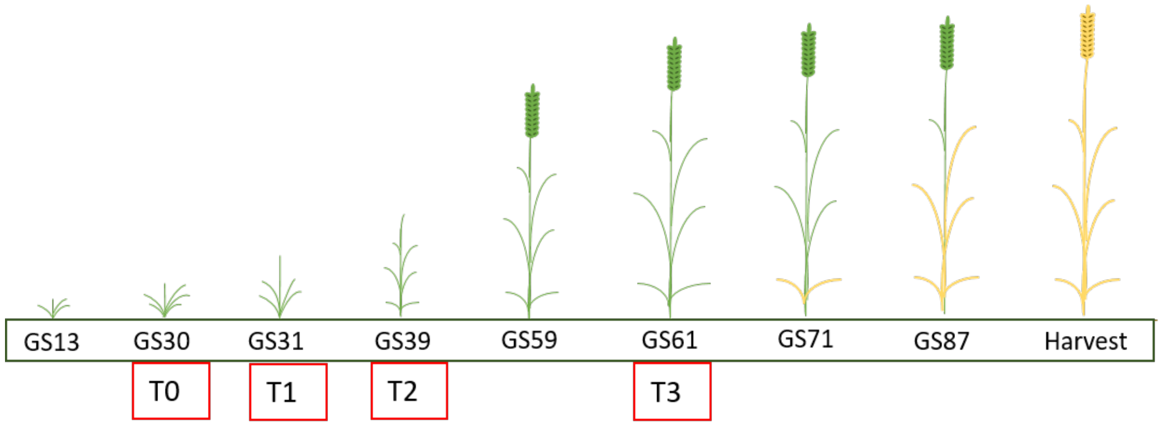

Figure 2. Winter Wheat growth based on Zadok's growth stages with key fungicide timings

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, see Figure 3.

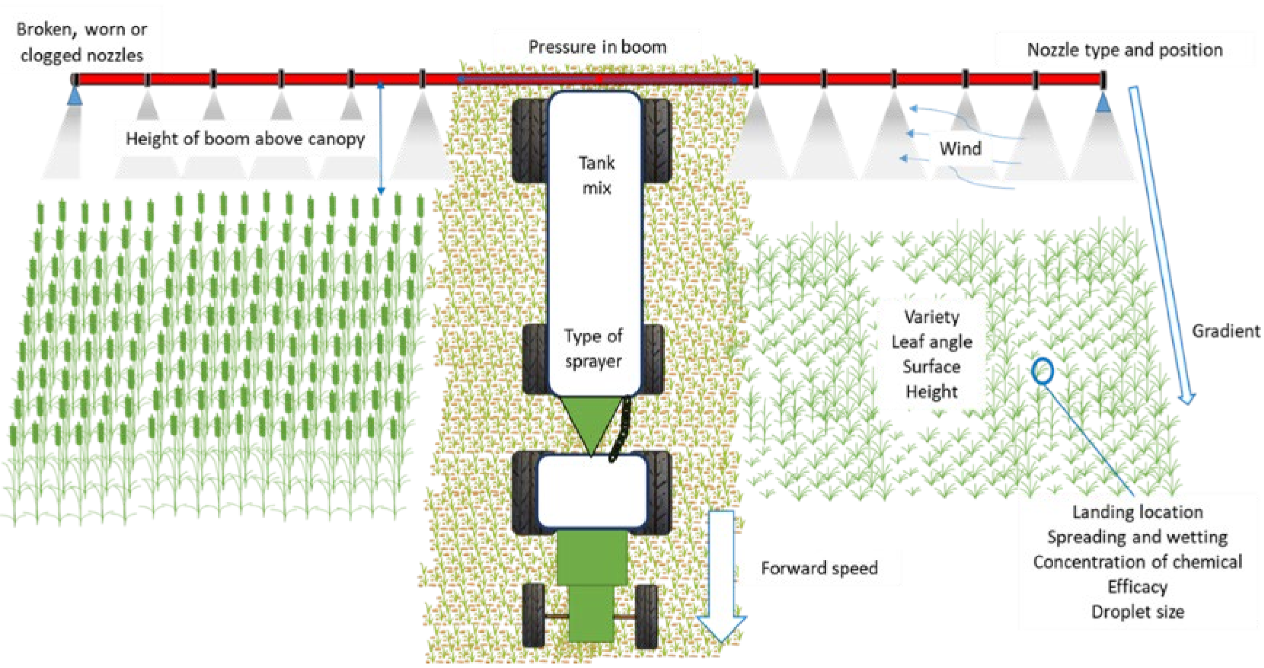

Figure 3. Influencing factors on variation of spray deposition

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).

Destructive sampling means the same canopy cannot be monitored until the end of the season but 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, future spray decisions can be made using remote sensing technologies.

3.2. Method for quantification of spray deposition on winter wheat canopies

Objective (2) considers 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.

3.2.1. 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). 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 (λ) Table 1.

Table 1. Dye specifications for deposition testing

Tracer	*Supplier*	*Buffer Required*	*λmax (nm)*	*λexcitation (nm)*	*λemission (nm)*
Green S (E142)	Honeywell and Stein Ltd	De-ionised water	634	382	381, 750
BSF (Brilliant Sulfoflavine)	Chroma Color Corporation	De-ionised water	454	283	620
Acid Red 52 (rhodamine B)	Sensient Colors Group	De-ionised water	564	450	590
Uranine (fluorescein)	Sensient Colors Group	NaOH	490	480	520

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 Sufloflavine 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., λ_{max}, emission/absorption). Dyes were individually spiked into a known quantity of water (Acid Red 52, Green S and Brilliant Sufloflavine) 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 Sufloflavine) or Spectrofluorometer (Uranine) were used to determine quantity of a tracer in a solution. Through knowing the λ_{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.

Acid Red 52 was selected due to its non-persistence, and suitability for the simultaneous work on non-destructive sampling.

3.2.2. Spray deposition, winter wheat trial

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), see Figure 4.

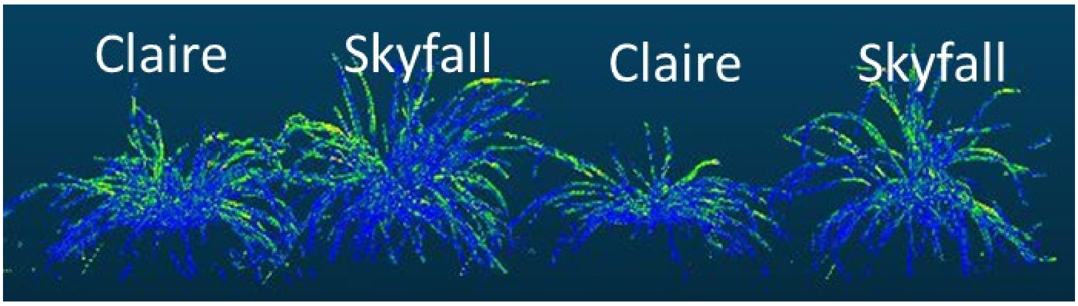

Figure 4. 3D laser scan of winter wheat varieties with different canopy shapes

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 5.

Figure 5. Pots of winter wheat under the track sprayer at Silsoe Spray Application Unit Ltd., Bedfordshire

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).

3.2.3. 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 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.

Figure 6. Samples bagged with 20 ml of deionised water before the rinsate was analysed in spectrophotometer

3.2.4. 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.

3.3. Canopy variation in winter wheat with remote sensing

For Objective (3), we observed 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.

3.3.1. Commercial field study of winter wheat canopy variation

Field measurements of crop biophysical parameters were conducted in the southeast of the UK, during the 2019 growing season. Two commercial farms, 20 miles apart, employing standard agricultural practice were selected, with all except one field having uniform applications of fertiliser and fungicides. Three fields from each farm were selected, see Table 2, with all fields growing Skyfall, apart from one growing Zyatt. The fields ‘Great Dole,’ ‘Lavendon’ and ‘Home Field,’ are situated in Olney, Buckinghamshire. And ‘Avenue,’ ‘Ivy Ground’ and ‘Near Warden,’ are in Silsoe, Bedfordshire.

Table 2. Site, field name, size, variety of winter wheat grown and fungicide application method for commercial fields.

Site	*Field Name*	*Size (ha)*	*Variety*	*Application*
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

Crop growth stages were determined by regular crop walking between February and June 2018. Table 3 shows the timing of the field measurements used to develop empirical calibrations using satellite imagery at the required leaf visibility and growth stage for the optimal timing of fungicide.

