LODGING DETECTION IN WHEAT USING SENTINEL-1 AND SENTINEL-2 DATA

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February 2019

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ABSTRACT

Wheat is one of the most important food world - wide that enhances the global food security. Among the anomaly that affects it during its growing period is lodging. Lodging is the displacement of roots and stems from their vertical position. This causes reduced food production. Therefore, there is need for a timely, cost effective and accurate tool to monitor lodging in order to install measures to control its effects. Remote sensing using earth orbiting satellites offers a solution to this. Sentinel 1 and Sentinel 2 data is freely available at an improved revisit period which is cost effective due to large area coverage. This study explores the use of Sentinel 1 polarizations and Sentinel 2 bands, vegetation indices and field data to detect lodging. Field data was collected in two wheat growing stages. The results show that the changes in some of the band reflectances in Sentinel2 and backscatter in sentinel 1in the VH and VV polarizations can be used to detect lodging. Significance tests show that VH polarization is significant in detection in both the wheat growing stages. Further research needs to be carried out to explore the use of optical sensors to detect crop lodging.

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1. INTRODUCTION

1.1. Background

Wheat is one of the staple food crops worldwide that contributes to food security. About 20% of the world's food calories and proteins are provided by wheat (Shiferaw et al., 2013). With the world population continuously increasing, its production has a crucial bearing on world food security. Italy is one the largest producers of wheat in Europe and produces a significant amount of common (or soft) wheat and durum wheat, which is used to prepare pasta, one of the staple food in Italy (David et al., 2017). Therefore, monitoring wheat during its growth period is vital in detecting anomalies that contribute to its reduced production.

Figure 1 shows wheat growing stages which include vegetative, reproduction and maturation. The vegetative period is characterized by a slow increase in height from germination to tillering (Singh, 2017). The root system develops from germination and may continue for 60-70 days, its function being to support the plant throughout its life. Moreover, if there is no competition due to plant density, the roots may spread 1.2m horizontally and 1.8m vertically with most root on top of the soil (Jackson & Williams, 1995).

Wheat, like any other cereal crop, is prone to lodging during the growing period, which affects its growth and limits yield quantity and quality. Lodging is the displacement of roots and stems from their vertical position (Pinthus, 1973). The main causes of lodging are heavy rainfall, strong wind, excess application of fertilizer, early sowing date, high plant density, narrow stem diameter, excessive height, disease, soil density and the crop variety (Telker, 2017).

Root lodging occurs early in the season while stem lodging occurs mainly during the grain filling stage Root lodging occurs mainly during mid-vegetative stage before brace roots develop due to: overcrowding of plants that cause shallow roots; soil density; wet conditions at planting; and drought conditions that prevent roots from penetrating vertically (Delkalb, 2013). Root lodging causes the plants to pool away from the soil. After root lodging, cracks parallel to planting rows occur and can be observed on the opposite side to lodging when the soil dries up (Pinthus, 1973).

The substages in the reproduction period range from stem elongation to flowering. Maturation and ripening stage takes about 35-40 days are characterized by the growth of grain and increase in grain weight and size (Singh, 2017). This is the stage where stem lodging normally occurs as a result of rainfall and strong winds especially if the stems are tall and weak. Winter wheat is sown between October and November and is harvested between late May and early June, in Italy. It takes about nine months for the wheat to grow. Stem lodging is usually first observed around May when the wheat is at the flowering stage.

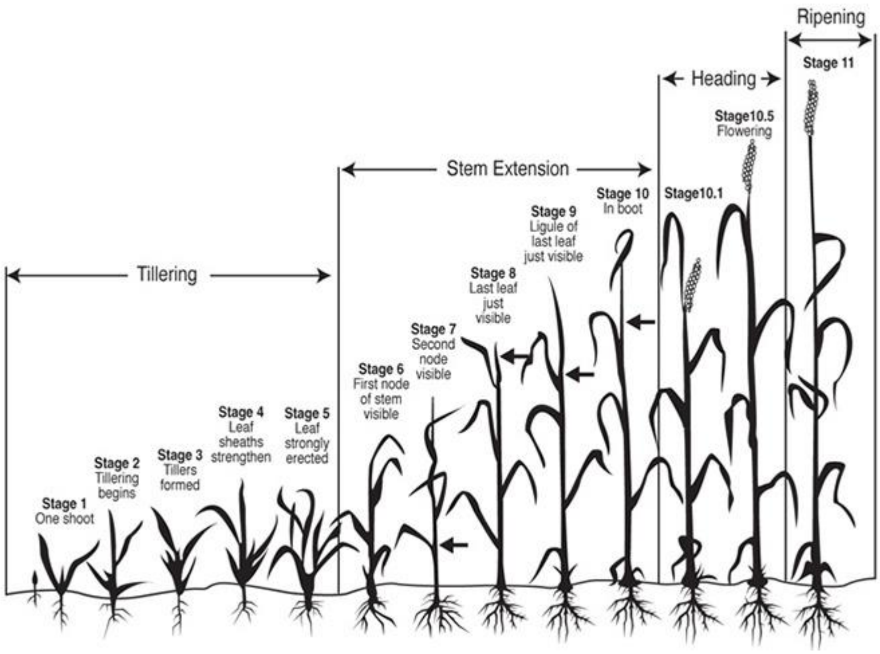


Figure 1. Wheat growth stages (Source: https://prairiecalifornian.com/wheat-growth-stages)

Lodging results in high moisture content that may lead to delayed harvesting and may necessitate additional grain drying (Telker, 2017). Moreover, it suppresses the circulation of water, photosynthesis and grain filling in crops which greatly reduce yields and grain quality. Also, the cost of mechanized farming is increased due to lodged crops (Zhao et al., 2017). Lodging further increases the likelihood of pests and diseases in crops due to the humid microclimate surrounding the lodged area (Berry et al., 2003). Lodging destroys the canopy structure. Moreover, it causes the plant to lose its upright position causing a reduction in height. The height reduction depends on the lodging angle. Furthermore, the heads get deformed, and the kernels shrivel (Telker, 2017). However, there is a possibility of the field to field variations in the intensity of lodging in the same region due to different field management practices (Berry et al, 2003).

Field methods of detecting lodging include making visual observations, measuring and calculating traits that affect lodging (Zhu et al., 2016). Measurements of variations in crop height may be used as one of the indicators of crop stress due to lodging (Bell & Fischer, 1994). Moreover, lodging can be assessed by stem inclination angle of the plants. Crook & Ennos, (1994) considered plants with an inclination angle of more than 45° to be lodged. Furthermore, the extent of lodging was estimated, and the type of lodging recorded. Field methods require continuous monitoring and are time-consuming.

Wu & Ma, (2016) assessed the risks of lodging using measurements of root capacitance to determine its strength which is an important factor in root lodging. Wu & Ma,(2016) further expressed that though existing simulation models relating crop lodging and biochemical properties are promising, they are time-consuming and require knowledge of plant and environmental conditions affecting lodging. Zhu et al., (2016) used a simplified model to assess rice lodging using plant height and weight of spikelets. Baker et al. (1998) in his model, used weather, plant form and soil in assessing wheat lodging. Berry et al., 2003) improved the model of Baker et al., (1998) to account for spatial non- uniformity and temporal changes in plant structure during growth. However, it is still difficult to predict the spatial and temporal aspects of lodging using simulation models (Zhao et al., 2017).

1.2. Remote sensing for lodging assessment

Satellite remote sensing technology can be used as a tool to monitor wheat lodging. In contrast to field methods that are labour intensive and time-consuming, satellite data coverage is wide, timely and repetitive. The data can be collected using optical or radar sensors (McNairn & Shang, 2016). RADAR remote sensing is based on variations in backscattering while optical remote sensing is based on the spectral reflectance of electromagnetic energy. Therefore, changes in leaf structure and moisture due to lodging can be detected using optical bands in the visible, NIR and SWIR ranges of the electromagnetic spectrum. SWIR is sensitive to the existence of water content in leaves, and its reflectance decreases with water content (Ji et al., 2011). This causes it to be particularly useful in detecting lodging and further improves the classification of crops. Also, optical data can be used to estimate biophysical parameters of plants via vegetation indices (Veloso et al., 2017).

The arrangement of leaves and stems causes canopy reflectance to be different between the lodged and non -lodged. In a study, Liu et al. (2012) showed that hyperspectral reflectance increased from visible to short wave infrared when lodging occurred??. According to Liu et al. (2012), vegetation indices sensitive to photosynthesis can be used to detect lodging. During lodging, the leaves and stalks cover bare soil and therefore there is higher reflectance in the infrared band which results in the contrast between lodged and non -lodged areas(Zhang et al. , 2014). On the contrary, Wang et al. (2018) results showed that reflectance in visible and NIR could not be used to detect lodging. Moreover, since lodging causes crops to bend over, height changes can be used to detect lodging.

RADAR sensors have the advantage of operating day and night regardless of the weather conditions and can operate through the atmosphere in all weather conditions (Chen et al. , 2016). Therefore, the data are readily available in all weather conditions. SAR is an imaging technique that allows sensing the environment with high spatial resolution by emission and reception of electromagnetic microwave signals (Ferro-Famil & Pottier, 2016). SAR images can be defined by operating band and polarization. Polarization refers to the electric field of transmitted and received electromagnetic wave respectively and can be vertical (VV), horizontal (HH) or crossed (HV,VH) (McNairn & Shang, 2016). SAR is mainly sensitive to crop biophysical parameters such as canopy structure and therefore multitemporal SAR images can accurately be used to identify canopy structural changes in crops (McNairn & Shang, 2016). In addition, SAR is sensitive to dielectric properties of materials which are a function of moisture conditions (ESA, 1995).

Vegetation structure changes during lodging, therefore, SAR data can provide useful information due to the sensitivity of the generated signal to the plant structure (Lussem et al., 2016.). Moreover, Son et al. (2018) in his literature reveal the response of RADAR to non-vertical plants. After lodging, there is an increase in backscatter (Bouman et al., 1990).

Previous studies on monitoring crop lodging using satellite remote sensing have mainly been conducted using RADAR remote sensing. This could be due to the limitation of optical sensors since the spectral information between lodged and non-lodged is relatively weak (Han et al., 2017). Optical sensors cannot penetrate through clouds and therefore it is difficult to obtain clear images when it is cloudy or raining. Radarsat-2 PALSAR was used to detect lodging damage based on canopy structure between lodged and non-lodged (Zhao et al., 2017). Chen et al. (2016) also used Radarsat-2 to detect sugar cane lodging and concluded that it is only possible to detect lodging using multi-date data. Yang et al., (2015) detected lodging through the response of different observables in time series Radarsat-2. Therefore time series data is vital in detecting lodging. Han et al., (2017) monitored maize lodging by constructing a model that explored VH and VH+VH channels and concluded that dual polarized Sentinel-1 could be used to detect lodging. In one study using an optical sensor, Liu et al. (2005) used two Landsat images to detect wheat lodging and found out that canopy reflectance in the visible increased while NDVI decreased with lodging angle.

Among the studies that have been conducted to monitor crop lodging using UAVs, Wang et al., (2018) in his study, used band ratio textural features analysis in the visible region and concluded that the band ratio of green/blue was the maximum discriminator of wheat lodging. Chu et al., (2017) used height changes calculated from 3D structural information, and maize spectral features to detect lodged maize. Moreover, Yang et al., (2017) in his study used 3D information and texture features and achieved high classification accuracy using decision tree classification method. However, Liu et al. (2018) stated that colour and texture features in visible and near-infrared could not be used to detect lodging. Therefore, hybrid image analysis of visible and thermal images and support vector machine algorithm were used to establish a lodging model in his study to distinguish between the lodged and non- lodged areas. However, Rajapaksa et al. (2018) achieved high accuracy using texture features extracted using grey level co-occurrence.

Based on the literature, studies that have been conducted to detect lodging in maize, wheat, sugarcane and rice have mainly focused on Radarsat-2 and UAV's data. Radarsat-2 have mainly been used due to SAR sensitivity to the changes in crop structure. UAV's are normally used because of their flexibility and their high spatial resolution. Only one study has been conducted using Landsat and Sentinel-1 to detect lodging.

Sentinel data is freely available at an improved temporal and spatial resolution. With both Sentinel-2A and 2B in operation, a revisit period of 5 days can be achieved. With both Sentinel-1A and 1B in operation, a revisit period of 6 days can be achieved (Mansaray et al., 2017). However, geographic regions near the poles have more frequent revisit period due to overlaps in adjacent orbits as they come close together near the poles (Torres et al., 2012). Given the good spatial and temporal resolution of Sentinel-1 and 2 and their availability, there is now the possibility to exploit time series of earth observation information from these platforms to detect crop lodging.

1.3. Conceptual diagram

Figure 2 shows the conceptual diagram of the study. The boundary of the system is Bonifiche Ferraresi farm, Ferrara, Italy. The elements of the system include fields growing both soft and Duram wheat. Rainfall and strong winds are outside the boundary and interact with the wheat fields resulting in some fields being lodged early, others later and some remaining non-lodged, depending on variety, soil and other environmental characteristics. The focus is on earth observation, which is used to distinguish between non- lodged and lodged wheat. Field data is used to test the accuracy of the satellite sensors in detecting wheat lodging.

