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Dip **TERRITORIO E SISTEMI AGRO-FORESTALI**
Master degree in **SUSTAINABLE AGRICULTURE**

USE OF REMOTE SENSING TECHNIQUES TO ANALYSE LODGING LEVEL IN CEREAL CROPS

SUPERVISOR:
Prof. Francesco Marinello

CO-SUPERVISOR:
Dr. Donato Cillis
Dr. Daniele Pinna

CANDIDATE:
Sophia Zanelli
Matricola n. 1239905

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ABSTRACT

Nowadays, there is high attention to sustainability in all areas of human activities. But what does sustainability mean? As the World Commission on Environment and Development says, sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs".
Definitively, it is possible to affirm that sustainability is based on three main pillars: the social one, the economic one and the environment. If all those pillars will be met, sustainability can be reached.

What about agriculture? There are several definitions for Sustainable Agriculture, one says that Sustainable Agriculture is the efficient production of safe, high quality agricultural products, in a way that protects and improves the natural environment, the social and economic conditions of farmers, their employees and local communities, and safeguards the health and welfare of all farmed species (Sustainable Agriculture Initiative Platform).

The aim of this dissertation is to illustrate how Precision Agriculture can help not only farmers, but also agriculture business operators to process the right decision in order to satisfy sustainable principles.

New technologies are useful to manage resources employed in agricultural processes such as soil, water, fertilizers or pesticide, but also to reduce wastage maximizing yields and, consequently farm profit.

In particular, the dissertation is going to illustrate how monitoring technologies implementation is useful to manage soil, crop and weather with proximal and remote sensing. Those collected data can be processed, corrected and interpreted by operators in order to generate Decision Support System which is useful to improve company's decision-making capability.

The study focuses on one of the main extensive crops, barley, in particular on its lodging.

Different barley varieties were tested on 195 plots located in Idice, province of Bologna, North-East Italy to assess which one can better resist to lodge and to demonstrate how Unmanned Aerial Vehicle can be useful to monitor crop evolution. In fact, UAV was employed to collect data and, to validate them, crop smart scouting was necessary.

After data collection and correction, a Digital Elevation Model has been created in order to evaluate three classes: lodged crop, partially lodged crop, no lodged crop.

The study evidences how remote sensing, in particular UAV's, can help to process data otherwise hard to collect, giving useful information to farmers and business operators to make the right decision with high accuracy in short time.

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Chapter 1
INTRODUCTION

1.1 New technologies for sustainability

Nowadays, there is a growing interest in sustainability. But what does this term mean? There are several definitions but, according to World Commission on Environment and Development, “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development, 1987).

From this paper on, many World Milestones have been subscribed:

- Agenda 21 (Rio de Janeiro, 1992): a voluntarily action plan concerning environment, economy and society signed by more than 170 countries around the world during the United Nations Conference on Environment and Development (UNCED).
- Millennium Declaration (New York, 2000): "Only through broad and sustained efforts to create a shared future, based upon our common humanity in all its diversity, can globalization be made fully inclusive and equitable". This document is composed by 8 chapters containing a

statement of values and defining principles and objectives for the international agenda for the 21st century (United Nations, 2000).

- UN 2030 Agenda (2015): It is a plan of action for people, planet and prosperity adopted at the United Nations Sustainable Development Summit on 25 September 2015. It includes 17 Sustainable Development Goals and 169 targets that should be achieved by 2030 (Agenda 2030 per lo sviluppo sostenibile, 2023).

Figure 1.1 UN sustainable development goals

- EU 2020 strategy (2010): it is the EU's agenda for growth and jobs for the decade 2010-2020. It promotes smart, sustainable and inclusive growth to improve competitiveness and productivity of Europe's economy: "Europe can succeed if it acts collectively, as a Union. We need a strategy to help us come out stronger from the crisis and turn the EU into a smart, sustainable and inclusive economy delivering high levels of employment, productivity and social cohesion. Europe 2020 sets out a vision of Europe's social market economy for the 21st century." (European Commission, 2010).