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

Site	*Fungicide Application*	*Satellite Image date*	*Field sampling date*	*Required growth stage*	*Range of observed growth stage*	*Comment on application timing*
Olney	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
Silsoe	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

High resolution (3m) imagery provided by SOYL, Frontier Agriculture, based on Planet satellite data (Planet Team) was used to determine ground calibration sites in February 2019. Images of each field were stratified into eight NDVI values (where NDVI=(NIR-R)/(NIR+R), using the red (R) and near infrared (NIR) spectral bands) and a sample point in each range was selected (Wood et al. 2003), see example in Figure 7. This rapid calibration method increases the efficiency of the sample design by using the satellite imagery as an auxiliary variable for estimating canopy ‘greenness’ or photosynthetically active vegetation. 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^2 quadrats were positioned in an arrow formation, 2m apart, in the direction of drilling. During all measurements, GPS points were taken for each quadrat, using the Trimble with an accuracy of 0.2 metres.

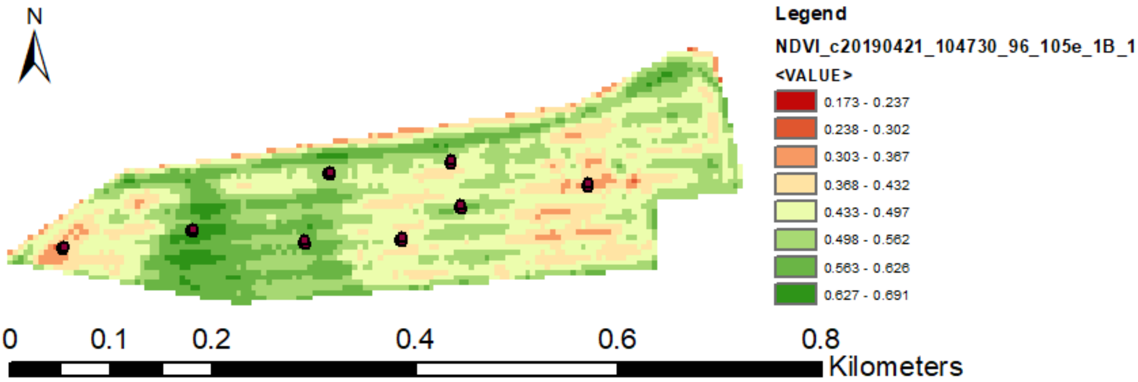

Figure 7. Stratified NDVI values in Avenue field, Silsoe showing selected ground sample sites, one in each of the NDVI ranges.

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 (GS), 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^3) 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 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 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.

3.4. Rapid method for understanding regional variation in wheat

Manual assessments of in-field variability are time consuming and expensive, but this information is needed to implement VRA and to assess its economic benefit. For Objective (4) a method was developed to understand the range of variation in winter wheat canopy, using the vegetation index, NDVI, from satellite imagery from Sentinel 2 (Copernicus 2019b), which is available for automated processing in Google Earth Engine, (Gorelick et al. 2017).

3.4.1. 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 Objective (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.

3.4.2. Regional study of wheat crop variation using Google Earth Engine

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. 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.

Table 4. The number of wheat fields in England in 2018, (CEH, 2018)

Region	*Number of fields*
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

Visual pre-inspection of the Sentinel 2 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 each field in the East of England, T1, and distributed as a frequency. Data points were removed where the image was too cloudy to retrieve NDVI. The fields were split into categories of variability using the standard deviation and plotted as a heat map of variation using ArcGIS.

3.5. Evaluating Variable Rate Application of fungicides on winter wheat – Cost benefit analysis

For the final objective (5), 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. Both scenarios used the commercial farms in Objective (3) as a starting point for the calculations. 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).

3.5.1. 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 to VRA.
3. T1 calculation for VAGB from NDVI from the field experiment (objective 3) is a reasonable representation of variation in the field.
4. NDVI value range (0.3 - 0.7) accurately represents canopy crop cover.
5. The dose rate required to suit biomass increases in a linear fashion (Tackenberg et al. 2017), based on the NDVI range (0.3 – 0.7).
6. There were no yield deficits as consequences of these applications.

3.5.2. Scenario 1 – Uniform application, cost per hectare

The fungicides selected were used at T1 as part of a mix sprayed at Olney, in 2019. The farm agronomist chose an application rate of 80% recommended manufacturer dose rate of Aviator 235 Xpro. This spray is recommended for a wide range of diseases with actives, bixafen and prothioconazole (Bayer). The uniform application rate used was 200L/ha. The cost of the Aviator 235 Pro was £291.67/10L, (Olney Farm, 2021). Agronomy information was not available for Silsoe Farm so recommendations for Olney were used. This has limitations, but the understanding a cost difference for Silsoe is still useful for this study.

3.5.3. Scenario 2 – VRA, cost per hectare

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 19th April 2019. NDVI pixel values were extracted from within each field, in Figure 8 and Figure 9.

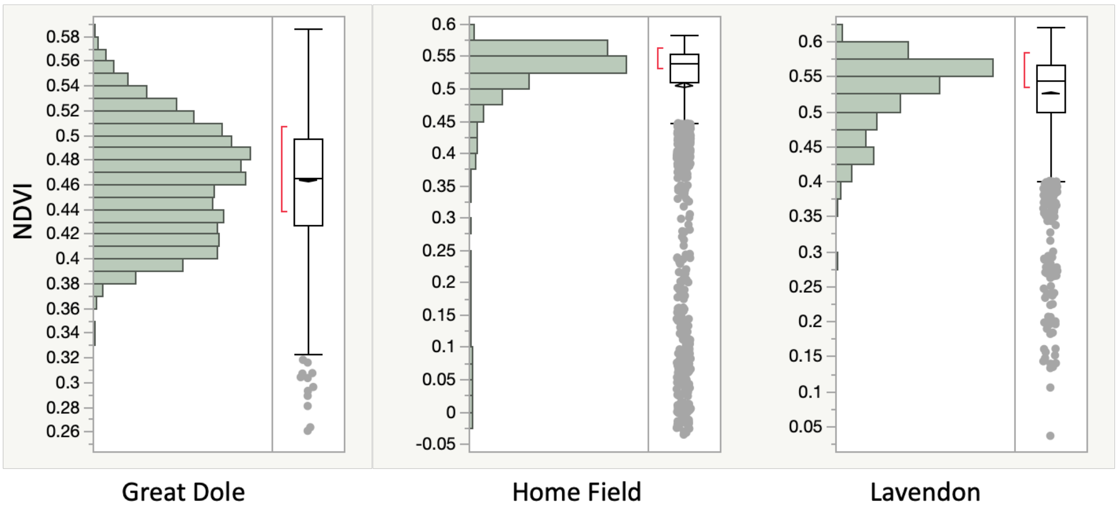

Figure 8. Distribution of NDVI pixel values for each field from the Olney farm

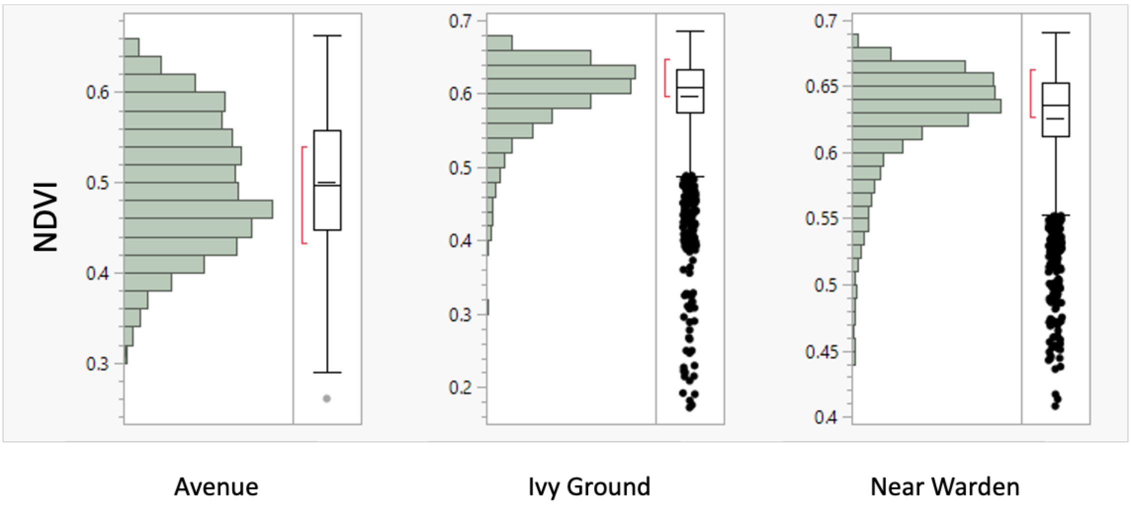

Figure 9. Distribution of NDVI pixel values for each field from the Silsoe farm

These pixels were then grouped into bins of 0.1 (NDVI value) width. Each range was matched with a dose rate of L/ha based on those from Tackenberg et al. (2018), where canopy had at least 95% coverage (or NDVI>=0.7), 100% of the uniform (80%) application rate of 200 L/ha (in Scenario 1), was applied. and where canopy had 30% coverage or less (NDVI <0.3), then 25% of the application rate was applied (NDVI value is 0.3), see Table 5

Table 5. Application rates for crop canopy percentage and NDVI value, where rates were the linear relationship for application rate modified from Tackenberg et al. 2018 and NDVI min and max values were taken from min and max NDVI seen in the experimental fields at T1 in 19 Apr 2019.