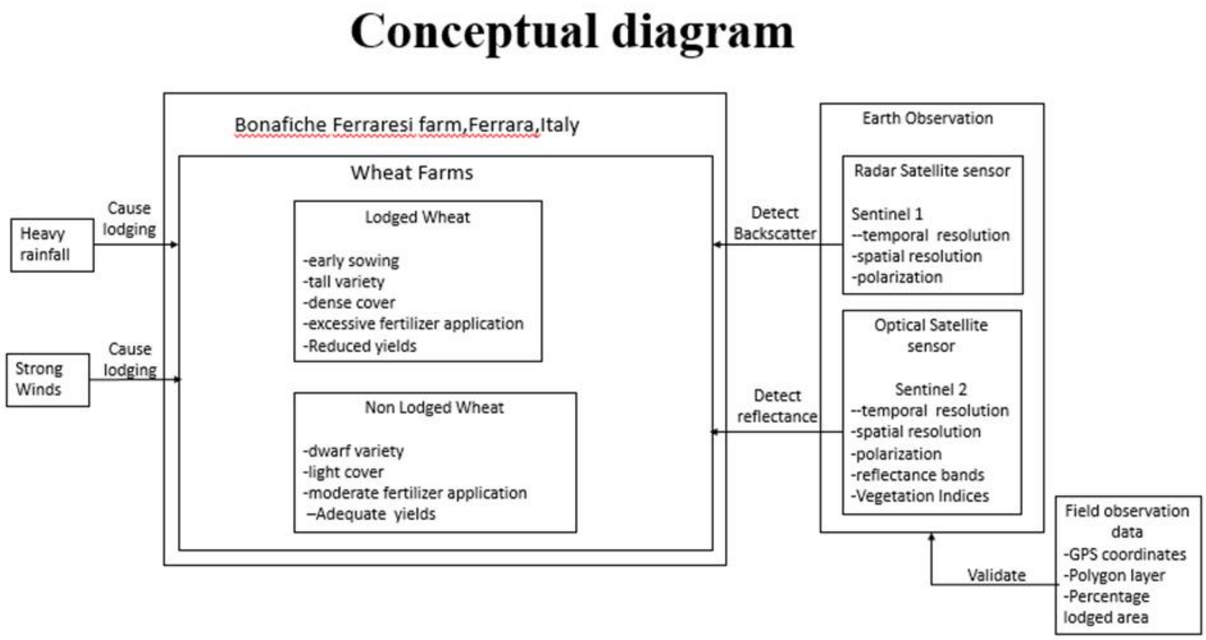


Figure 2. Conceptual diagram of the research

1.4. Research problem

Wheat lodging greatly reduces grain yields and quality. Providing cost-effective, accurate, timely information about when and where lodging has taken place is vital. This is required in the prediction of yields, estimation of losses and instilling proper agricultural management measures. Moreover, the information can be used as a basis for compensating farmers for losses (Wang et al., 2018). Furthermore, providing information about the lodged areas can assist in planning for earlier harvests and checking for secondary disease development (Zhao et al., 2017).

Unlike field methods, which normally results to disputes during compensation, remote sensing can be used to assess crop lodging at a higher accuracy (Yang et al., 2017). Furthermore, field methods are time-consuming and their quantification is further complicated by the metrics employed to measure lodging (Rajapaksa et al., 2018).

The launch of Sentinel 1A and B SAR sensors and Sentinel 2 A and B optical sensors has provided opportunities to detect lodging at a high temporal and spatial resolution. Furthermore, the data is freely available.

Review of the literature revealed that, very few studies have been conducted using optical satellite sensors to detect crop lodging. Moreover, only bands in the visible region have been used. Therefore, it is important to explore the potential if other spectral bands in optical satellites sensors like Sentinel 2 to acquire more information about crop lodging.

Although studies to detect wheat lodging have been conducted using UAV's at a better spatial resolution compared to satellite data, UAVs are still limited in terms of area coverage, cost and on the weather conditions they can operate on, as compared to satellite imagery. The review of the literature showed that, no study has been conducted using Sentinel1 and Sentinel 2 to detect wheat lodging. Therefore, the research aims to use sentinel 2 optical satellite data and sentinel 1 radar data to detect wheat lodging. The research will further explore other bands like SWIR, red edge and vegetation indices.

1.5. Objectives

In view of the above-mentioned research problems, the following objectives have been defined to investigate and formulate a robust methodology for lodging detection in wheat crop using remote sensing technique.

1. To analyze changes in the Sentinel-1 backscatter data in lodged and non-lodged wheat fields.
2. To analyze changes in reflectance of different spectral bands and vegetation indices from Sentinel-2 reflectance data in lodged, and non-lodged wheat fields.
3. To identify the best polarization(s) to detect wheat lodging using Sentinel-1.
4. To identify the best spectral band(s) and vegetation indices using Sentinel-2.

1.6. Research questions

1. Does backscatter change in wheat fields after lodging occurs?
2. Do reflectance and vegetation indices change in wheat fields after lodging occurs?
3. Which polarization among VV, VH and VV/VH can best discriminate between lodged and non-lodged wheat?
4. Which spectral bands or vegetation indices (NDVI and IRECI) can best discriminate lodged and non-lodged wheat?

1.7. Hypotheses

1. H_o: There is no significant change in backscatter between lodged and non-lodged wheat plots.
   H_1: There is a significant change in the backscatter of lodged and non-lodged wheat plots.

2. H_o: There is no significant change in band reflectance and vegetation indices of lodged and non-lodged wheat plots.
   H_1: There is a significant change in band reflectance and vegetation indices of lodged and non-lodged wheat plots

3. H_o: The Sentinel-1 VH polarization cannot be used to detect lodging in wheat.
   H_1: The backscatter from VH is strongly affected by lodging and therefore can be used to detect lodging.

4. $H_{o:}$ Sentinel-2 spectral bands and vegetation indices cannot be used to detect wheat lodging.
   $H_{1:}$ Sentinel-2 spectral bands and vegetation indices are sensitive to lodging and can be used to detect wheat lodging.

2. STUDY AREA AND DATA SETS

2.1. Study area

The study was conducted in the Bonifiche Ferraresi farm located in Jolanda di Savoia, Ferrara, Italy (Figure 3). It lies between 11°54’ 7”E to 12°00” 0”E and 44° 49’ 40”N to 44°53’ 17”N. It is approximately 3,850 hectares. The average monthly temperatures range from 3° C (37°F) to 26°C (78°F), with January being the coldest month and July being the hottest month. The average monthly rainfall ranges from 45mm to 78mm, with July receiving the lowest rainfall and November receiving the highest rainfall. May and June have average precipitation of about 60mm, with temperatures of 20° and 23° C respectively. The soil type in the area is mostly clay and partly silty. The crops grown on the farm are cereals such as rice, durum and soft wheat, corn, barley, soy and sunflower. Moreover, fruits such as apples, pears, watermelons, melons and vegetables and legumes such as tomatoes, potatoes, green beans, beans, sugar beets and alfalfa are also grown. The wheat fields are about 35 and were planted between 25th October to 1st November. Harvesting was done in the last week of June and first week of July.

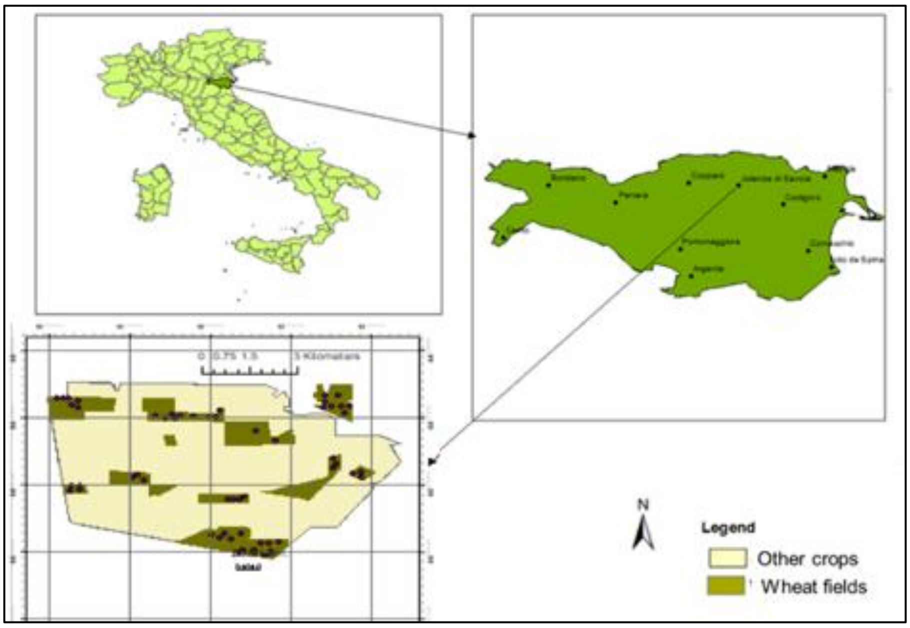


Figure 3. Location of the study area (Bonfiche Ferraresi farm, Jolanda di savioa, Ferrara, Italy), the wheat fields and the sample plots within the wheat fields

2.2. Field data

The field data were collected between the 2nd of May 2018 and the 12th of June by Ms Sugandh Chauhan, a PhD candidate in the NRS department, ITC. The size of the sample plots were 60m by 60m which each contained five subplots of 2 m by 2m. The plots were selected through stratified random sampling. The field data consisted of GPS coordinates at the centre of the sample points, date and time of field observation and estimated lodged area. A total of 59 samples were taken at two wheat growing stages, i.e. lodging in the flowering period and lodging in the milk/dough stage. The date of field data collection was from early May for flowering to mid-May while for milk stage it was from late May to early June. The range of percentage area that lodged in each observed plot ranged from 0 to 98%. The flowering stage consisted of 23 samples, and the milk/dough stage consisted of 36 samples. The samples consisted of 8 different varieties of wheat. Figure 4 shows some field photographs of the non-lodged and lodged wheat plots during the two growth stages.

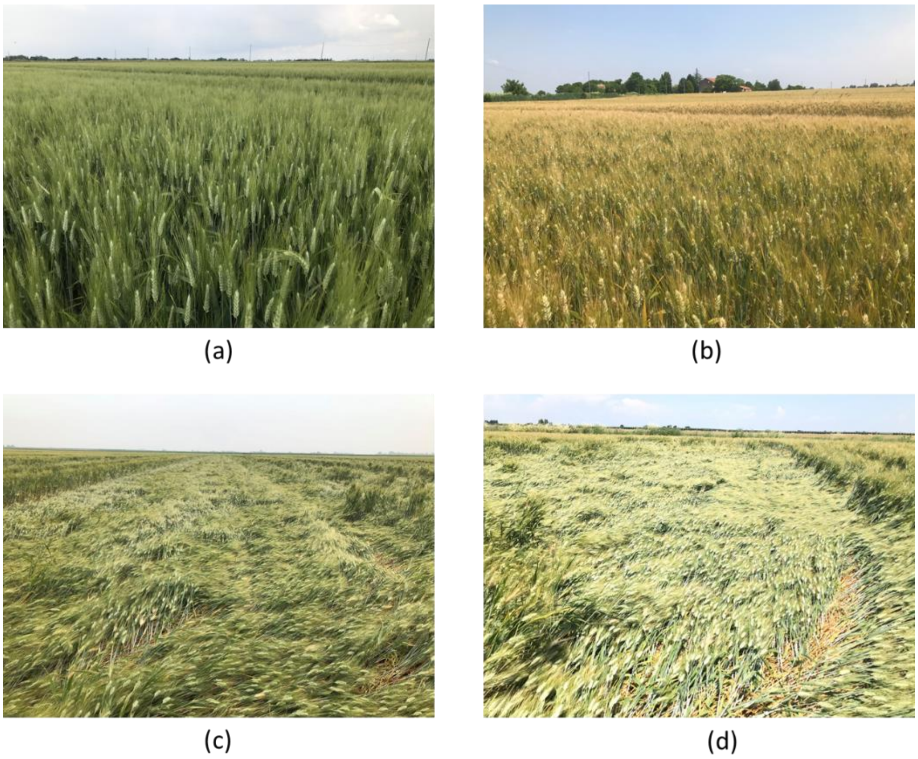


Figure 4. a) Non-lodged wheat at flowering stage, b) Non-lodged wheat at milk stage, c) Lodged wheat at flowering stage, d) Lodged wheat at milk stage

2.3. Sentinel-2 images

Both Sentinel-2A/B level 2A products and Sentinel-1A/B GRD products were downloaded from the open source Copernicus hub. Both ascending and descending Sentinel-1A and Sentinel 1B products were downloaded. GRD products are already multi looked and projected to the ground range.

Sentinel-2 level 2A products are atmospherically corrected to provide Bottom of Atmosphere (BOA) reflectance images. Level 2A products are composed of tiles in cartographic geometry (UTM/WGS84 projection). Sentinel-2 consists of 13 bands with their characteristics shown in Table 1. Due to the limitations of cloud cover over the area during the study period, only six Sentinel-2 images were selected. The date of acquisition of these images is shown in Table 2, while the dates of the Sentinel-1 imagery are shown in Table 3.