Agricultural sector is facing with production's sustainable intensification to satisfy consumer demand and, at the same time, should generate income for farmers paying attention to climate changing and land conservation (IBF Servizi S.p.A., 2021).

As seen in the previous paragraphs, sustainability is a wide concept that can be summarized on three main pillars:

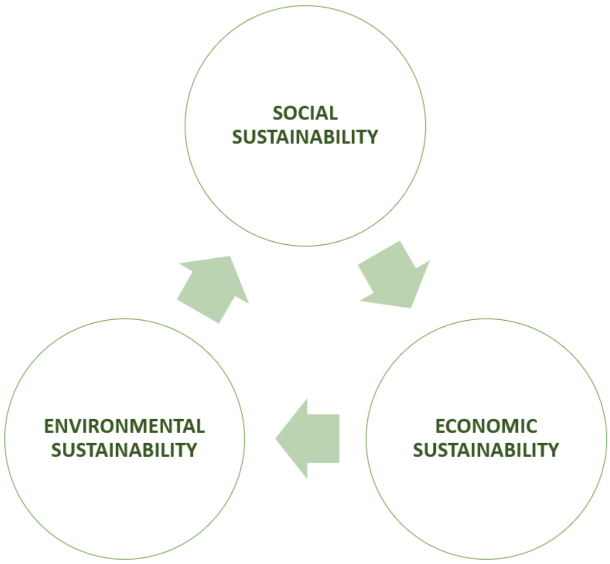

Figure 1.2 Those three main pillars work together to achieve sustainability

As is known, agriculture plays an important role in ecosystem services that can positively or negatively impact on environment, especially in biodiversity growth in rural ecosystem and natural resources (such as soil, water and air) preservation (IBF Servizi S.p.A., 2021).

Therefore, modern agriculture should take advance of new technologies to optimize natural resources use, reducing wastage and maximizing yields in terms of quantity and quality (IBF Servizi S.p.A., 2021).

From this need, there is higher attention on Precision Agriculture (PA) that can help farmers reduce input use, avoid wastage and, consequently, maximize input efficacy using technologies and good agricultural practices.

Precision Agriculture can support farmers from tillage to harvest, integrating information from different information level. The main topic of PA is space and time variability (Oliver, 2013): it is essential to recognize different features of soil and factors that can affect production in order to better manage them. To reach this object, technicians and farmers should use advanced technologies and appropriate machines to implement sito-specific operations (Kitchen *et al.*, 2002).

The first analysis that should be done is the identification of Management Unit Zone (MUZ), that are the sub-areas where the soil or the crop have similar response to a certain factor. To define them is essential integrate different data such as soil map, proximal and remote sensing, or yield map to have areas of interest complete vision (IBF Servizi S.p.A., 2021).

In the next chapter, those topics will be illustrated.

1.2 The present work

The present work aims to define lodging detection methods using remote sensing approach. In addition, an overview on remote and proximal sensing technologies and how they can help decision makers in soil and crop management and weather monitoring. Collected data can be processed and interpreted to generate Decision Support System useful to improve company's decision-making capability.

In particular, the study focuses on barley, one of the main extensive crops and its lodging.

UAV was employed to collect data about several barley varieties on 195 plots located in Idice, province of Bologna, North-East Italy to assess which one can better resist to lodge and to assess how Unmanned Aerial Vehicle can be useful to monitor crop evolution. To validate collected data, crop smart scouting was necessary.

After data collection and correction, a Digital Elevation Model has been created in order to define three classes: laid crop, partial laid crop, no laid crop.

The study evidences how remote sensing, in particular UAV's, can help to process data otherwise hard to collect, giving useful information to farmers and business operators to make the right decision with high accuracy in short time.

Chapter 2

DIGITAL TECHNOLOGIES IN SUPPORT OF EXTENSIVE CROP MANAGEMENT

Precision Agriculture can be defined as “the application of modern information technologies to provide, process and analyze multisource data of high spatial and temporal resolution for decision making and operations in the management of crop production” (National Research Council, 1997).