NDVI Value	*Crop Canopy Cover (%)*	*Application Rate (L/ha)*	*Comparison with uniform rate (saving)*
0.7	95	200	100%
0.6	80	166	83%
0.5	65	131	66%
0.4	50	97	49%
0.3	30	50	25%

The farm equipment was costed at £25,700 for a John Deere PWM ExactApply to be used in conjunction with a sprayer (Mowbray 2021). 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.

4. Results

4.1. Findings of spray deposition trial

The spray solution recovered is referred to as spray liquid recovered (µl). 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 552 mm, fresh weight ranged from 0.144 to 38.4 g, and dye spray liquid recovered ranged from 2.31 µl to 302 µl. Microlitres of dye dose per gram of biomass ranged from 3.57 µl/g to 16.1µl/g.

Spray liquid (µl) recovered for the height (mm) and weight (g) is shown in Figure 10 and Figure 11. 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 10 shows height indicated spray liquid recovered, R^2 = 0.49, RMSE at 41.6 µl

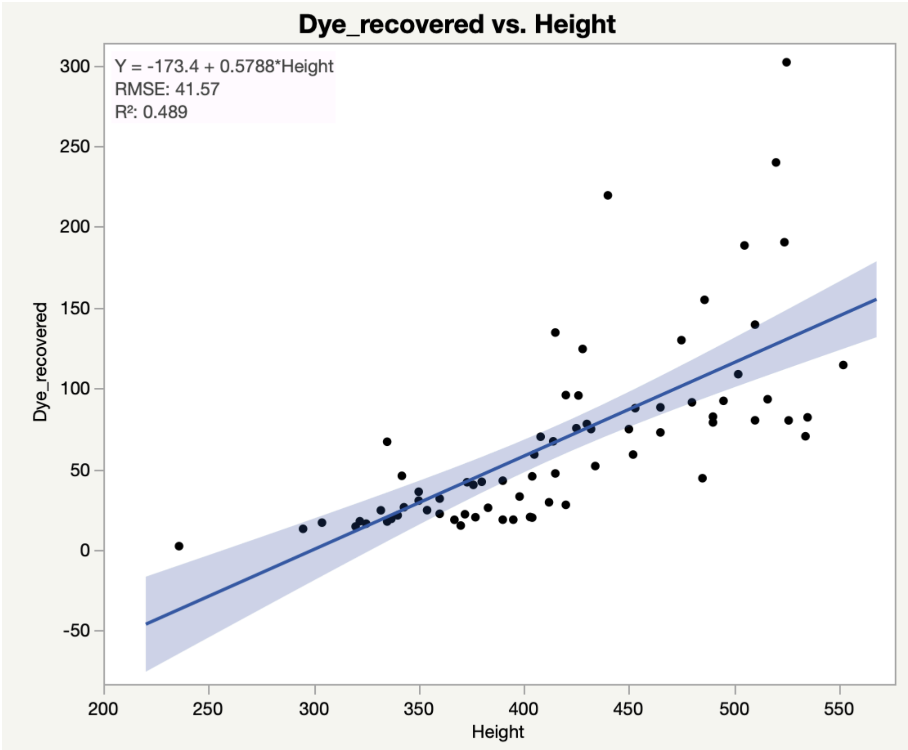

Figure 10. Spray liquid (dye) recovered (µl) vs height (mm) of winter wheat.

Figure 11 shows weight as a good indicator of spray liquid recovered, with an R^2 of 0.89 and a RMSE of 19.2 µl. Figure 12 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.

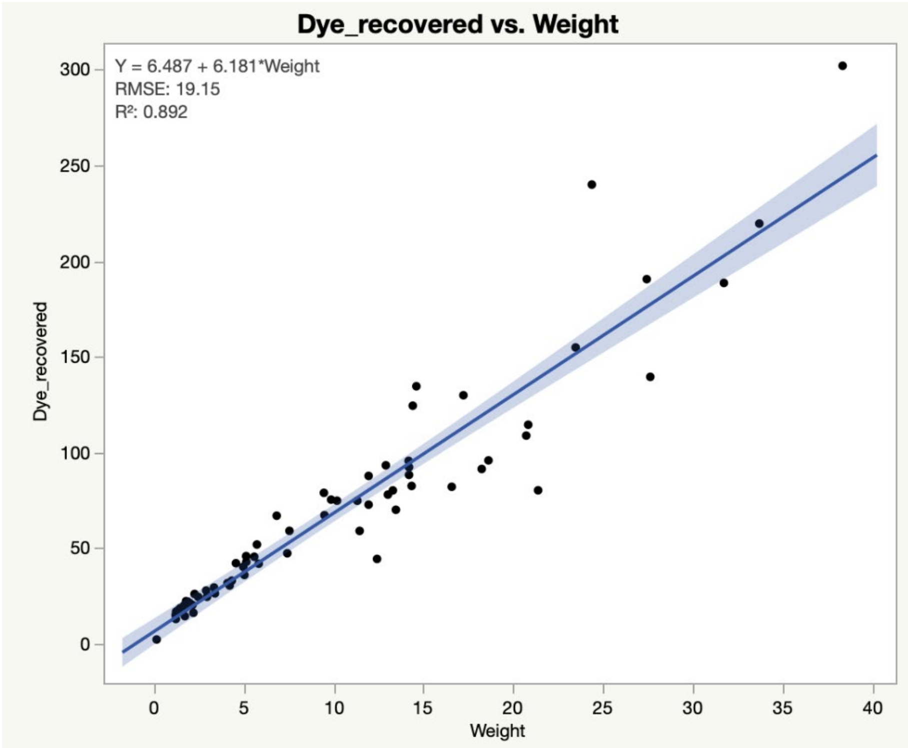

Figure 11. Spray liquid recovered (µl) vs weight (g) of winter wheat.

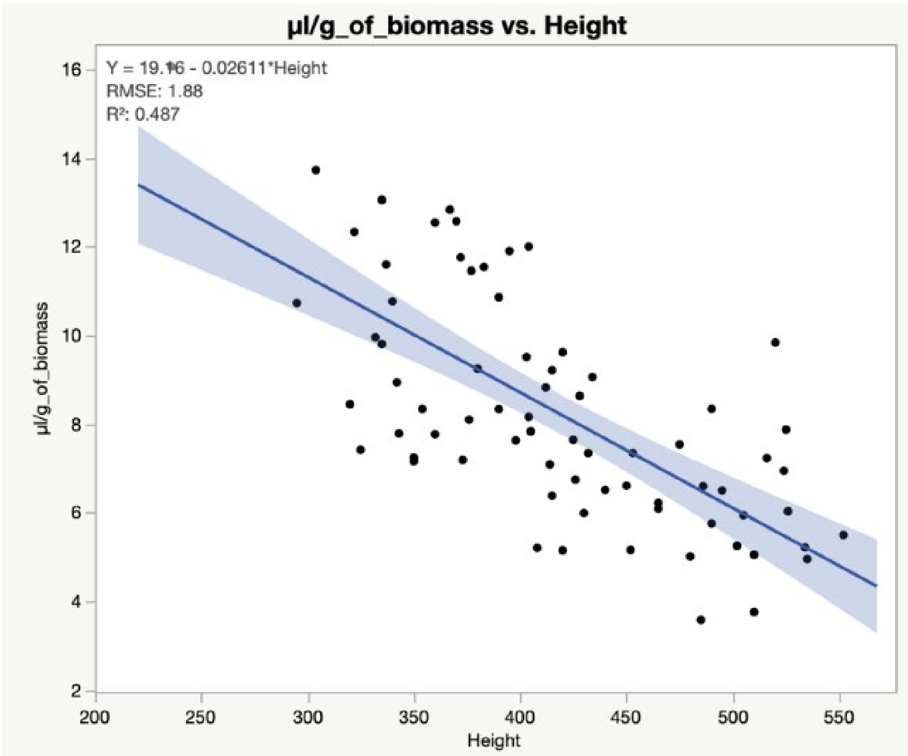

Figure 12. µl of dye deposited per gram of biomass (g) vs height (mm)