Table 1. Characteristics of Sentinel-2 bands

Sentinel-2 Bands	Central Wavelength (μm)	Resolution (m)	Bandwidth (nm)
Band 1 – Coastal aerosol	0.443	60	27/45 (2A/2B)
Band 2 – Blue	0.490	10	98
Band 3 – Green	0.560	10	45/46 (2A/2B)
Band 4 – Red	0.665	10	38/39 (2A/2B)
Band 5 – Vegetation Red Edge	0.705	20	19/20 (2A/2B)
Band 6 – Vegetation Red Edge	0.740	20	18
Band 7 – Vegetation Red Edge	0.783	20	28
Band 8 – NIR	0.842	10	115
Band 8A – Narrow NIR	0.865	20	20
Band 9 – Water vapour	0.945	60	20
Band 10 – SWIR – Cirrus	1.375	60	20
Band 11 – SWIR	1.610	20	90
Band 12 – SWIR	2.190	20	180

Table 2. Sentinel-2 data for the period of study

Sensor	Date	Cloud cover within study area
2B	24/4/2018	Small part hazy
2B	4/5/2018	Very small patch of cloud cover
2B	14/5/2018	One larger patch of cloud cover in the south eastern part
2A	19/5/2017	Few small patches of cloud cover
2A	3/6/2018	Patches of cloud
2B	13/6/2018	Patches of cloud

Table 3. Available Sentinel-1 images

1A ascending products	Date
S1A_IW_GRDH_1SDV_20180501T170623_20180501T170648_021714_025757_0622	1/5/2018
S1A_IW_GRDH_1SDV_20180513T170624_20180513T170649_021889_025CF5_8423	13/5/2018
S1A_IW_GRDH_1SDV_20180525T170625_20180525T170650_022064_02627C_6E36	25/5/2018
S1A_IW_GRDH_1SDV_20180606T170625_20180606T170650_022239_0267FC_7AE7	6/6/2018
1B ascending products	**Date**
S1B_IW_GRDH_1SDV_20180507T170541_20180507T170606_010818_013C70_7509	7/5/2018
S1B_IW_GRDH_1SDV_20180519T170541_20180519T170606_010993_014216_C74A	19/5/2018
S1B_IW_GRDH_1SDV_20180531T170542_20180531T170607_011168_0147C9_8311	31/5/2018
S1B_IW_GRDH_1SDV_20180612T170543_20180612T170608_011343_014D3F_3206	12/6/2018
1A descending products	**Date**
S1A_IW_GRDH_1SDV_20180512T051915_20180512T051940_021867_025C3D_C448	12/5/2018
S1A_IW_GRDH_1SDV_20180524T051916_20180524T051941_022042_0261CB_DB8F	24/5/2018
S1A_IW_GRDH_1SDV_20180605T051851_20180605T051916_022217_026754_234D	5/6/2018
1 B descending products	**Date**
S1B_IW_GRDH_1SDV_20180506T051814_20180506T051839_010796_013BC2_152D	6/5/2018
S1B_IW_GRDH_1SDV_20180518T051814_20180518T051839_010971_014165_CB64	18/5/2018
S1B_IW_GRDH_1SDV_20180530T051815_20180530T051840_011146_01471D_51A9	30/5/2018
S1B_IW_GRDH_1SDV_20180611T051816_20180611T051841_011321_014C98_AFE6	11/6/2018

3 METHODOLOGY

3.1 Sentinel-2 image pre-processing

The atmospherically corrected images were resampled to 10m resolution, and the study area was subset using a shape file of the study area provided by Ms. Chauhan.

3.1.1 Extraction of reflectance

Surface reflectance values were extracted automatically from the image for the wheat polygons using spectral extraction tool in SNAP software. A 5 by 5 pixel window was used which was slightly smaller than the sample plot area to stay within the plot and avoid selecting pixels that may go beyond the 60 x 60m sample plot boundary. For analysis, spectral values were extracted from the images as near as possible to the date of field data collection. For plots with no observed lodging, an image before the field observation date was used, for plots with some lodging observed, the image after the field observation date was used.

3.1.2 Calculation of vegetation indices

Two vegetation indices, the Normalized Difference Vegetation Index (NDVI) and the Integrated Red Edge Index (IRECI) were selected for lodging detection. Vegetation indices are created by combining one or two bands to characterize the vegetation status (Qi et al, 1994). NDVI is commonly used to detect vegetation health and the greenness of vegetation using the near-infrared and red bands while IRECI is an index that includes red edge bands that are important in detecting chlorophyll. During lodging there is reduced photosynthetic activities and water content in the plant that leads to plant stress that can reduce the chlorophyll content. Sanchez et al, (1983) in his study with maize concluded that change in water stress affects chlorophyll in maize and this can be studied in wheat. During lodging the plant structure changes and the stems will be included in the field of view thus changing greenness as a result of leaves and stems being in the field of view. The formulation for the two indices is given below:

$$NDVI = \frac{NIR - Red}{NIR + Red} \tag{1}$$

(Fernández-Manso et al, 2016)

$$IRECI = \frac{NIR - Red}{Rededge1 / Rededge2} \tag{2}$$

(Frampton, Dash, Watmough, & Milton, 2013)

3.2 Sentinel-1 image pre-processing

Preprocessing of Sentinel 1A/B descending and ascending images was executed using SNAP toolbox. The preprocessing steps are as follows;

1. Sub-setting: The study area shapefile was used to subset the images.
2. Apply orbit file: This was done to update the orbit information in SAR metadata to enable accurate satellite position.

3. Radiometric calibration: This process was for calibrating and converting intensity values to represent the true backscatter.
4. Image stacking: Was done to prepare the images for multitemporal speckle filtering and then the images were co-registered using a high-resolution SRTM 3-sec DEM.
5. Multi-speckle filtering: The process was conducted to reduce granular noises inherent in SAR images. A box filter with a 5 x 5 window size was used.
6. Terrain correction: This process was performed to remove the topography distortions. Range doppler correction was used to correct for geometric distortions that occur during the acquisition of SAR images. The
7. Conversion of DN values from linear to decibels was finally performed to obtain backscatter intensity in decibels.

3.2.1 Extraction of backscatter/backscatter ratio

Mean backscatter values for VV and VH polarizations for each sample plot were extracted automatically, using the spectral tool in the SNAP toolbox. A 5 by 5 by pixel window was used representing a 50m by 50m area on the image being that the pixel size was 10m by 10m. Backscatter values were extracted from the closest image to field data collection date of each sample point. For non-lodged sample plots the closest image acquisition date before observation date was used, whereas for lodged sample plots the closest image acquisition date after the observation date was used. The VH/VV ratio was calculated by subtracting VV from VH (subtraction is the correct formulation for computing the ratio of two logs).

3.3 Exploratory analysis

Scatter plots and box plots of reflectance, vegetation indices and backscatter values for logded and non-lodged wheat fields at milking and flowering stages were studied to visualise differences in these values against lodging area percentage and to determine a suitable threshold to group the samples into lodged and non-lodged.

3.4 Statistical test of significance

The non-parametric Kruskal-Wallis test (also known as a one-way ANOVA on ranks) was used to determine if there was a statistical difference in the reflectance, vegetation indices and backscatter values between the two groups (lodged and non-lodged). The separate of the dataset into lodged and non-lodged is explained in the results section. Kruskal-Wallis was used because the sample sizes for the two groups were not equal. The formula for Kruskal-Wallis is given as.

$$H = (N-1)\frac{\sum_{i=1}^{g} n_i(\bar{r}_{i\cdot} - \bar{r})^2}{\sum_{i=1}^{g}\sum_{j=1}^{n_i}(r_{ij} - \bar{r})^2}, \text{ where:}$$

- n_i is the number of observations in group i
- r_{ij} is the rank (among all observations) of observation j from group i
- N is the total number of observations across all groups
- $\bar{r}_{i\cdot} = \frac{\sum_{j=1}^{n_i} r_{ij}}{n_i}$ is the average rank of all observations in group i
- $\bar{r} = \frac{1}{2}(N+1)$ is the average of all the r_{ij}.

(3)

https://en.wikipedia.org/wiki/Kruskal%E2%80%93Wallis_one-way_analysis_of_variance

3.5 Software used

The software used were Sentinel Application Platform (SNAP) for image processing, Microsoft Excel and R for statistical analysis and plotting of results and Microsoft Word for research writing.

4 RESULTS

The section presents the findings based on the analysis of backscatter, reflectance and vegetation indices by lodging area percentage and then between two subsets of the data labelled as lodged and non-lodged sample plots. The analysis considers two growth stages of wheat i.e flowering and milk. Further, both stages were grouped together to increase the sample size and also analysed.

4.1. Changes in SAR backscatter in relation to lodging area percentage

Having no much difference between varieties the backscatter was analyzed for flowering, milk and combined flowering and milk stages. Figure 5 presents the changes in backscatter of VH polarization for all samples in the wheat growing stages of flowering, milk and both stages combined. There is an increase in backscatter in VH polarization from around -19/-22 dB to -12/-14 dB with increasing percentage lodging in both the flowering and milk stage and when both the stages are combined.

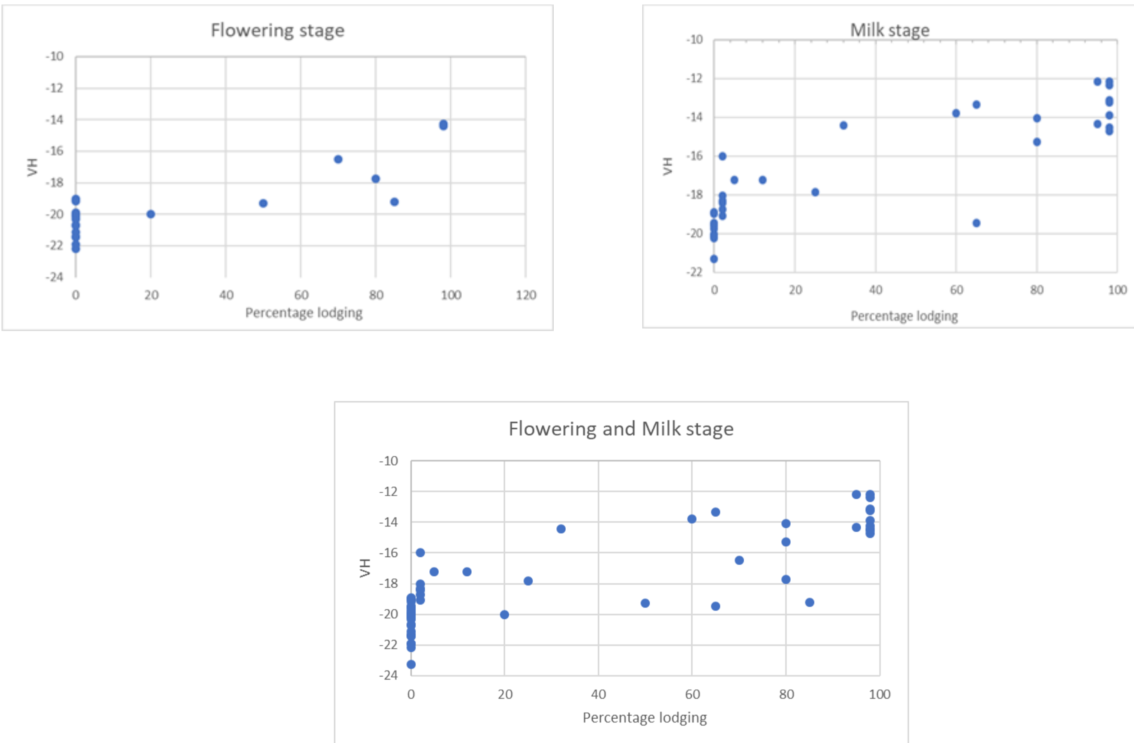


Figure 5. Change in VH backscatter with increase in lodging percentage in the flowering, milk and combined flowering and milk stage.

Figure 6 shows the change in backscatter with percentage lodging in VV polarization. The results show a general increase in the backscatter with the percentage lodging from -12/-15 dB to -7/-9 dB in both the stages of wheat growth and when both the stages were combined.

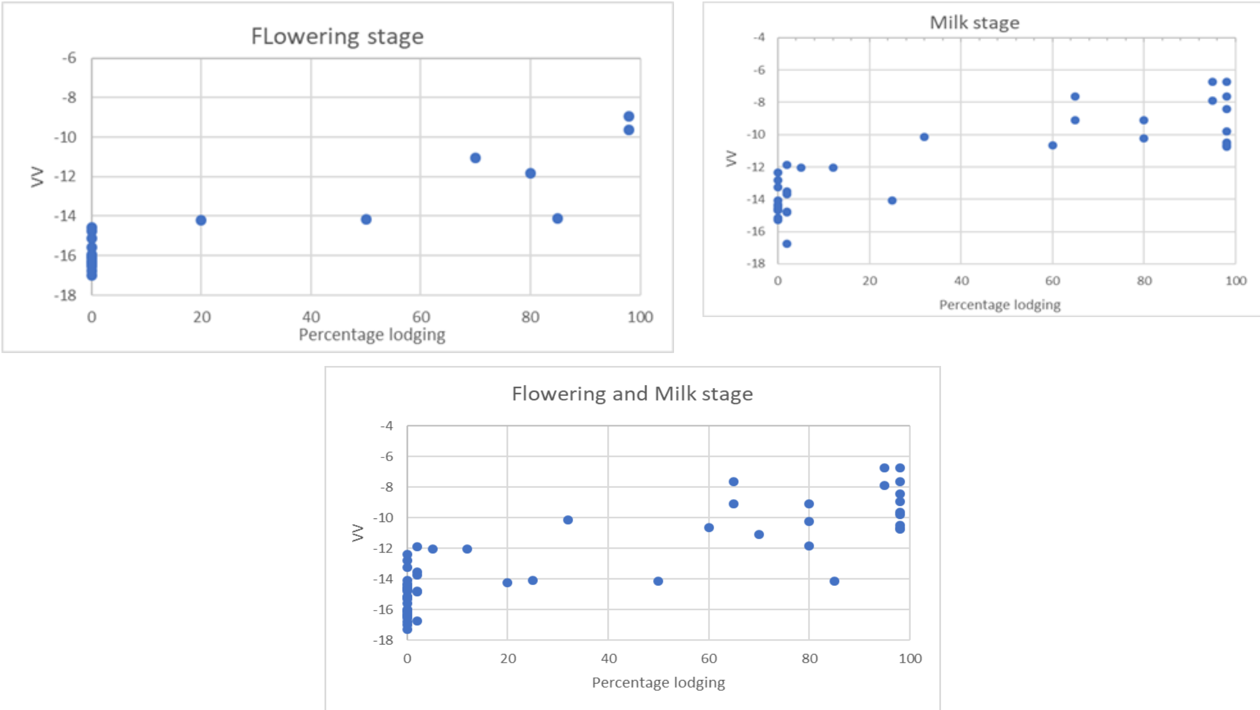


Figure 6. Change in VV backscatter with increase in lodging percentage in the flowering, milk and combined flowering and milk stage.

The results in Figure 7 show that the VH/VV ratio seems to be relatively constant with change in percentage lodging. This is to be expected given that both VH and VV increased with lodging percentage and hence the ratio between the two remains relatively constant.