Precision Agriculture has several objectives: crop profitability and sustainability, product quality improvement, weed and pest management efficiency, energy, water and soil conservation avoiding environmental pollution, especially waterways. This approach is not to be confused with good practices that do not take in account systems dynamism (Peruzzi *et al.*, 2014).

The main fundamentals of Precision Agriculture are information, technology and management: georeferenced data collected at these three levels can be integrated and interpreted to carry out information about future management, but they can also be consulted to evaluate the validity of management strategies adopted during the year or to define product traceability (Peruzzi *et al.*, 2014).

2.1 Proximal sensing

As said, soil and time variability measurement and interpretation are fundamental for Precision Agriculture; data can be collected by proximal and remote sensors.

Proximal sensors are defined as instrument that can detect data in direct contact with the object (usually soil or culture) or at distance less than 2 m (Viscarra Rossel *et al.*, 2010).

Proximal sensors allow us to quickly collect a huge amount of data at relative low cost and they can be upload in on-the-go systems that can further reduce acquisition time (Viscarra Rossel *et al.*, 2011).

On the other hand, data collected by proximal sensors can be affected by several factors such as environment (temperature or humidity) or soil and plant conditions and so, sito-specific calibrations are necessary (Priori *et al.*, 2018).

2.1.1 Soil

As known, soil is one of the most influencers of the principal function connected to environment and food production such as carbon storage, hydrogeologic regulation etc… those functions are strictly related to physical, chemical and biological soil characteristic (Priori *et al.*, 2018). Some examples: soil structure can significantly affect water infiltration and availability for plants, soil tillage and even potential fertility; carbonate content affects pH and, consequently, nutrients availability and elements competition (Priori *et al.*, 2018).

It's easy to see how a detailed soil variability map can help decision makers to choose the best options for agricultural operations (Priori *et al.*, 2018).

First detections and maps started around 1900 (Brevik *et al.*, 2016), but their scope was strictly cognitive and cultural; from 90's on, with the advent of Global Navigation Satellite System (GNSS) and Geographic Information System, data collected increased and a better spatial resolution occurred (Priori *et al.*, 2018).

Data collected by proximal sensors can be analyzed and interpreted and, through interpolation, detailed variability soil map can be made (Priori *et al.*, 2018).

How can be those maps employed by decision makers? Essentially, two are the main uses: soil problems individuation and reduction or soil agronomic precision management. In the first case, maps can help farmers to individuate soil problems such as waterlogging or soil compaction and then try to reduce it; in the second case, soil maps represent the basis for soil and crop sito-specific management allowing farmers to decide when and how act (Priori *et al.*, 2018).

It should be stressed that methodology and sensors should be chosen on the basis of the type of analysis that have to be done and that integration between different methodologies and sensors can provide reliable output instead of one single tool.

- Geophysical proximal sensors: the principal geophysical proximal sensors employed in agricultural sector are electromagnetic induction (EMI) sensors, georesistivimeters and Ground Penetrating Radar (GPR).

  EMI sensors can detect apparent electrical conductivity (EC_a) using two coils, one of them (transmitter coil) produces primary magnetic field and its variation in soil proximity generates a secondary magnetic field that can be detected by the receive coil (Priori *et al.*, 2018). The ratio between those magnetic field represent the apparent electrical conductivity (EC_a). The output, consisting in point data, needs an interpolation process to provide an EC_a map (Priori *et al.*, 2018).

  Those data can be influenced by several factors: water content, organic matter, salinity, clay etc…so a correct interpretation and soil sampling are crucial to obtain a reliable result (Priori *et al.*, 2018).

  Recently, also mobile georesistivimeters have been developed. They use a couple of metal wheels that enter current in the soil and the other couple measure the drop of potential. The output maps are quite similar to the previous one, reminding that electrical resistivity is the opposite of EC_a. Those sensors are widely used because they allow rapid execution, stability of measurement and they are not sensitive to external factor as EMI sensors. On the other hand, the most relevant limit is the possible non-optimal contact between electrodes and soil, especially in arid and stony soils (Priori *et al.*, 2018).