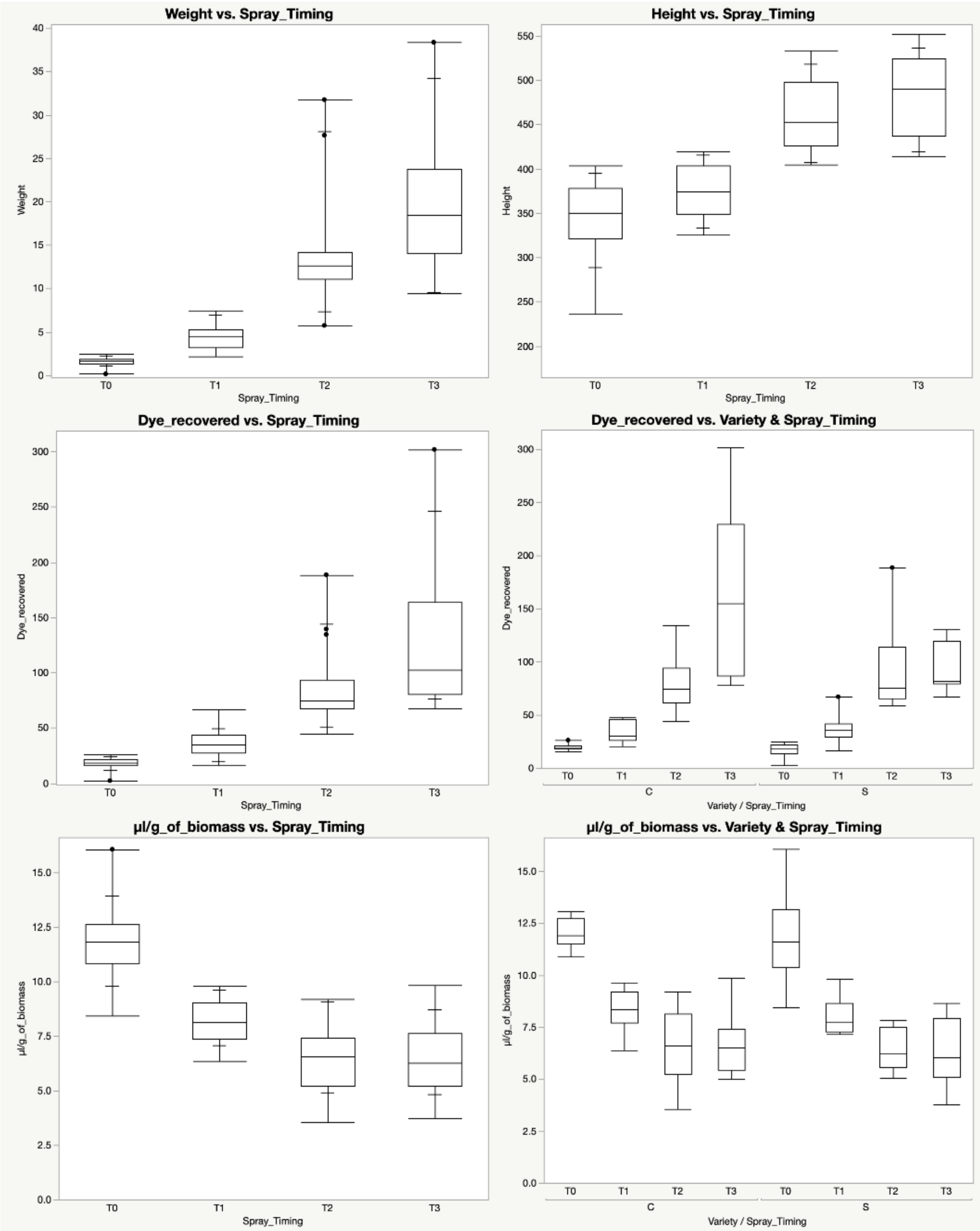

Figure 13. left to right, top to bottom. Time series, spray timings, T0, T1, T2, T3. a) Weight (g). b) Height (mm). c) spray liquid (dye) recovered (µl). d) spray liquid (dye) recovered (µl), split by varieties (C = Claire and S = Skyfall). e) spray liquid (dye) recovered (µl), per gram of biomass. f) spray liquid (dye) recovered (µl), per gram split by varieties.

The boxplots in Figure 13 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 13a 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 13b 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 13c 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 13d, 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 13c but shows the difference between varieties, in that Claire had significantly higher levels of variation at T3 than Skyfall.

Figure 13e describes µl 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 μl/g decreases as the canopy grows, but the range of variation is consistent.

Figure 13f describes the μl 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.

4.2. Variation in winter wheat with remote sensing

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 stage (GS) and leaf emergence (LE), Table 3. 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 2018b). 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.

4.2.1. Volumetric Above Ground Biomass

Variation of VAGB at application times at field level is shown in Figure 14. 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.

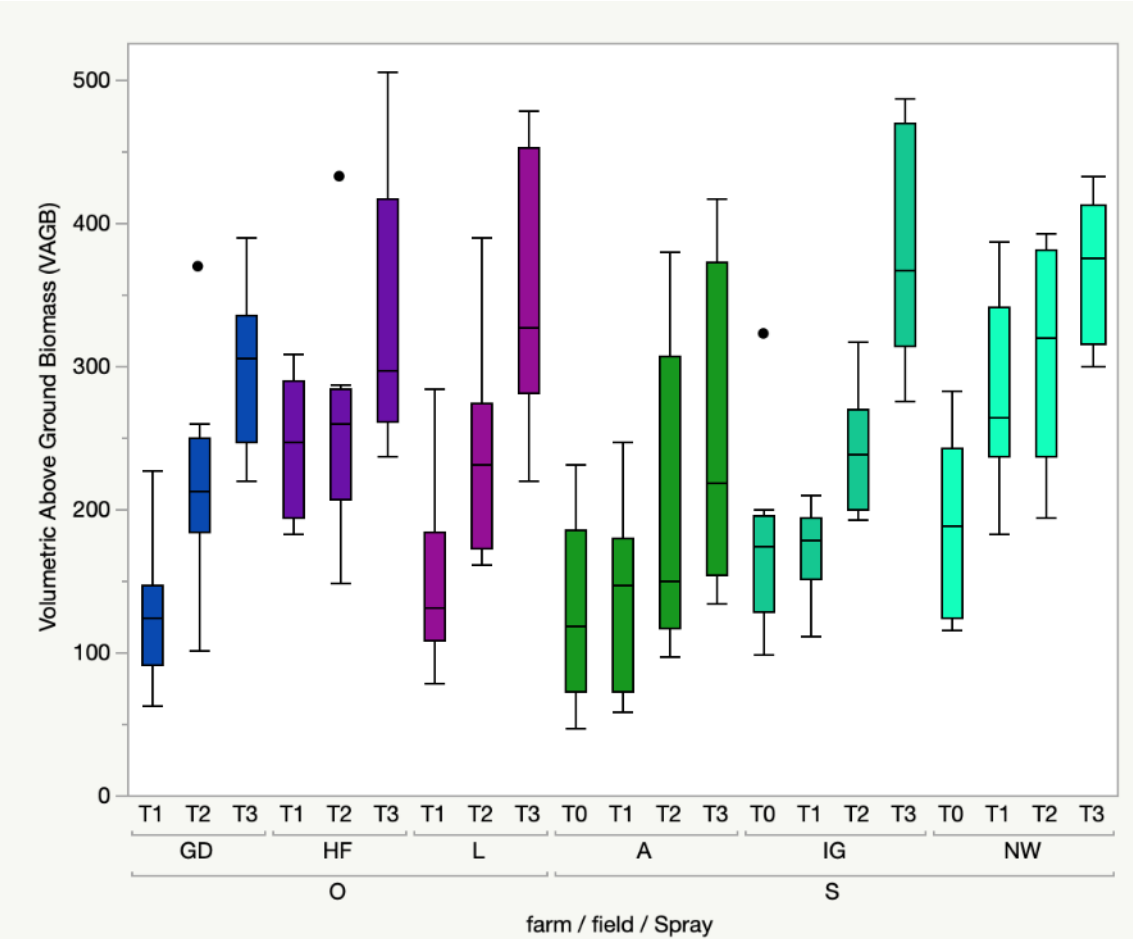

Figure 14. Boxplot of Volumetric estimation of Above Ground Biomass (m³) split by fungicide timing, field, and farm. (T0-T3 – fungicide timings; Fields: A - Avenue, IG - Ivy Ground, NW - Near Warden, GD - Great Dole, L - Lavendon, HF - Home Field; Farms: O-Olney, S-Silsoe). Boxplot shows interquartile range, and the whiskers show extent of the range of variation. No data is available for Olney T0.