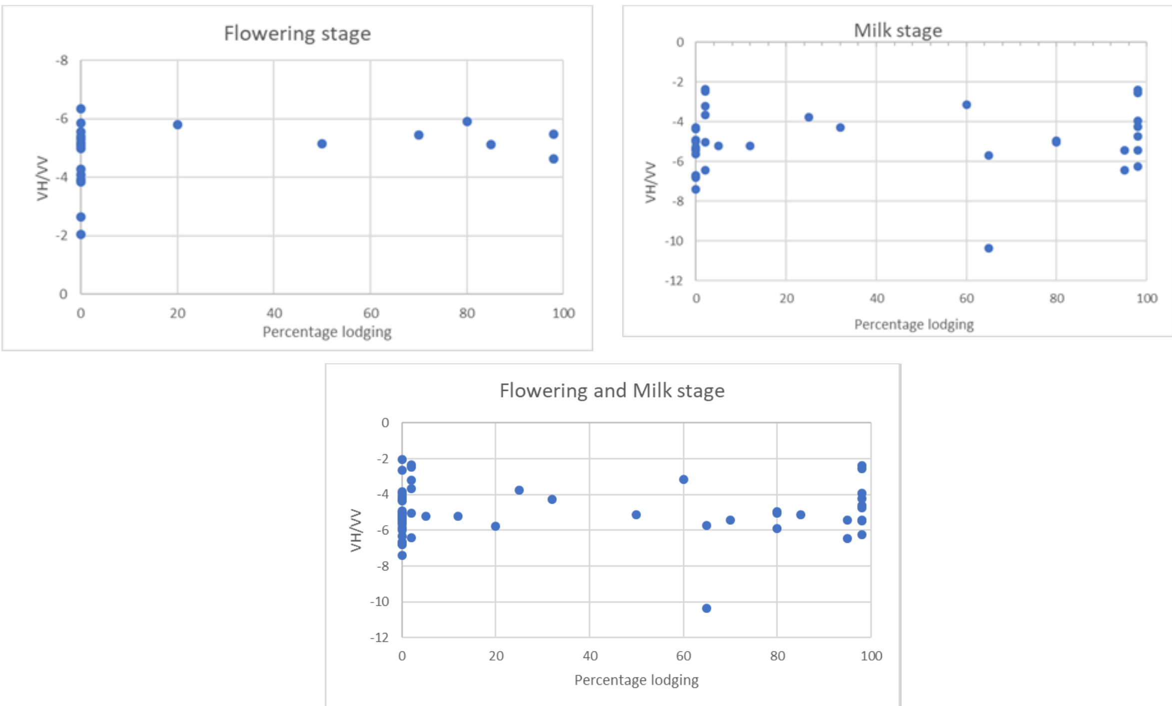


Figure 7. Change in the VH/VV ratio with increase in lodging percentage in the flowering, milk and combined flowering and milk stage.

4.2 Changes in reflectance and vegetation indices in relation to lodging percentage

The samples for different varieties show changes in reflectance with percentage lodging, (Figure 8). The reflectance in all bands increased with percentage lodging in both the flowering and milk stage for almost all the varieties but the increment is different in various bands. The difference in reflectance due to varieties including the Senatore Capelli which is the tall variety. was observed to be smaller than then the difference in reflectance due to lodging and so the varieties were pooled into one sample for further analysis of reflectance and vegetation indices with respect to lodging area percentage.

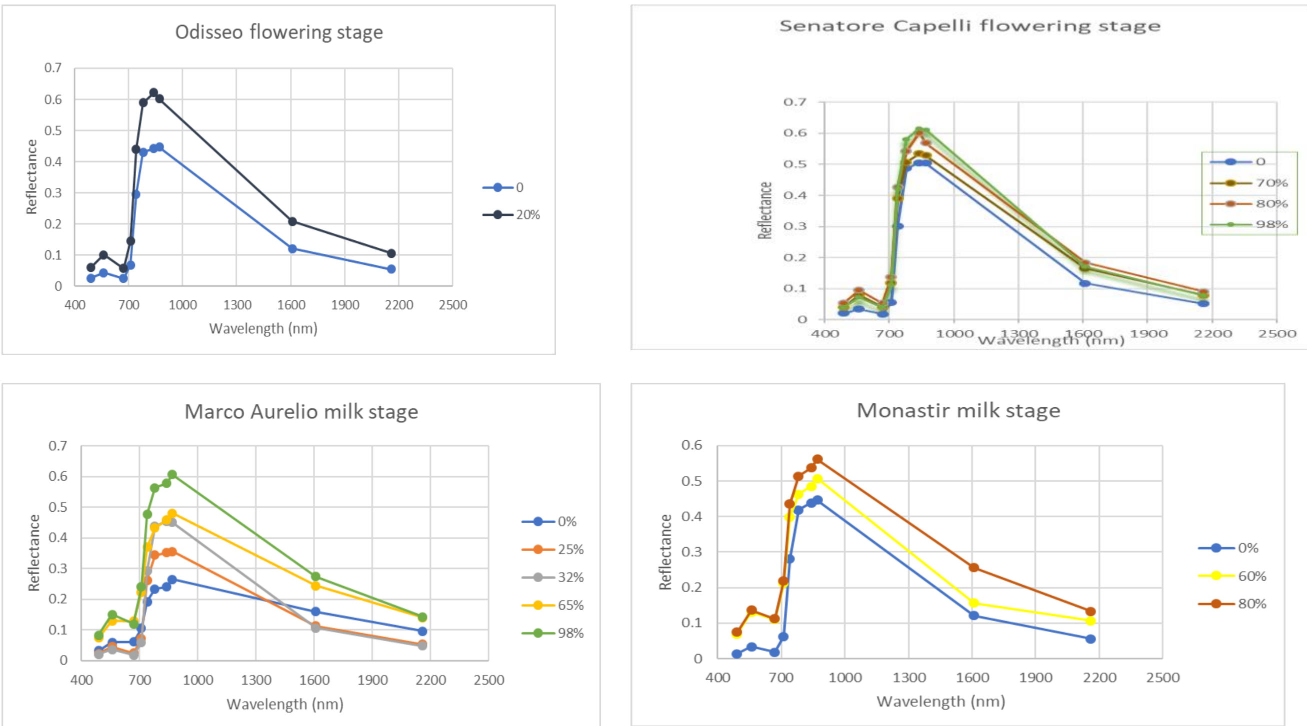


Figure 8. Change in reflectance for different crop varieties with increase in lodging percentage

Given the large number of bands in Sentinel-2, we show a selection of bands in this section that represent the general observed relationships between lodging area percentage and reflectance.

The reflectance in the Red-edge1 wavelength increases with percentage lodging in both the flowering and combined flowering and milk stage as shown in Figure 9.

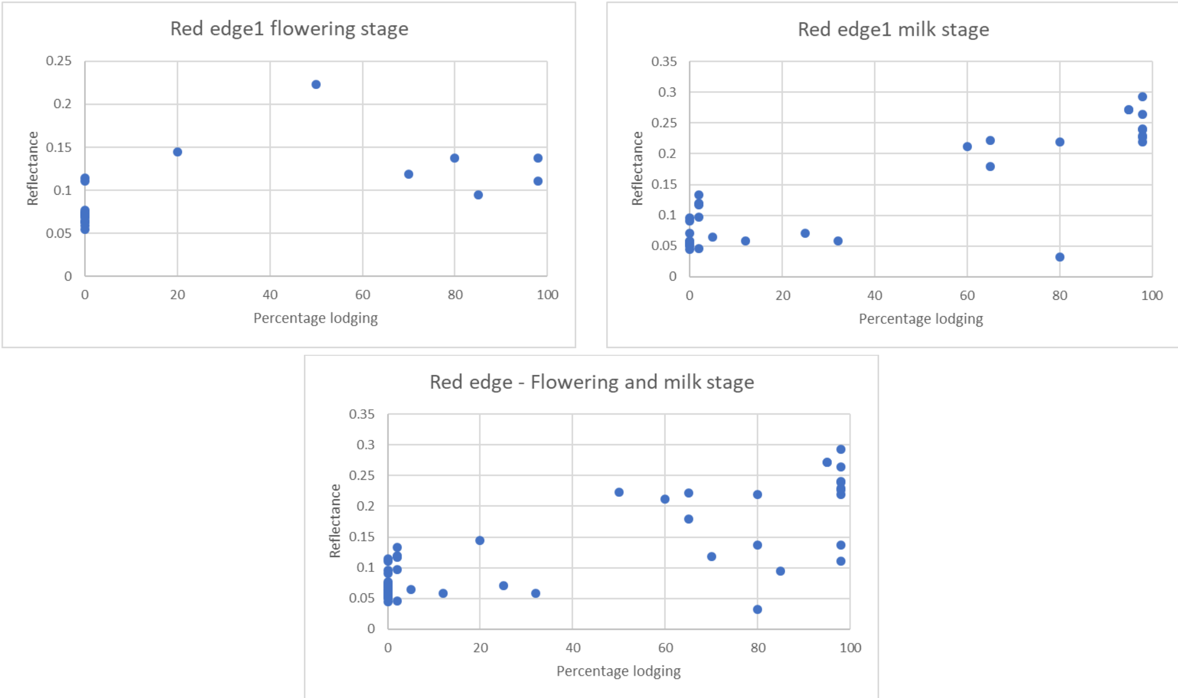


Figure 9. Change in red edge-1 reflectance with increase in lodging percentage in the flowering, milk and combined flowering and milk stage.

The reflectance in the green band increases both in the milk and in the combined milk and flowering stage (Figure 10).

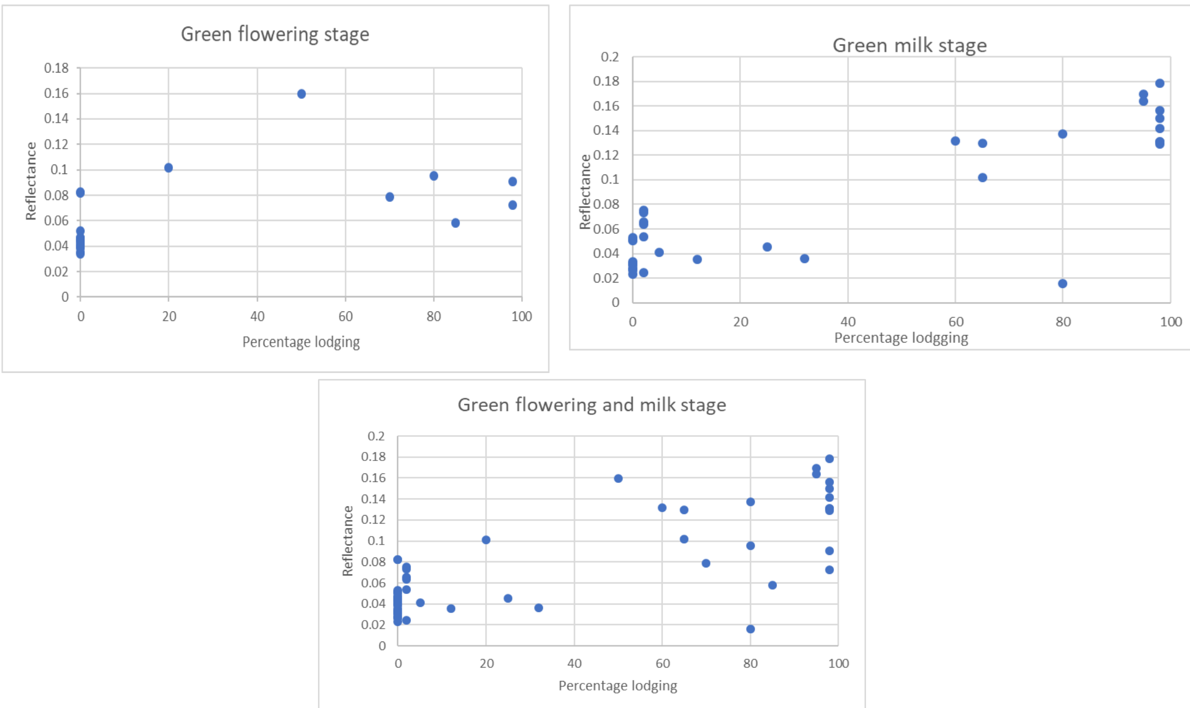


Figure 10. Change in green band reflectance with increase in lodging percentage in the flowering, milk and combined flowering and milk stage.

The reflectance in the SWIR increases in the milk and combined milk and flowering but there was not much increase in flowering stage. (Fig 11)

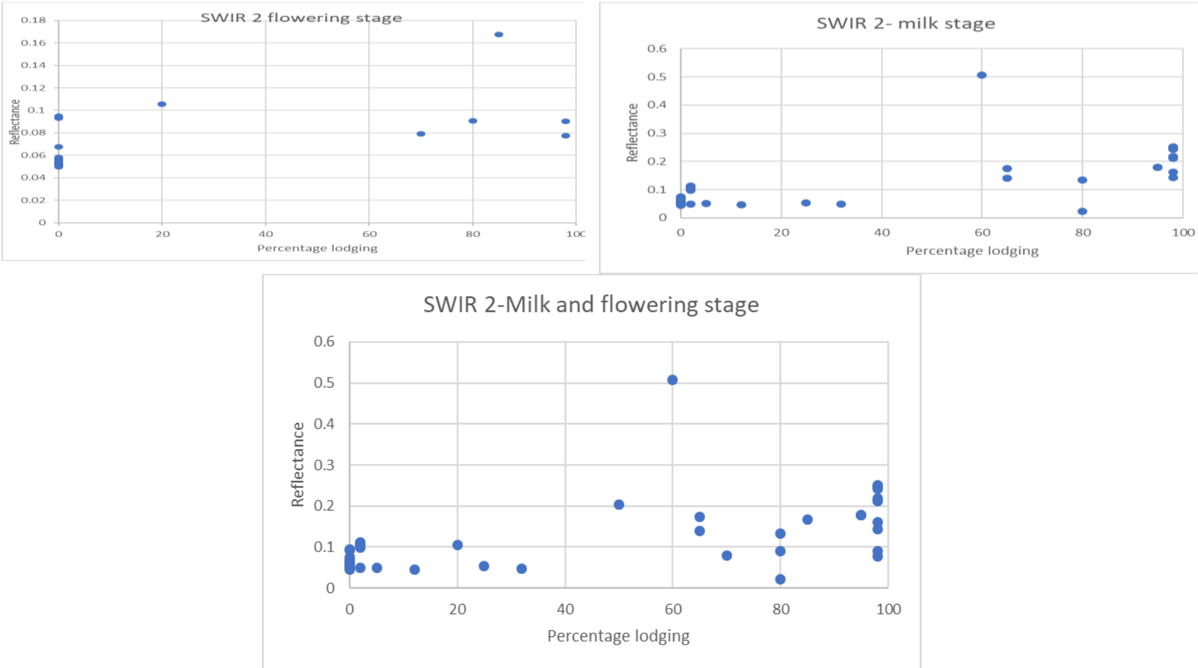


Figure 11. Change in SWIR reflectance with increase in lodging percentage in the flowering, milk and combined flowering and milk stage.