Figure 2.1 Veris georesistivimeter (IBF Servizi)

Ground Penetrating Radar (GPR) sensors work through electromagnetic pulse and refraction and reflection they undergo during their propagation. They evidence changing in matter composition, in porosity or in water content (Conyers *et al.*, 1997). As other geophysical sensors, there is not a unique connection between the output and one specific soil characteristic because data collection is influenced by huge number of factors. Also, this is one of the most expensive methods to detect soil characteristics (Priori *et al.*, 2018).

- <u>Proximal sensors based on spectroradiometry</u>: gamma-ray spectrometer sensor is made by scintillator crystal, usually cesium iodide or sodium iodide emitting photons if exposed to gamma rays. A detector transforms strength and number photon emission in electrons. From the spectrum, with mathematical models, gamma ray total counts (TC) can be calculated (Priori *et al.*, 2018). With this sensor, chemistry and mineralogy soil variations can be detected (Van der Klooster *et al.*, 2011) in simple and quick way. Two are the main critical points for this technology: soil investigation is reliable in the first 30-40 cm (then, gamma rays are absorbed by soil) and values are strictly correlated to the place of investigation because they are influenced by soil composition, pH and water chemism (Dierke *et al.*, 2013). As consequence, it is quite impossible creation of general models of soil characteristics by only gamma ray investigation (Priori *et al.*, 2014). This method is largely used to analyze composition soil variability in wide areas or to predict soil texture, soil stoniness and carbonate content in few hectare areas (Priori *et al.*, 2018).

Reflectance Vis-NIR spectrometry technology is becoming more and more important because it is a rapid technique, relatively cheap and it can directly or indirectly define several soil properties (mainly soil organic matter, water content, soil texture and mineral content) from one scan. These techniques are based on spectral reflectance (the ratio between electromagnetic radiation reflected by soil surface and electromagnetic radiation that impact on the soil surface). Each soil has specific spectral sign based on each component spectral sign such as minerals, water and organic matter content and even the elements distribution (Baumgardner *et al.*, 1985; Sellitto *et al.*, 2008). As other sensors, *in situ* measurements require calibrations based on place specific characteristics (Roger *et al.*, 2003).

2.1.2 Crop

Crop monitoring objective is the individuation of vegetal conditions crop to obtain physiological parameters that are useful to have information of how manage the plot of interest (IBF Servizi S.p.A., 2021). Crop space and time variability depends on several factors: micro-climate, phenological phase, cultural and nutrition management, weed competition and phytosanitary conditions (Heege, 2013).

Figure 2.2 Dualex sensor (IBF Servizi)

The need to monitor crop variability leads to the development of sensors able to collect data in non-destructive and non-invasive way (Priori *et al.*, 2018).

After opportune site-specific calibrations, proximal sensors can rapidly provide data at relatively low cost about vegetation cover, nutritional status, photosynthetic system and evapotranspiration efficiency, water status, secondary pigmentation level, plant health and productive response (Priori *et al.*, 2018).

Spectrometer Vis-NIR and fluorimeters can be used to detect vegetation status: measurements are based on vegetation's reflected or emitted electromagnetic radiation that can rapidly and non-destructively provide fundamental indirect information on crop status. Vegetation spectral response is characterized by distinctive features linked to pigments' absorption characteristics (Priori *et al.*, 2018). The main data should be analyzed is the reflectance in red and Near InfraRed and, consequently, spectral response in red-edge, the transition region that is very sensible to variation of physiologic status (Carter *et al.*, 2001).

Optical proximal sensors can be classified on different criteria: kind of measurements, radiometric resolution, energy source and how they operate (stationary or mobile, in the second case, plugged in on tractors or rods) (Priori *et al.*, 2018).