Figure 15 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 16 compares points 1 and 2 at each of the spray application timings. The biomass difference is significant in this case. Figure 17 shows the ground photography and stratified NDVI in Near Warden for comparison as it was the least variable field.

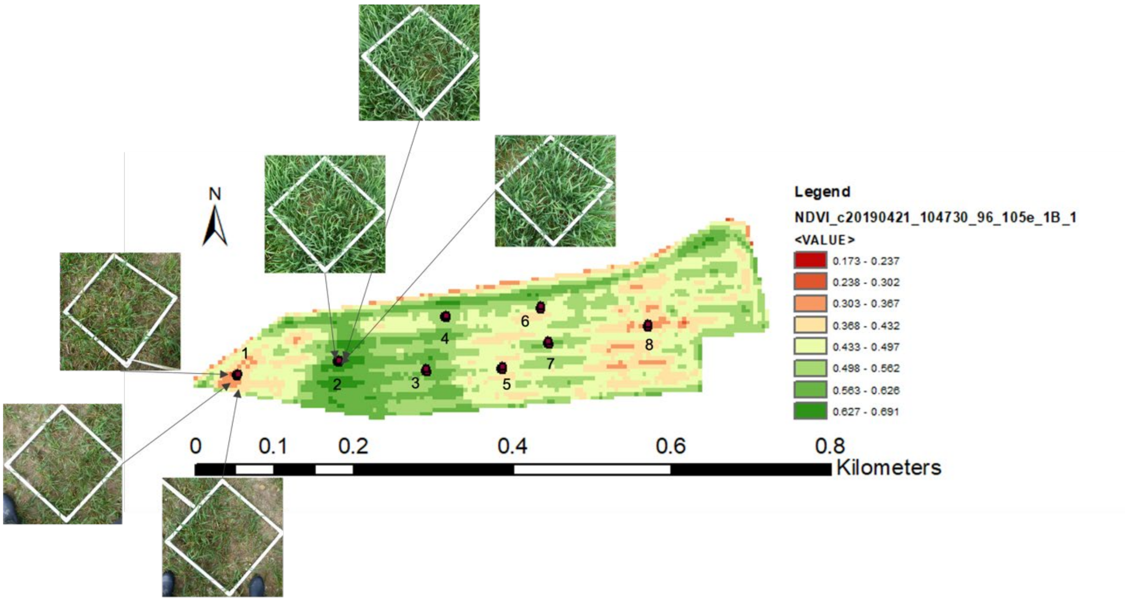

Figure 15. Avenue, Silsoe, taken at T1 from Planet scope basic scene product image, 21/04/2019, showing variation between quadrats of points 1 and 2.

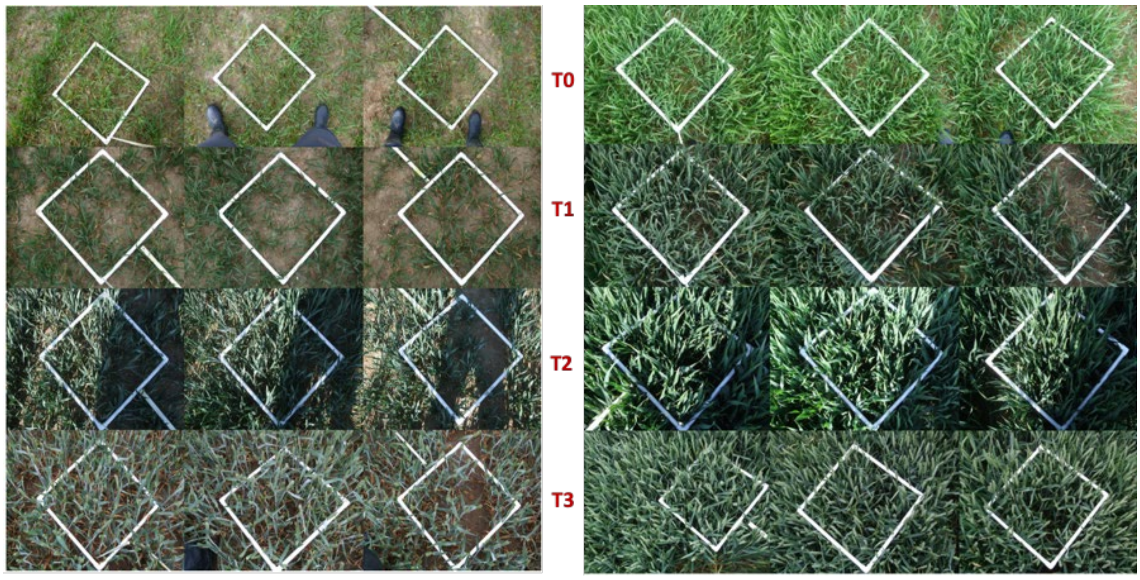

Figure 16. Ground photographs of sample quadrats (0.25 m^2) in Avenue field, Silsoe, points 1 and 2, showing crop variation at the key fungicide application timings

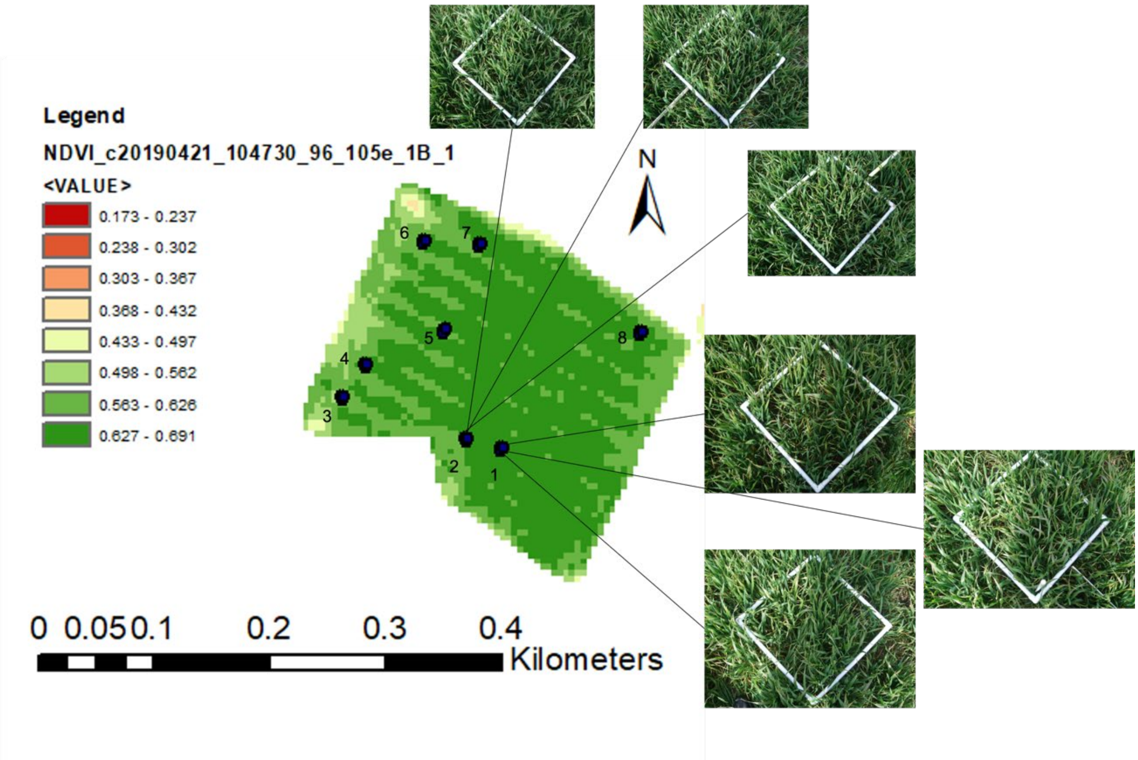

Figure 17. Near Warden, Silsoe, taken at T1 from Planet scope basic scene product image, 21/04/2019, showing variation between quadrats of points 1 and 2.

4.2.2. NDVI of wheat canopy variation from satellite imagery

NDVI variation is shown in Figure 18. 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.

4.2.3. VAGB vs NDVI

Variation at each spray timing of VAGB (left) and NDVI (right) is shown in Figure 19 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.