The values for NDVI in the milk stage decrease as percentage lodging increases, whereas there is little change during the flowering stage and in the combined milk and flowering stages (Figure 12)

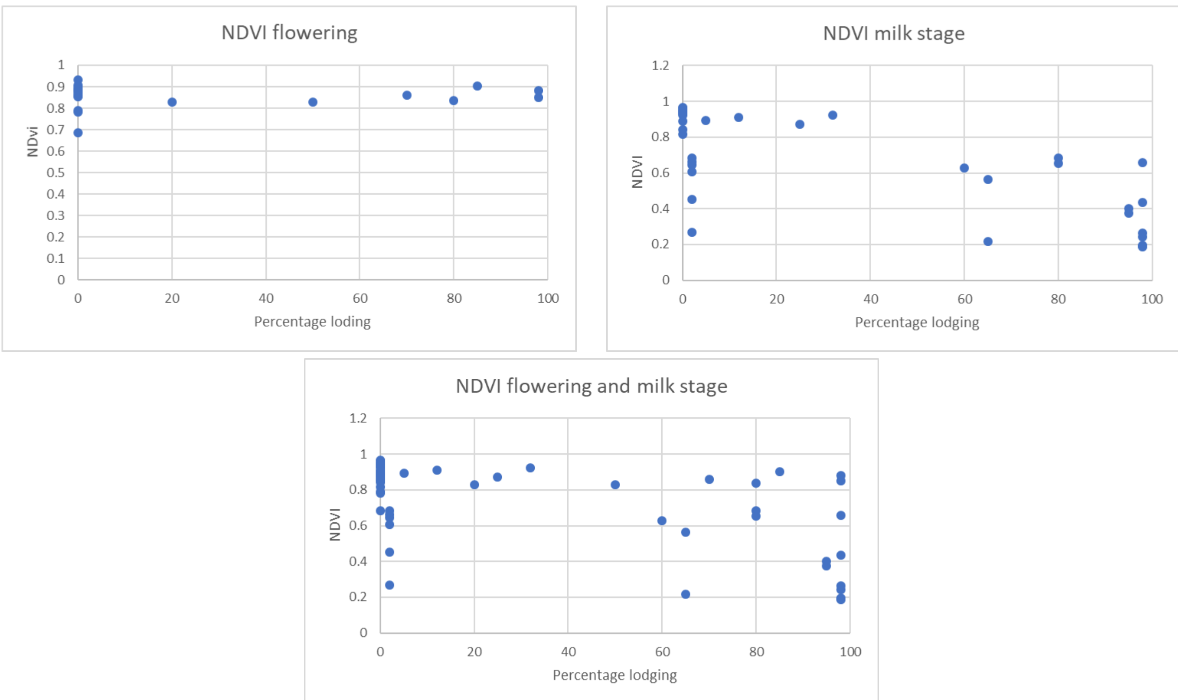


Figure 12. Change in NDVI with increase in lodging percentage in the flowering, milk and combined flowering and milk stage

IRECI values (Figure 13) do not change much with the percentage lodging in the flowering and both flowering and milk stage. There is a slight increase in the backscatter values in the milk stage.

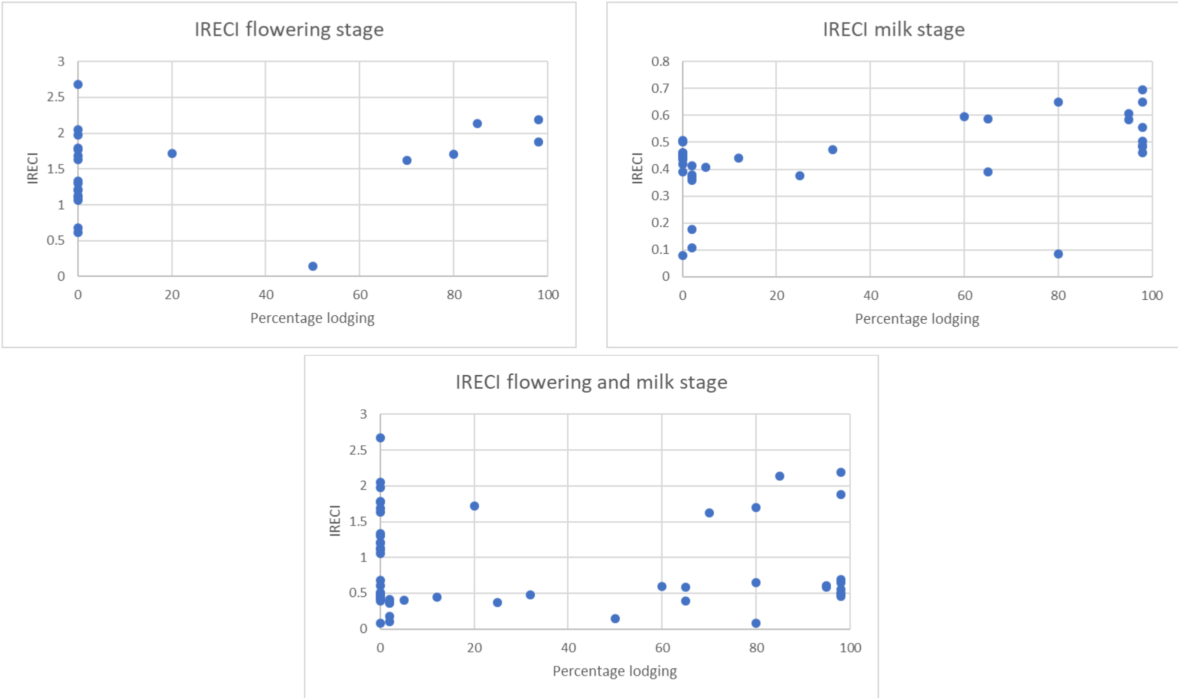


Figure 13. Change in IRECI with increase in lodging percentage in the flowering, milk and combined flowering and milk stage.

4.3 Identification of the best polarization for lodging detection

Threshold setting

After a visual inspection of the distribution of lodging percentage across the plots it was observed that a cluster of plots had lodging area percentage values of zero or less than 20% and another cluster had values above 60%. Based on this, a threshold was set at 50% where any plot with 50% or less of its area lodged was labelled as non-lodged and any plot with more than 50% of its area lodged was labelled lodged. Figure 14 shows an example of reflectance in the green band for all plots with a vertical line representing the 50% threshold and a horizonal line showing that most plots on the left of the line have low reflectance and most points on the right side have higher reflectance.

The field plot data were separated into two groups and the Kruskal-Walles test was applied to test whether the samples in the groups originated from the same distribution. There were 14 plots in the non-lodged group and 13 plots in the lodged group

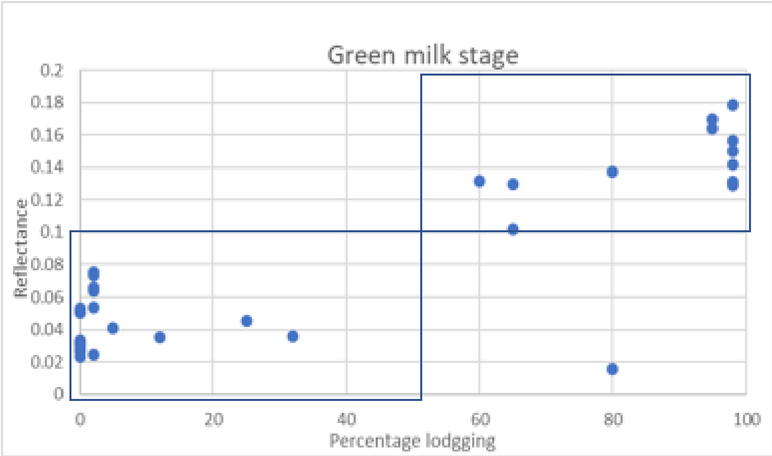


Figure 14. A visual representation of the 50% threshold using the green band as example.

The box plots in Figure 15 suggest that based on VH polarization, the lodged and non-lodged wheat can be differentiated since the lodged wheat have a higher median value and there is no overlap in the interquartile ranges.

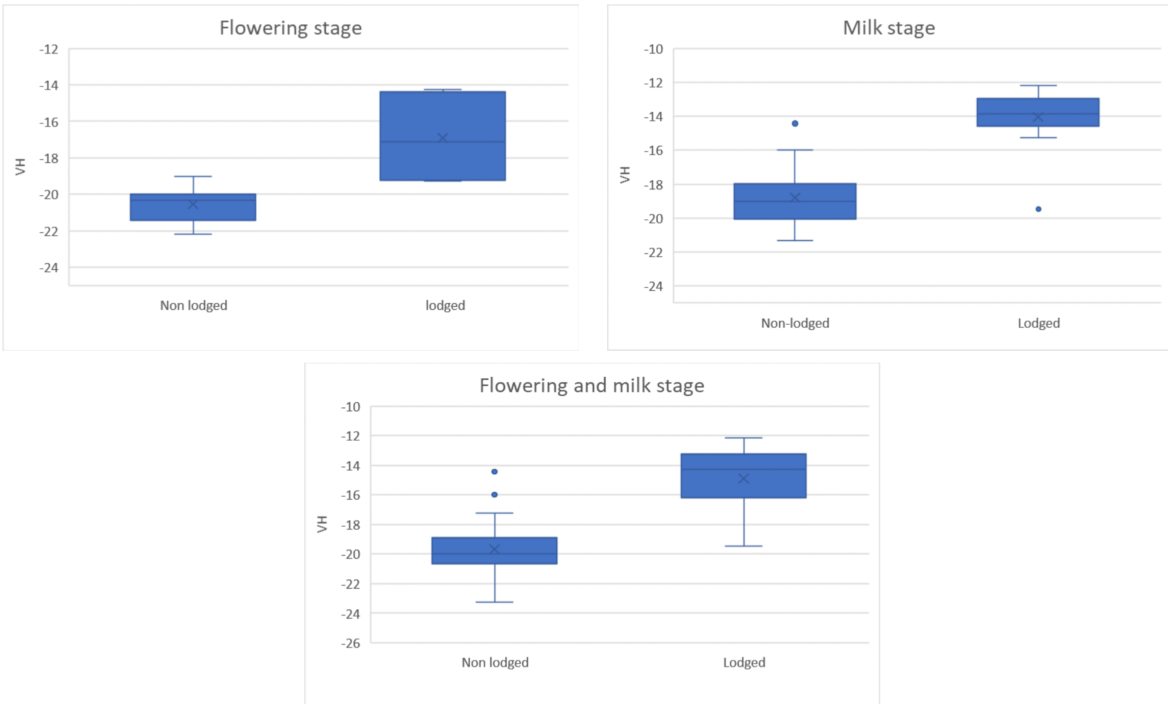


Figure 15. Box plot for lodged and non-lodged wheat at flowering, milk and both stage combined in VH polarization

The box plots in Figure 16 show that based on VV polarization, the lodged and non- lodged wheat can also be differentiated since the lodged wheat have a higher mean.

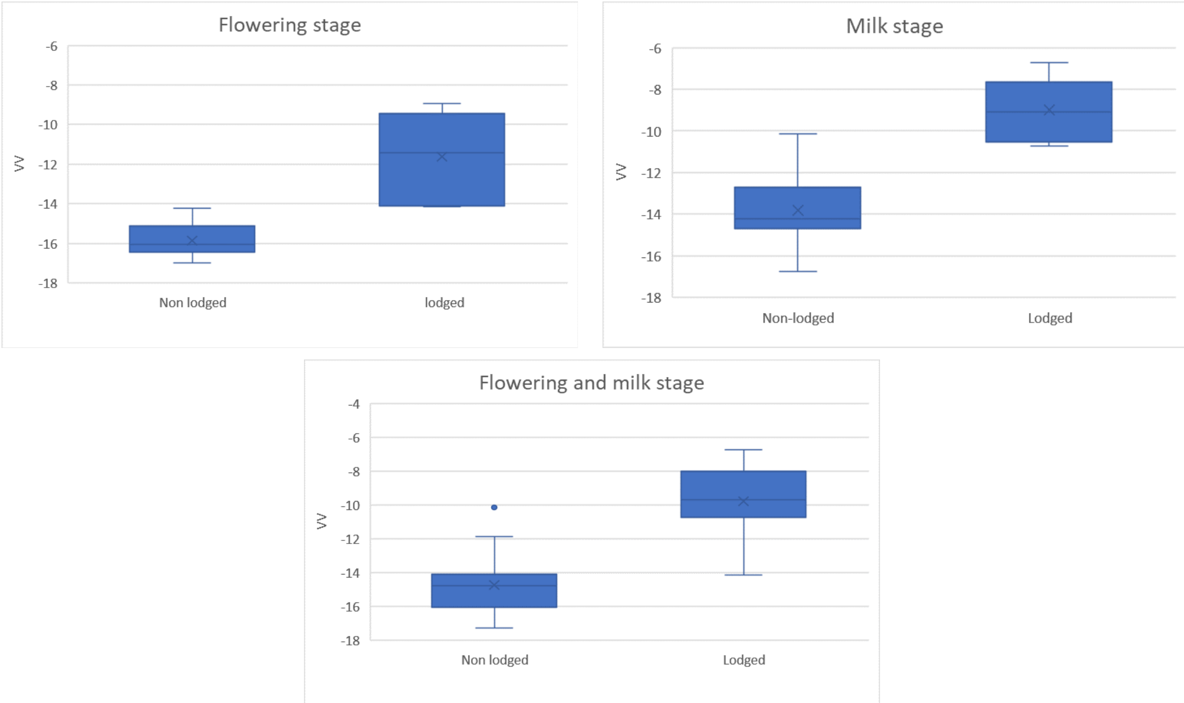


Figure 16. Box plot for lodged and non-lodged wheat at flowering, milk and both stage combined in VV polarization

The results in Figure 17 show that the mean of box plots for VH/VV polarization for the lodged and non-lodged wheat fields is almost the same in the flowering, milk and the combined flowering and milk stages. This makes it difficult to use this band ratio to distinguish the lodged and non-lodged wheat fields.