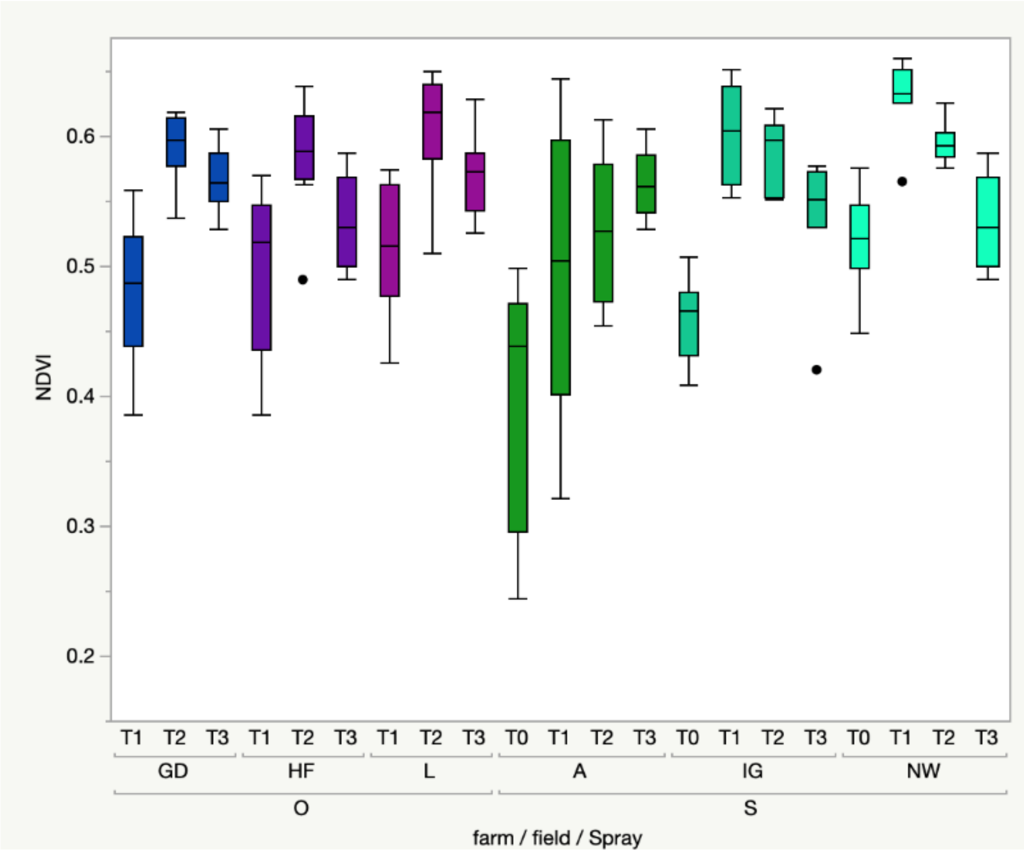

Figure 18. Boxplot of NDVI split by fungicide timing, field, and farm. (A - Avenue, IG - Ivy Ground, NW - Near Warden, GD - Great Dole, L - Lavendon, HF - Home Field, T0-T3 – spray timings). No data is available for Olney T0.

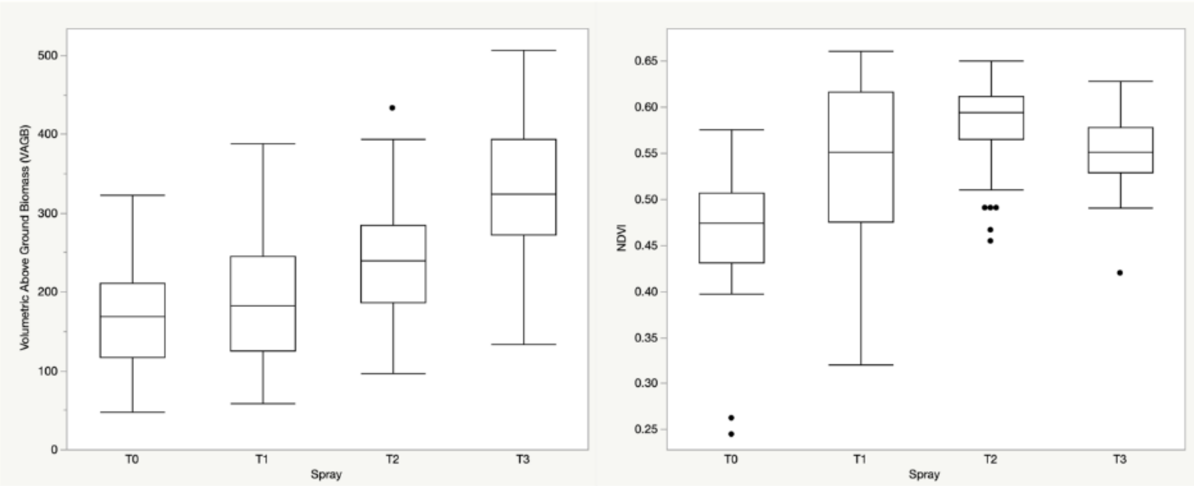

Figure 19. Boxplot of (left) variation in VAGB (m^3) and (right) NDVI at fungicide timings for all fields combined.

4.2.4. 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 20. 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 21.

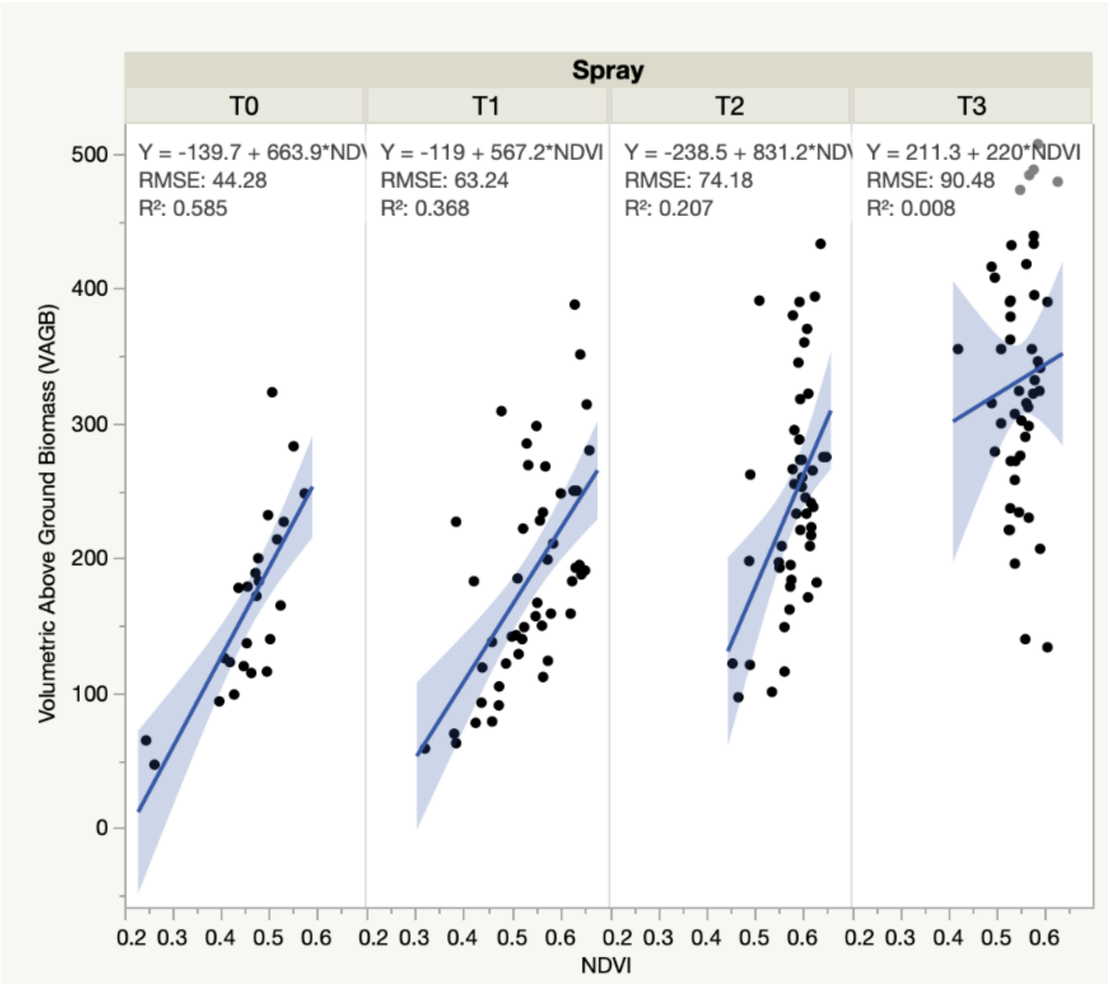

Figure 20. Linear fit of NDVI to predict Volumetric estimation of Above Ground Biomass (m^3), split by spray timing. No data is available for Olney T0.