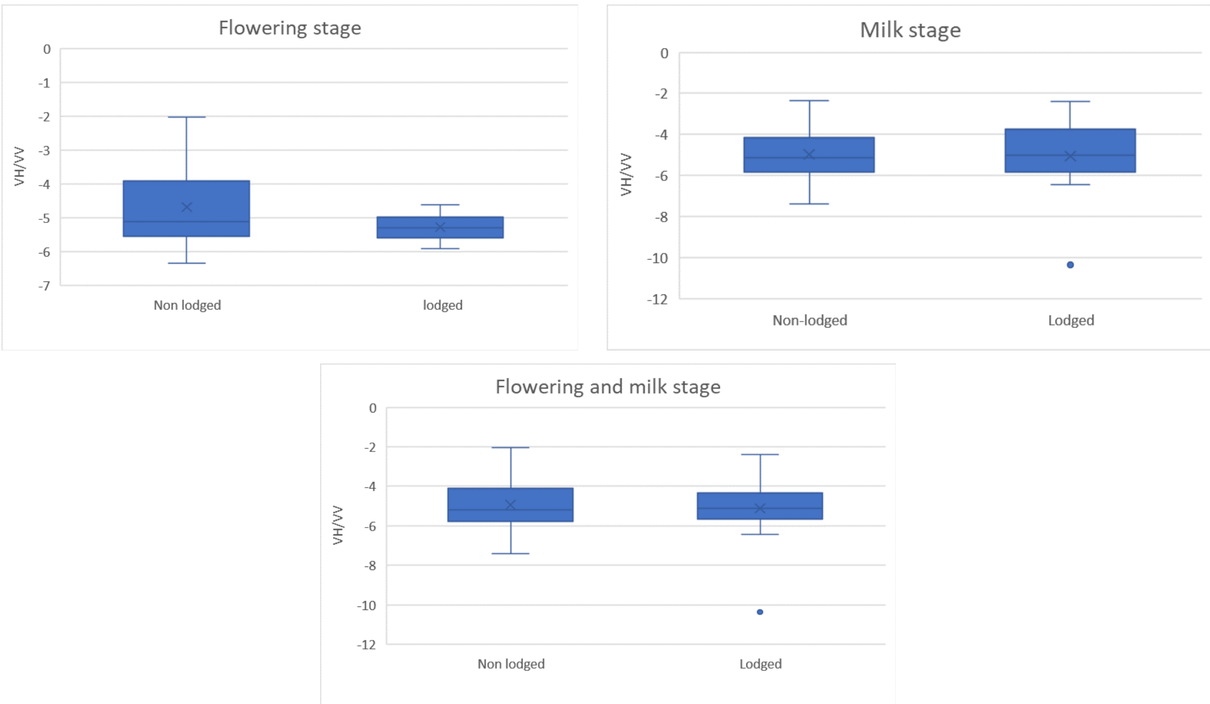


Figure 17. Box plot for lodged and non-lodged wheat at flowering, milk and both stage combined in VH/VV polarization

The results of the Kruskal-Wallis significance test for differences in backscatter between lodged and non-lodged samples are summarized below. The p values in Table 4 indicate highly significant differences in backscatter in both VH and VV polarizations between lodged and non-lodged samples in flowering, milk and the combined stages. As expected, based on the scatterplots and boxplots, there is no significant difference in the band ratio. Non-significant p values (>0.05) are shown in red in the table.

Table 4. p values for VH, VV, VH/VV polarizations

Growth stage	Bands	p-value
Flowering stage	VH	9.9953e-04
	VV	3.5601e-04
	VH/VV	0.6241
Milk stage	VH	6.0101e-07
	VV	1.8532e-07
	VH/VV	0.0016
Flowering and milk stage	VH	5.6829e-08
	VV	7.4311e-09
	VH/VV	0.8854

4.4 Identification of best spectral band and vegetation index for lodging detection

The results in Figure 18 indicate that there is a change in reflectance between the lodged and non-lodged wheat samples in all the bands. In the flowering stage, there is an increase in reflectance but it varies from band to band. In the milk stage, the reflectance for the lodged wheat is less for the NIR-1, Red-edge2 and Red-edge3.

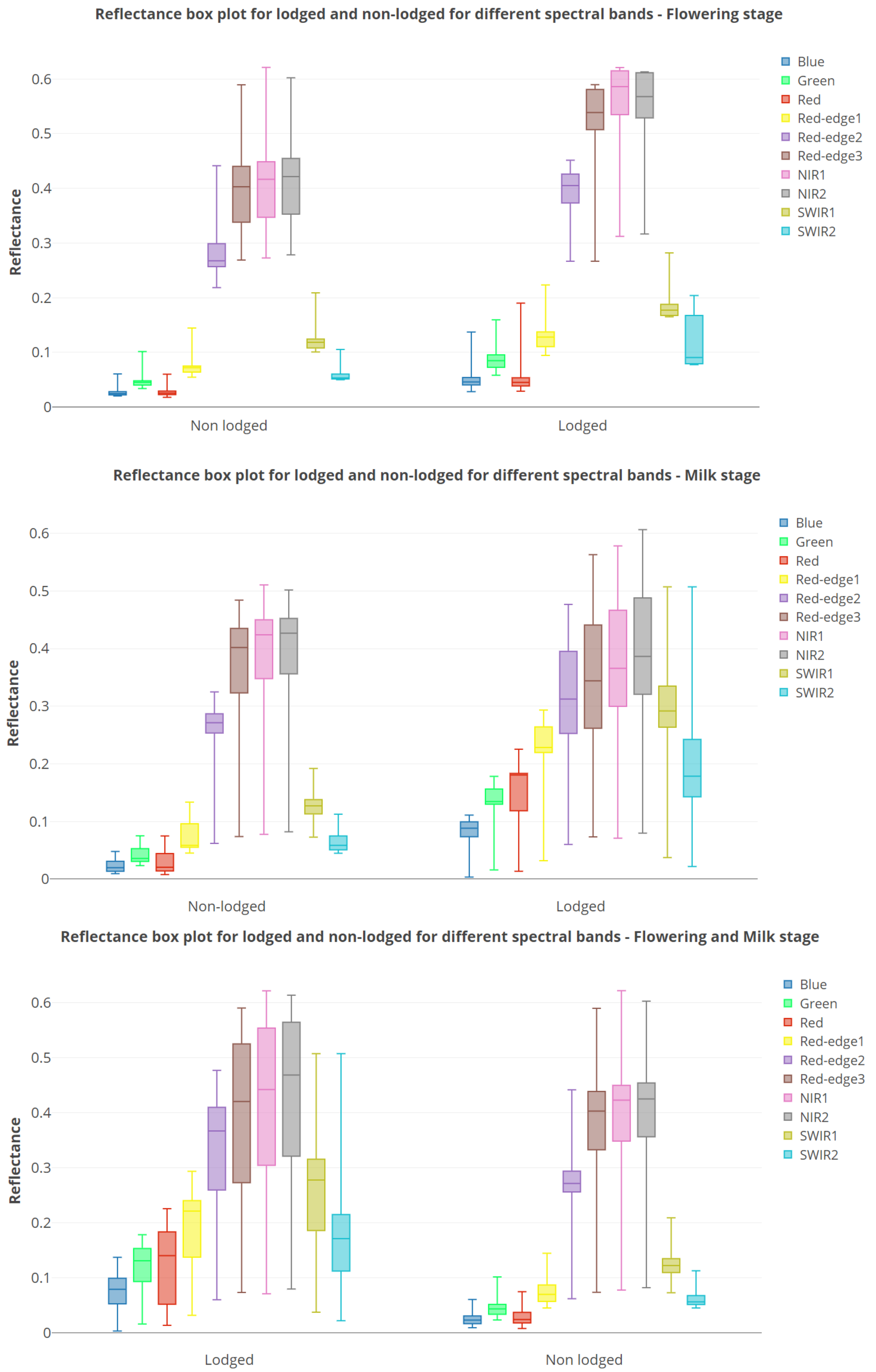
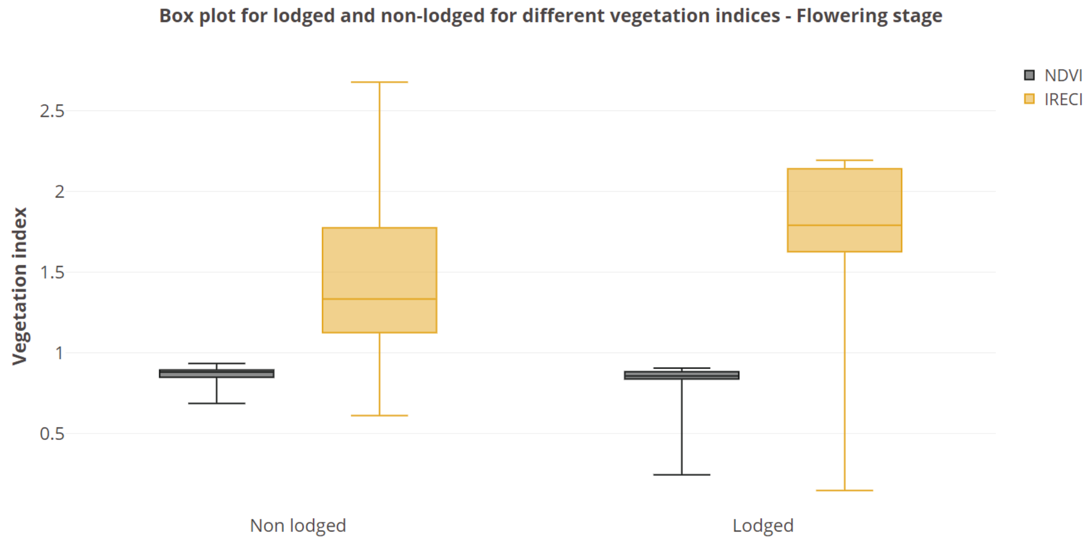
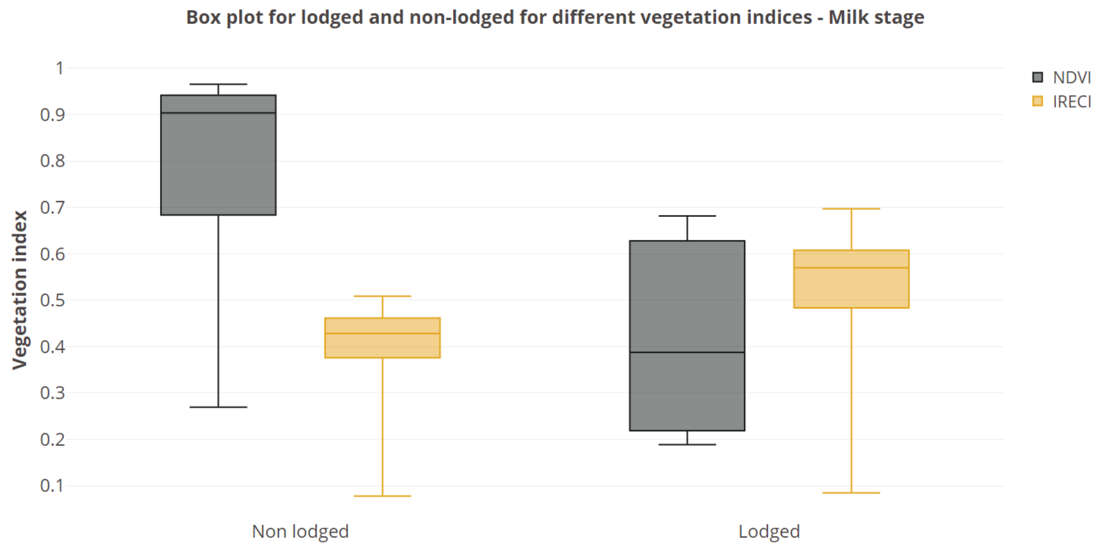


Figure 18. Box plots representing reflectance for lodged and non-lodged samples in the flowering stage, milk stage and combined flowering and milk stage.

The results in Figure 19 show that the IRECI vegetation index is better in distinguishing the lodged and non-lodged wheatfields. The mean of the lodged and non-lodged samples are quite different whereas for NDVI the mean value is the same. In the milk stage, the mean for the box plot for NDVI for the lodged is low compared to the non-lodged, and thus the two groups can be separated.