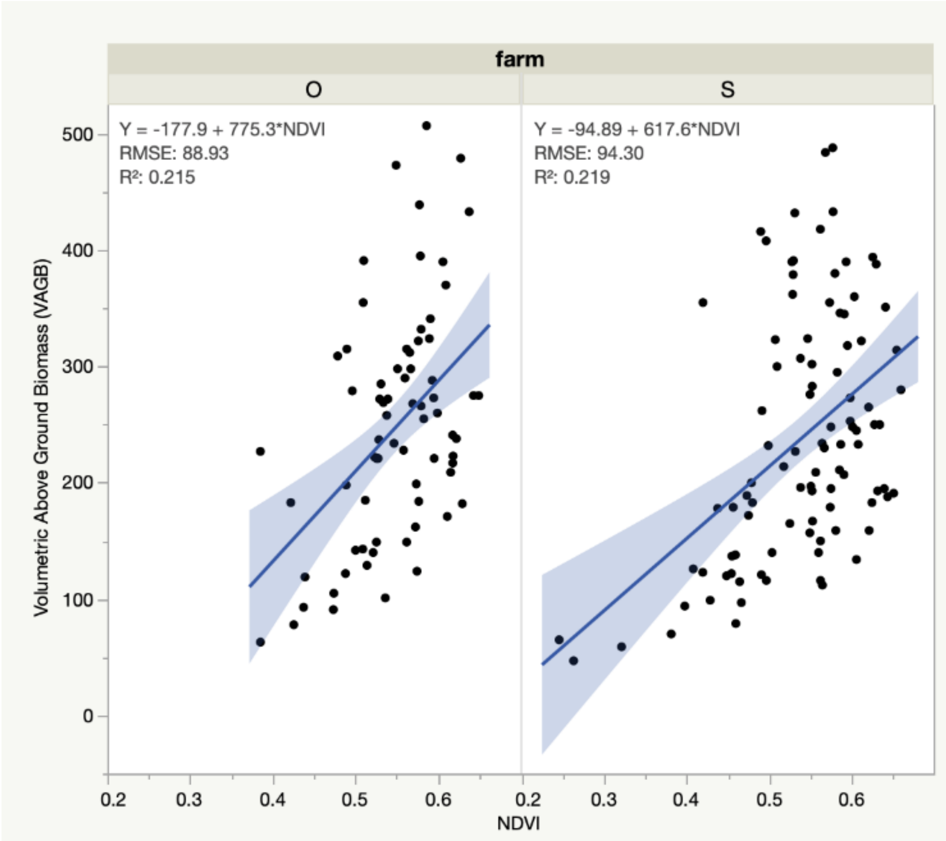

Figure 21. Linear fit of NDVI to predict Volumetric estimation of Above Ground Biomass (m^3), split by farm, O= Olney, S = Silsoe. No data is available for Olney T0

4.2.5. 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 6, (Tackenberg et al. 2017). These values are used 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 6. 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.

NDVI Value	*Crop Canopy Cover (%)*	*Active L/ha*
0.7	95	1.9
0.6	80	1.6
0.5	65	1.3
0.4	50	1
0.3	30	0.6

4.3. Monitoring Eastern regional variation in winter wheat at T1

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 22. 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 19th April 2018, and are shown in Figure 23. 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.

The map in Figure 24 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.

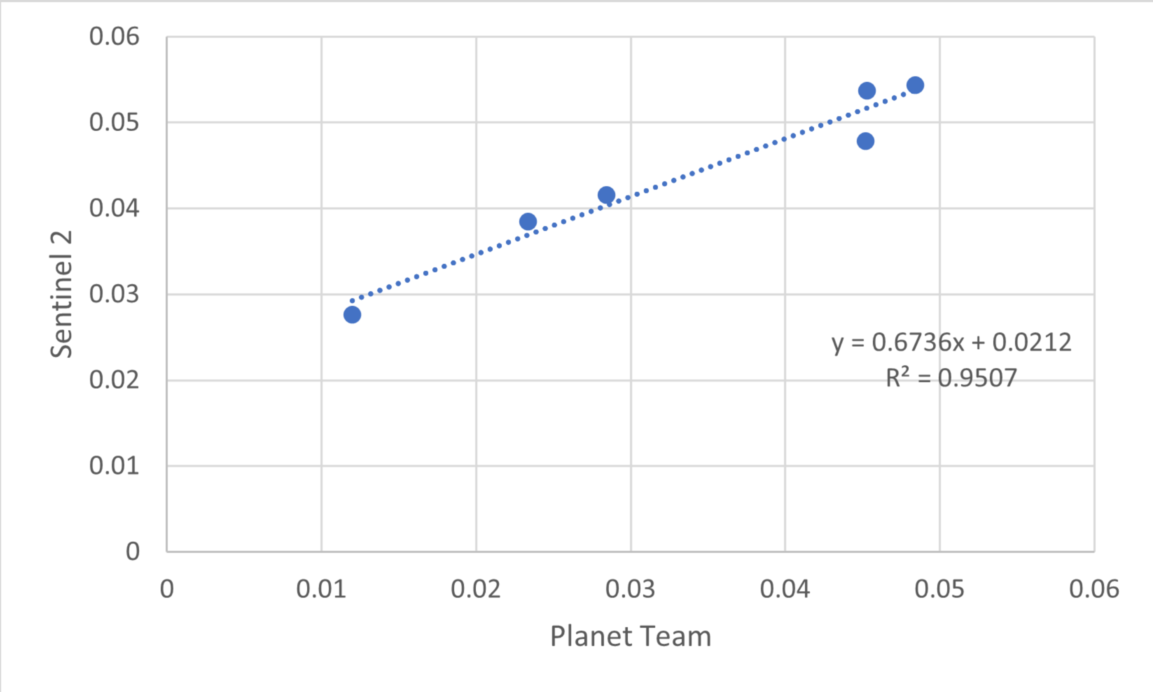

Figure 22. Standard deviation of NDVI at fungicide application timing T1 extracted from Planet constellation, used for field study, and Sentinel 2, used for quick estimation method in regional analysis.

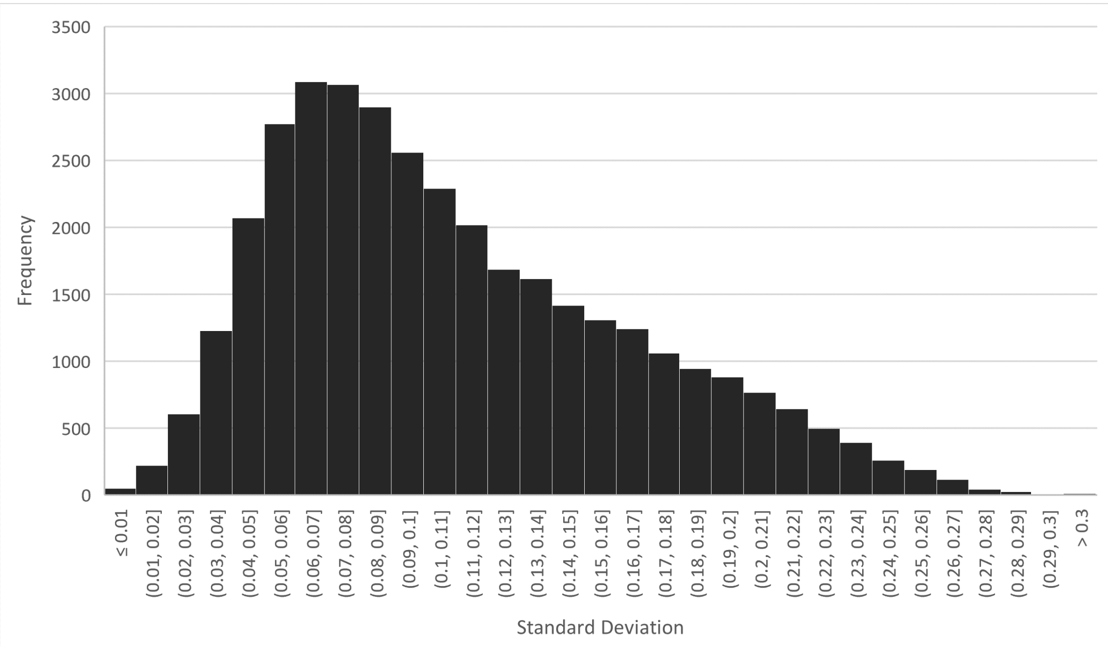

Figure 23. Histogram of standard deviation of NDVI extracted Sentinel 2 imagery of all fields in East of England in 2018 at T1, 19th April 2018, CEH Landcover + and Google Earth Engine.