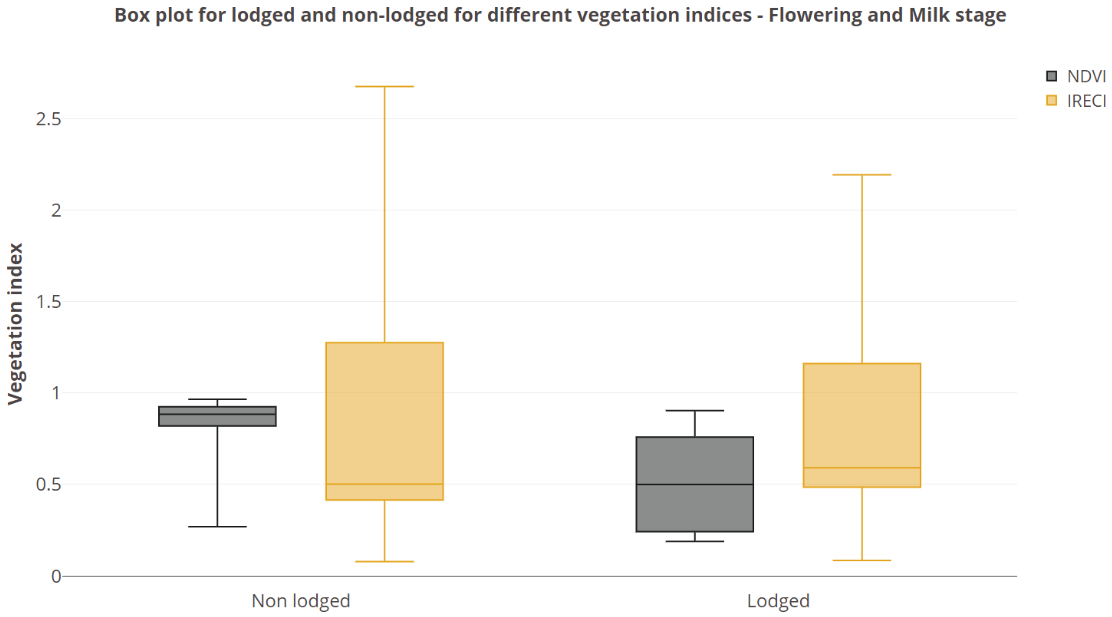


Figure 19. Box plots are representing NDVI and IRECI variation for lodged and non-lodged in the flowering stage, milk stage and combined flowering and milk stage.

Table 5 presents the p values from the Kruskall-Wallis tests as a measure of the significance of the difference in reflectance and vegetation indices between lodged and non-lodged sample plots and as a means of identifying the best band(s) or vegetation indices for detecting lodging. All bands show significant differences the flowering stage, whereas Blue, Green, Red, Red-edge1 and SWIR_2 are significant in both crop stages. The two vegetation indices show significant differences between lodged and non-lodged only in the milk stage. while Red edge, NIR_1 and NIR_2 are significant during the flowering stage.

Table 5. p values for different spectral bands and vegetation indices

Bands	Flowering stage	Milk stage	Flowering and milk stage
Blue	0.0143	1.8406e-05	1.7868e-07
Green	0.0051	1.8406e-05	8.8756e-08
Red	0.0117	8.7628e-06	6.9040e-07
Red-edge1	0.0033	1.8406e-05	1.2618e-07
Red-edge2	0.0078	0.1887	0.0190
Red-edge3	0.0357	0.5812	0.6196
NIR_1	0.0357	0.5812	0.4517
NIR_2	0.0357	0.6731	0.3208
SWIR_1	0.0251	0.8711	2.5201e-07
SWIR_2	0.0041	1.8406e-05	3.2531e-07
NDVI	0.3627	1.5899e-05	3.9928e-06
IRECI	0.2936	6.5622e-04	0.4141

5. DISCUSSION

In this study, the ability of Sentinel-1 and Sentinel-2 data to detect wheat lodging is explored for the first time. Field samples from lodged and non-lodged wheat fields were studied at two crop stages to understand the changes in 1) backscatter and 2) reflectance and selected vegetation indices and to identify 3) the best polarization and 4) spectral bands as well as vegetation indices to detect lodging using Sentinel-1 and Sentinel-2 data.

5.1 Analysis of backscatter data from Sentinel-1

The results of this study showed that lodged samples generally had higher backscatter values in both polarizations and in both growing stages for VH and VV polarization. The backscatter from VH and VV polarizations increased with the percentage lodging at different wheat growing stages. This is consistent with the study by Son et al. (2018), who used Sentinel-1 data and noted that the backscatter signal responds differently to plants with different canopy structures and the backscatter values depends on the shape and orientation of leaves such that crops with different orientations will have different backscatter values and can be related to changes in orientation due to lodging.

In relation to studies that were specifically about lodging, Bouman et al. (1990), using ground-based X-band (3-cm waves) radar backscattering, also found that lodging increased the backscatter of crops. This increase is caused by the changes in vegetation structure as the arrangement of leaves and stems differ between lodged and non-lodged plants when the stems bend. Healthy plants generally are in upright position while lodged plants are non-vertical which leads to a different interaction between the SAR signal and the crop. Another explanation is that multi scattering occur from the combination of the stems and leaves in the lodged plants increasing the backscatter since more stems will be visible in the overhead field of view than for the non- lodged. In this thesis, we show that the same holds true when using satellite-based C-band SAR data, suggesting that Sentinel-1 can be used to identify wheat crop lodging over a large areas. Here we also explored the relationship in two different growth stages. Moreover, Zhao et al., (2017) in his study found that HV and VV polarization increased after lodging in wheat and Canola using Radarsat-2 sensor.

5.2 Analysis of reflectance and vegetation indices

The results of this study showed that the reflectance increased with the percentage lodging for different crop varieties. This result is similar with the result from Liu et al. (2012) who used an ASD FieldSpec Pro FRTM Spectroradiometer and found that the canopy reflectance increased from visible to SWIR bands when lodging occurred. The bands used by Liu et al. (2012) are similar to the blue, green, red, NIR and SWIR bands in Sentinel-2. While visible bands and NIR bands can be used to detect changes due to crop structure, SWIR spectral bands can be used to detect moisture changes in the crops which will increase as a result of lodging (Ji et al., 2011). On contrary, Wang et al. (2018) in his study demonstreated that reflectance in the visible and NIR could not be used to detect lodging. Based on my assumption this could be as a result of the intensity of lodging. Spectral properties of the non-lodged and slightly lodged plants may not be very distinct, and that is why a threshold was set in this study to separate the two groups. The results in this thesis agree with Liu et al. (2012) though here we use broadband multispectral Sentinel-2 data as opposed to narrowband hyperspectral data.

It was observed in this study that NDVI values at the milk stage decreased with increases in percentage lodging. This result confirms the result of the study by Liu et al. (2015) who found that NDVI decreased with lodging angle (severity). However, thier study was not based on samples from different crop growth stages as only two images were used (an image before and after lodging). In this study, when data from both flowering and combined flowering and milk stage were used, the NDVI values remained constant when the percentage lodging increased.

5.3 Best polarization for discriminating between lodged and non-lodged wheat crops

The results of our analysis showed that in comparison to VV and the VH/VV ratio, the data from VH polarization was most promising for detecting crop lodging at all the crop growing stages (p values for VH polarization were in the flowering stage were 9.9953e-04 and 5.6829e-08 in the milk stage). This is because VH polarization is more sensitive to changes in crop structure from vertical to horizontal which is accompanied by height changes that causing an increase in the return signals between the lodged and non-lodged crops. Cross polarizations such as VH increases due to multiple scattering effects (Yang et al., 2015). Cross polarization will, therefore, be more sensitive to the combination of more the stems that will be visible in the overhead field of view for the lodged plants.

5.4 Best reflectance bands and VIs for discriminating between lodged and non-lodged wheat crops

Spectral bands that were sensitive to wheat lodging were blue, green, rededge_1 (705 nm), and SWIR2 (2210 nm) at all the milk and flowering crop stages as well as the two stages combined. The p values were 0.0143, 1.8406e-05, 1.7868e-07 for blue in the flowering, milk and combined milk and flowering. The rest were as follows respectively in the three groups: 0.0051, 1.8406e-05, 8.8756e-08 for green, 0.0117, 8.7628e-06, 6.9040e-07 for red, 0.00331,06e-05, 1.2618e-07 for red edge 1.

NDVI could distinguish between the lodged and non-lodged wheat fields at the milk stage but not at the earlier flowering stage. Based on the literature, SWIR bands are useful in detecting plant moisture content while the spectral bands from the visible will detect changes in reflectance due to changes in plant structure (Ji et al, 2011). Red edge bands are sensitive to changes in chlorophyll content. Lodging causes plant stress due to a decrease in water content. This can interfere with chlorophyll production(Sanchez et al.,. 1983). Therefore, the red edge bands are important as well in monitoring lodging.

5.5 Discussion on the data used in this study

The data used in this study consisted of Sentinel-1 intensity data, Sentinel-2 reflectance and VI data and field observations of the % area of wheat in 60 x 60 m plots that was lodged during two wheat growing stages (flowering and milk). The Sentinel-1 satellite data consisted of ascending and descending modes. Sentinel-2 data had the problem of cloud cover, and hence some images during the milk stage could not be used. Both sensors provided sufficient information to detect crop lodging, despite the missing optical images in the timeseries. Both Sentinel-1 and Sentinel-2 data could be obtained at a short revisit period in order to tally them with the timing of field data collection. Being that the field data included two different crop growth stages, separate analysis had to be done for the different growth stages as well as the combination of both to determine the changes in reflectance or polarization. One constraint is that the field observations were limited to few samples at each growth stage and only a few (four) sample plots were revisited more than once. Hence it was not possible to perform time series analysis which would be very useful to determine if Sentinel data can be used to detect the approximate timing of lodging.

5.6 Discussion on the methods used in this study

Only two vegetation indices - NDVI and IRECI - were used in this study. Further analysis is required utilizing various vegetation indices and multi variate methods where a number of spectral bands could be studied simultaneously. Non-parametric statistical tests were conducted to test the significance of spectral bands and polarizations to detect lodging. Other methods can be used to improve the result of such analysis such as machine learning algorithms.

We split the sample into two samples, lodged and non-lodged and tested for significant differences in SAR intensity, reflectance and Vis between the two groups. The selection of the threshold, 50% lodged area, was based on the distribution of % lodged area data. There were many points with no or low lodged area (<20% lodged area) and many points with very high (>60% lodged area) and the 50% threshold was chosen because it lay between these two groups. With a larger set of data points (as mentioned above), it may be possible to identify more than two groups, such as no lodging, moderate and severe lodging.

5.7 Future work

- The Liu et al. (2015) study was one of the few studies who utilzed an optical sensor, and so there is very little literature on the use of optical RS data for lodging detection and there is potential for further research to relate reflectance, texture and a range of spectral indices to (i) lodging affected area and (ii) the severity of lodging (i.e. angle of inclination).
- Crop height is an important factor for detecting crop lodging and the use of LiDAR or structure-from-motion approaches would generate point cloud information and high resolution digital canopy surface models that could be used to estimate lodging area.
- Here, we only considered Sentinel-1 and Sentinel-2 data separately, but with a great number of field data points, both data could be used together to develop a model, based on multiple regression models or non-parametric approaches, that relates changes in intensity, reflectance and Vis to lodged area lodging intensity.

5. CONCLUSION

6.1 Main findings

In this study, Sentinel-1 data and Sentinel-2 data were used for the first time to detect wheat lodging in two different crop stages. The lodged and non-lodged wheat fields could be distinguished using information from either platform.

Research question 1
Does backscatter intensity from Sentinel-1 change with percentage lodging?

It was found that the backscatter increased with the percentage lodging in both the VH and VV polarizations while it did not change much in the VH/VV ratio.

Research question 2
Does reflectance and vegetation indices from Sentinel-2 change with percentage lodging?

The reflectance changed with the percentage lodging but with the band to band variation. IRECI vegetation indices did not change with the percentage lodging in both the flowering and milk stage crop growing stages, but NDVI values decreased with percentage lodging during the milk stage but not in flowering stage.

Research question 3
Which are the Sentinel-2 bands and vegetation indices that can be used to detect wheat lodging?

Visible, Red edge bands and SWIR-2 (2210 nm) band could significantly detect the percentage lodging. IRECI vegetation index was significant in the flowering stage while NDVI was significant in the milk stage.

Research question 4
Which Sentinel-1 polarization can best detect wheat lodging?
The VH polarization performed better in discriminating between lodged and non-lodged wheat than VV and the VH/VV ratio, thus it could be considered as the best polarisation to detect crop lodging.

6.2 Recommendations

The following can improve further research on this topic;

1.The number of field data at each crop growth stage should be increased
2.The wheat field could be revisited several times so that changes in lodging can be monitored over time.
3. Multivariate methods or other vegetation indices such as Normalized Water Index, which is sensitive to changes in moisture content over time, could be included to enhance the lodging detection.