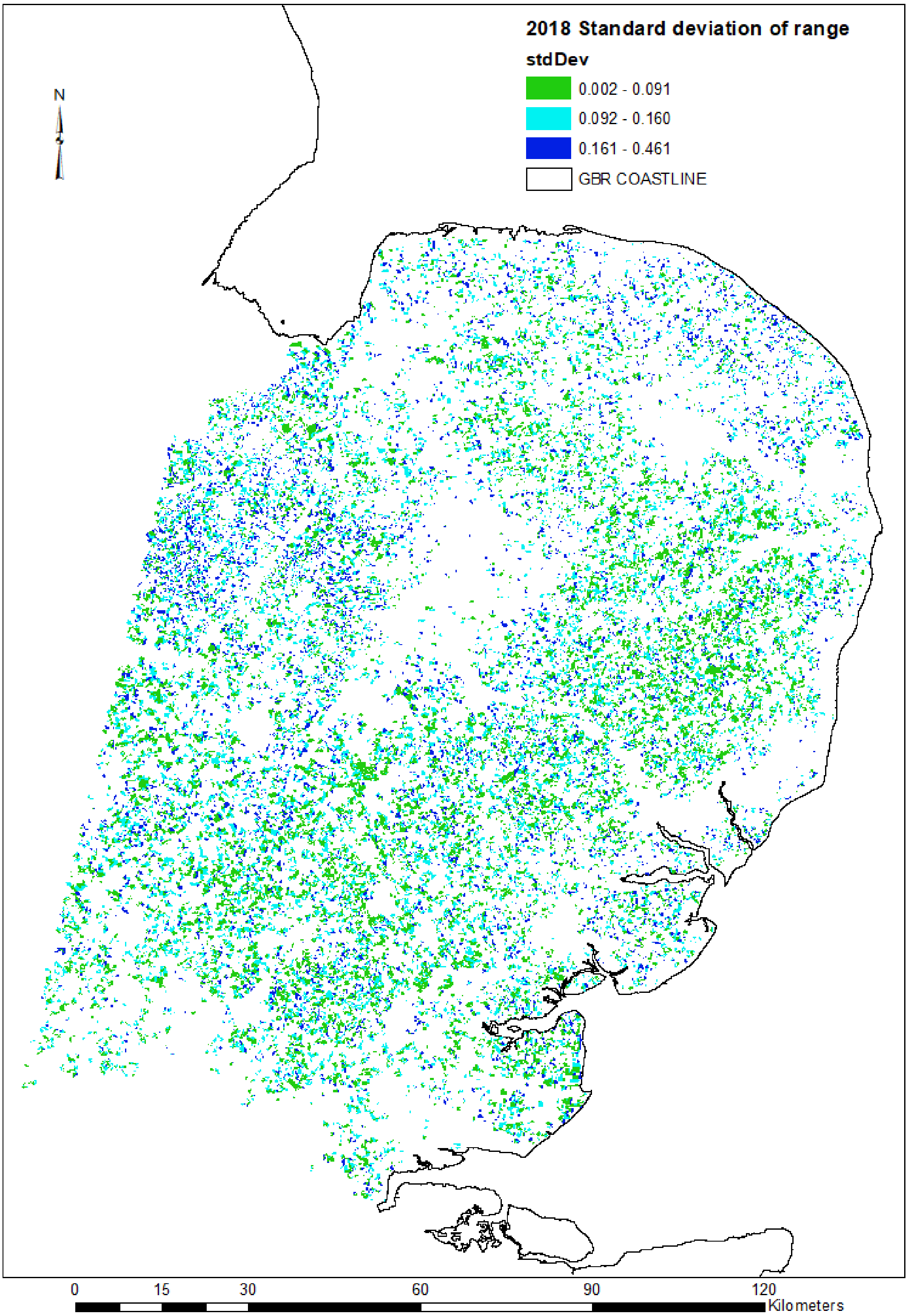

Figure 24. Map of standard deviation of NDVI at T1 for each winter wheat field grown in East of England in 2018.

4.4. Results of economic analysis of VRA of fungicide on winter wheat

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 chemical, Table 7. 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 7. 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	32.2	32.2	6440	939.18	6408	1137	459.82
Home Field	12.4	12.4	2840	361.67	2468	438	177.07
Lavendon	9.5	9.5	1900	277.09	1891	336	135.66
Total	54.1	54.1	11180	£1,577.93	10766	1911	772.55
Cost				**£1,577.93**		**£19.11**	
			Scenario 2: VRA				***Fixed Cost per ha (15.94)***
Great Dole	32.2	14.2	2840	414.17	2826	502	513.27
Home Field	12.4	4.13	945	120.34	940	167	197.66
Lavendon	9.5	7.4	1479	215.69	1472	261	151.43
Total	54.1	25.72	5264	£750.21	5238	930	862.35
Cost				**£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	8.1	8.1	1620	237.33	1612	189	116.478
Ivy Ground	7.7	7.7	1540	225.61	1532	180	110.726
Near Warden	5.7	5.7	1140	167.01	1134	133	81.966
Total	21.5	21.5	4300	629.95	4279	503	309.17
Cost				**£659.95**		**£5.03**	

Scenario 2: VRA							Fixed Cost per ha (15.94)
Avenue	8.1	4.5	904	131.78	899	160	129.114
Ivy Ground	7.7	5.7	1148	167.43	1142	203	122.738
Near Warden	5.7	4.5	904	131.85	899	160	90.858
Total	21.5	14.8	2955.6	431.1	2940.8	522.0	342.71
Cost				**£431.10**		**£5.22**	0
Scenario 1 total:				**Scenario 2 total:**		**£779.03**	
Saving						**£195.12**	

From the above cost benefit 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 25. 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.

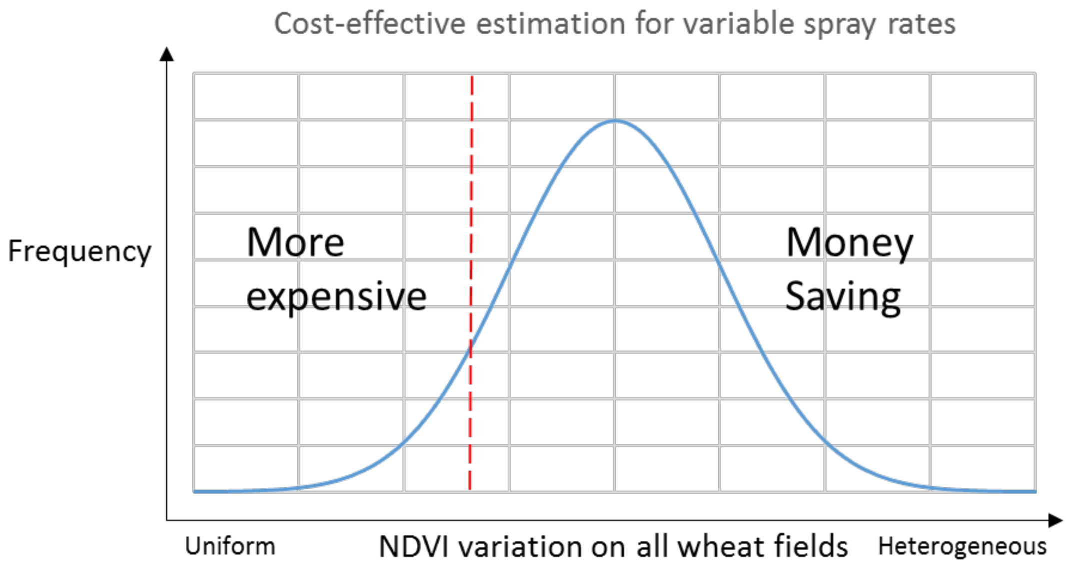

Figure 25. Frequency distribution of uniform and heterogeneous fields. The red line symbolises a hypothetical line where VRA becomes cost effective, regardless of the variability.

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).

5. Discussion

The intention of this project was to deliver a comprehensive foundation for variable rate application of fungicides on winter wheat canopies. To achieve VRA of fungicides as commonplace in UK crop protection, 5 key questions were answered.

5.1. What is the current 'state of the art' technology for VRA of PPPs?

The current 'state of the art' technology (Objective 1) 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.

5.2. What is the variation in spray deposition in winter wheat canopies?

Fungicide dose or spray dose, as was also researched in this research, varies at each spray application and between the applications. Objective (2) 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. 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.

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

Objective (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.

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

Objective (4) found that there was a large 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.

5.5. What and where is the economic benefit of VRA?

Objective (5) studied the financial benefits of reducing the rates of application based on a fungicide linear relationship for one farm. 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 fungicide. Therefore, the use of VRA could save significantly more and would be faster to pay off.

6. Future 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 2018a; 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.

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