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Appendix 1:Field data

1	Crop	Crop variety	Sowing date	uisition(YYYY-MM-	Lod_area(%)_flower	4	Lod_area(%)_milk/dough
2	Durum wheat	Senatore Capelli	31-Oct-17			2018-06-05T12:44:45Z	98
3	Durum wheat	Marco Aurelio	31-Oct-17			2018-06-05T12:00:45Z	2
4	Durum wheat	Marco Aurelio	31-Oct-17			2018-06-05T10:53:13Z	2
5	Durum wheat	Marco Aurelio	31-Oct-17			2018-06-04T08:38:07Z	2
6	Durum wheat	Marco Aurelio	31-Oct-17			2018-06-04T09:33:15Z	2
7	Durum wheat	Senatore Capelli	28-Oct-17			2018-05-26T06:44:58Z	95
8	Durum wheat	Senatore Capelli	28-Oct-17			2018-05-26T08:01:18Z	95
9	Durum wheat	Senatore Capelli	28-Oct-17			2018-05-26T08:54:37Z	98
10	Durum wheat	PR22D66	31-Oct-17	2018-05-02T15:25:3	0	2018-06-12T09:12:29Z	65
11	Durum wheat	Massimo meridio	4-Nov-17	2018-05-02T08:38:2	0		
12	Durum wheat	Marco Aurelio	26-Oct-17			2018-06-02T06:50:19Z	2
13	Durum wheat	Marco Aurelio	25-Oct-17			2018-06-02T08:15:21Z	5
14	Durum wheat	Marco Aurelio	25-Oct-17			2018-06-02T09:45:58Z	32
15	Durum wheat	Marco Aurelio	26-Oct-17	2018-05-04T08:26:2	0	2018-05-30T07:38:30Z	2
16	Durum wheat	Marco Aurelio	26-Oct-17	2018-05-04T10:59:3	0	2018-05-30T08:53:55Z	80
17	Durum wheat	Marco Aurelio	26-Oct-17	2018-05-04T11:52:5	0	2018-05-30T10:31:21Z	25
18	Durum wheat	Monastir/Odisseo	22-Oct-17			2018-05-17T10:41:06Z	0
19	Durum wheat	Monastir/Odisseo	22-Oct-17			2018-05-17T09:42:02Z	0
20	Durum wheat	Monastir/Odisseo	22-Oct-17			2018-05-17T08:28:42Z	0
21	Durum wheat	Monastir	1-Nov-17			2018-05-21T11:51:35Z	0
22	Durum wheat	Monastir	1-Nov-17			2018-05-21T12:51:01Z	60
23	Durum wheat	Monastir	1-Nov-17			2018-05-21T10:03:59Z	80
24	Durum wheat	Senatore Capelli	30-Oct-17			2018-06-11T08:23:19Z	98
25	Durum wheat	Senatore Capelli	30-Oct-17			2018-06-11T09:08:40Z	98
26	Durum wheat	Senatore Capelli	30-Oct-17			2018-06-11T09:34:15Z	98
27	Durum wheat	Senatore Capelli	30-Oct-17			2018-06-11T09:56:37Z	98

Appendix2: Backscatter in VH polarization in milk stage

3	Point	VH	VV	VH/VV
4	131E	-20.0728	-14.6697	-5.40312
5	133E	-18.9042	-14.6335	-4.270666
6	051E	-20.0301	-13.2386	-6.791541
7	052E	-18.9699	-14.6273	-4.342574
8	053E	-19.4696	-14.0765	-5.393149
9	054E	-20.1444	-15.1575	-4.986929
10	055E	-19.5426	-12.8042	-6.738486
11	056E	-20.0371	-14.4032	-5.633954
12	301E	-20.2208	-15.2953	-4.925512
13	313E	-19.7597	-12.3634	-7.396318
14	312E	-19.6055	-14.3239	-5.281567
15	311E	-21.297	-14.6078	-6.689156
16	081E(2)	-18.7439	-13.7038	-5.040076
17	041E	-15.9961	-13.5084	-2.487761
18	365E	-18.2988	-11.8826	-6.416203
19	364E	-18.4288	-14.7574	-3.671366
20	362E	-18.8435	-14.7868	-4.056751
21	363E	-18.0292	-14.8291	-3.200096
22	112E	-19.0955	-16.7336	-2.361916
23	073E	-17.2434	-12.04	-5.203466
24	083E(2)	-17.847	-14.0806	-3.766439
25	242 E	-19.2858	-14.2243	-5.061443
26	071E	-17.4645	-12.0907	-5.373794
27	082E(2)	-15.2835	-10.2499	-5.033575
28	303E	-14.0567	-9.10208	-4.954666
29	371E	-13.3333	-7.62204	-5.711269
30	374E	-14.3455	-7.90515	-6.440326

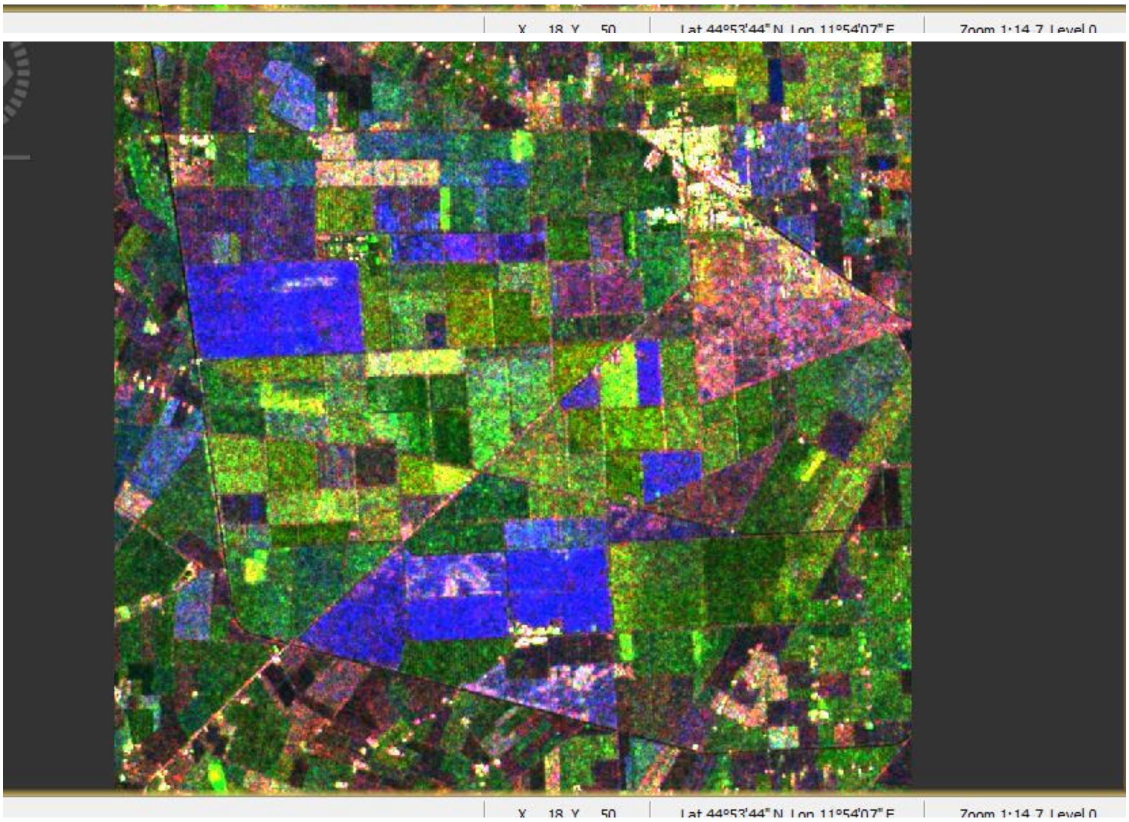
Appendix3: Band reflectance for field samples in milk stage

Point	2-Blue	3-Green	4-NIR	5-Rededge	6-Rededge	7-Rededge	8-NIR	8 A-SWIR	11-SWIR	12-SWIR
131E	0.032492	0.052904	0.044312	0.090164	0.3249	0.484136	0.510452	0.501556	0.137932	0.067544
133E	0.032224	0.05024	0.027592	0.070508	0.314568	0.458412	0.473948	0.472244	0.125132	0.058812
051E	0.015332	0.033384	0.014888	0.058412	0.278472	0.402788	0.429212	0.429276	0.133816	0.058856
052E	0.011464	0.027492	0.01136	0.051568	0.271784	0.401112	0.424996	0.427708	0.131552	0.058368
053E	0.013184	0.0306	0.014968	0.05516	0.253444	0.357836	0.375028	0.380956	0.126932	0.05852
054E	0.0111	0.02646	0.009972	0.050524	0.293532	0.458744	0.494096	0.490612	0.13362	0.05748
055E	0.014508	0.031464	0.013416	0.056608	0.286852	0.423464	0.448104	0.452192	0.135104	0.058652
056E	0.012484	0.027704	0.012696	0.050872	0.278248	0.434864	0.449956	0.469944	0.120432	0.051652
301E	0.013396	0.0321	0.014384	0.056524	0.278864	0.419148	0.439128	0.447492	0.114904	0.050744
313E	0.009272	0.023232	0.007764	0.045088	0.269364	0.42088	0.437972	0.440864	0.102316	0.044908
312E	0.019968	0.051308	0.038612	0.096024	0.271408	0.363868	0.381008	0.404012	0.148096	0.074728
311E	0.014008	0.031784	0.013912	0.055708	0.303812	0.470268	0.494536	0.493252	0.122436	0.055992
081E(2)	0.03532	0.053872	0.064164	0.097336	0.136544	0.15934	0.11148	0.167308	0.127004	0.101028
041E	0.01462	0.024416	0.029404	0.045904	0.061812	0.073652	0.077652	0.082072	0.072752	0.049288
365E	0.047836	0.075032	0.065388	0.116792	0.257024	0.322924	0.347776	0.361408	0.185768	0.098184
364E	0.03094	0.065424	0.06276	0.11988	0.234396	0.286772	0.306536	0.32856	0.189056	0.107096
363E	0.036348	0.073256	0.074684	0.133536	0.23858	0.28612	0.303176	0.326404	0.191992	0.11264
362E	0.0306	0.063752	0.063972	0.117752	0.222968	0.275376	0.295376	0.321304	0.189364	0.1096
112E	0.022656	0.041056	0.021348	0.064132	0.266192	0.370872	0.38588	0.376364	0.106212	0.050276
073E	0.019668	0.035396	0.019444	0.057744	0.271336	0.408948	0.42248	0.425396	0.101268	0.045576
354E	0.060508	0.101428	0.057784	0.144536	0.441272	0.589292	0.621272	0.602264	0.208928	0.105352
083E(2)	0.023596	0.045196	0.024044	0.0712	0.26216	0.343524	0.3516	0.356	0.11304	0.053356
114E	0.020216	0.03616	0.01776	0.05836	0.291572	0.437244	0.454788	0.450824	0.106756	0.04802
302E	0.069808	0.131404	0.110864	0.21206	0.398328	0.463408	0.485104	0.507152	0.507152	0.507152
333E(2)	0.068328	0.101676	0.15212	0.179388	0.195968	0.218276	0.237176	0.2509	0.263608	0.174516
071E	0.0734	0.129736	0.128096	0.222032	0.369936	0.432644	0.458136	0.480824	0.244284	0.1405
129E	0.040988	0.079	0.040472	0.1186	0.389944	0.507204	0.534804	0.528904	0.16486	0.079004
082E(2)	0.003308	0.01594	0.013444	0.031748	0.059972	0.073196	0.070964	0.07956	0.037352	0.021896

Appendix 4: Band reflectance in for field samples in flowering stage

Blue	Green	Red	Rededge_	Rededge_	Rededge_	NIR_1	NIR_2	SWIR_1	SWIR_2	lodging
0.020168	0.035384	0.020112	0.059056	0.2661	0.402968	0.41668	0.421376	0.10813	0.051052	0
0.02032	0.039024	0.022704	0.063696	0.24976	0.350208	0.353572	0.366184	0.10072	0.049916	0
0.0307	0.051772	0.033304	0.07708	0.218468	0.26878	0.272544	0.278496	0.12543	0.067424	0
0.025128	0.046676	0.02516	0.072288	0.255264	0.329576	0.338516	0.341272	0.11835	0.05792	0
0.023596	0.045196	0.024044	0.0712	0.26216	0.343524	0.3516	0.356	0.11304	0.053356	0
0.06048	0.082068	0.06	0.114652	0.267428	0.321548	0.321164	0.332032	0.16293	0.092952	0
0.027312	0.04648	0.027512	0.072044	0.294068	0.417264	0.427988	0.436736	0.12229	0.056232	0
0.026328	0.045968	0.026384	0.072988	0.304924	0.43878	0.449792	0.45582	0.12386	0.056244	0
0.02392	0.038856	0.022488	0.063876	0.298392	0.448836	0.461628	0.464716	0.11562	0.05102	0
0.024568	0.04042	0.023448	0.063192	0.293448	0.439644	0.448472	0.44994	0.12021	0.052724	0
0.025604	0.044048	0.025516	0.067876	0.28746	0.41088	0.423932	0.424744	0.12092	0.054684	0
0.059216	0.082396	0.052028	0.110856	0.343492	0.442272	0.442564	0.454224	0.18844	0.094656	0
0.020852	0.041984	0.022848	0.06968	0.266484	0.354592	0.371132	0.371444	0.1068	0.05146	0
0.023056	0.043524	0.026552	0.074516	0.250764	0.325776	0.341176	0.343528	0.1072	0.052692	0
0.022592	0.045248	0.027864	0.073128	0.257276	0.340796	0.348948	0.357832	0.10747	0.053232	0
0.021212	0.033904	0.017796	0.054688	0.3002	0.48712	0.505264	0.504612	0.1165	0.051036	0
0.060508	0.101428	0.057784	0.144536	0.441272	0.589292	0.621272	0.602264	0.20893	0.105352	20
0.137096	0.159632	0.190152	0.223408	0.26658	0.26658	0.31212	0.316556	0.282	0.203948	50
0.040988	0.079	0.040472	0.1186	0.389944	0.507204	0.534804	0.528904	0.16486	0.079004	70
0.054159	0.095477	0.0536	0.137195	0.425986	0.541923	0.602159	0.568605	0.18352	0.090645	80
0.028168	0.058076	0.028892	0.09446	0.37332	0.535556	0.569984	0.567064	0.16735	0.167352	85
0.040552	0.072488	0.038588	0.110592	0.420572	0.58094	0.615124	0.611376	0.17095	0.077552	98
0.050856	0.090864	0.049832	0.137448	0.451532	0.589788	0.621076	0.61322	0.18788	0.090412	98

Appendix 5: A stack of Sentinel 1 images



Appendix 6: Sentinel 2 image for the study area

Appendix 7:Green band reflectance in milk stage correlation