Radiometric sensors can be passive or active depending on the light source they use: solar light or external illumination in the first case, its own light source in the second case that allows less influence by external conditions variations. They can be characterized by selective or panchromatic light source: they can emit specific ranges of wavelength and then capture reflected radiation by crop by panchromatic receiver or, vice versa, they can emit panchromatic light and then capture reflected radiation by selective receiver for specific wavelength of interest (Priori *et al.*, 2018).

Basing on radiometric resolution, sensor can be multi- or iper-spectral: the first ones, mainly used for practical scope, use lower number of broadbands, usually 2-8 that lead to a lower detail, on the other hand, iper-spectral sensors can detect reflectance in high number of bands (narrowbands).

Optical measurements can be done with fluorimeters, mainly in research sector because of their cost. These sensors are able to detect light radiation intensity. Fluorescence is strictly connected to electronic transport rate, usable in photosynthesis, photorespiration and alternative electronic transport. Variations in photosynthesis could lead to moderate stress conditions (Priori *et al.*, 2018).

2.1.3 Microclimate

Microclimate monitoring is fundamental to realize model able to predict biotic and abiotic risks such as frost and heatstroke or pathogen attack (Priori *et al.*, 2018).

To monitor microclimate variability, thermo-hygrometer sensors are necessary: they can daily provide data on temperature, humidity and dew point. Those data will be used to obtain information on evapotranspiration and climate index. To implement data accuracy, anemometers, barometers and rain gauges can be plugged in on thermos-hygrometers (Priori *et al.*, 2018).

Leaf dampening sensors are useful to predict fungal diseases: water's veil presence allows spores motion and germination and, consequently, plant penetration. These sensors can collect data about humidity on the leaf and wetting hours (Priori *et al.*, 2018).

Figure 2.3 Weather station

If implemented with soil data, agronomic management (date, depth and density sowing, date, kind, quantity and way of fertilization, or irrigation plan, for example) and genotype, microclimatic information allows model calibration and parametrization. Prevision models can highlight different scenarios basing on different variabilities: they allow to predict the effect that specific agronomic choices could have on vegetation or yield, environmental impact or farmer benefit (IBF Servizi S.p.A., 2021).

An example: a farmer would schedule phytosanitary treatment against fungal pathogen. After data collection, two models may be derived: phenological crop phasis and pathogen epidemiology. After their integration, a map can be generated where areas with different risk level are classified. Models can't substitute human experience, so specialized technicians should scout crop and pathogen status to implement model resolution (IBF Servizi S.p.A., 2021).

2.2 Remote sensing

In the last decades, remote sensing has made great strides through the development of sensors pluggable on remote platforms as planes or satellites.

As proximal sensing, remote sensing allows to carry out information about vegetation's condition in a different scale of resolution.

All remote sensing systems exploit interactions between electromagnetic radiation and the object of the analysis. Sensors can catch the electromagnetic wave varying in amplitude, length and frequency that varies with temperature (IBF Servizi S.p.A., 2021).

Bodies emit radiations in different wave length called spectrum. We can only perceive a little part of the bands define 'visible' (VIS) or photosynthetically active radiation (PAR) between 0,4 e 0,7 μm. From 0,7 μm on, there is infrared band divided in Near Infra-Red (NIR, 0,7-1,3 μm), Short Wave Infra-Red (SWIR, 1,3-2,5 μm), Medium Wave Infra-Red (MWIR, 3-8 μm) and Thermal Infra-Red (TIR, 7-20 μm). Wave length lower than 0,4 μm are define as ultraviolet band (Casa *et al.*, 2018).

2.1.1 Satellite

Satellite systems are largely used in precision agriculture to obtain free or low-cost satellite images. Most of the satellite images come from public government space agencies as ESA (European Space Agency) or NASA (National Aeronautics and Space Administration).

Among satellite missions belonging to multispectral category the most used is Sentinel2 in in Copernicus Land Monitoring Services mission consisting of two satellites (A and B) that are used to monitor changes in the earth's surface. They cover a range from 56° South to 86° Nord in latitude. Images (available on ESA website) has 10 m, 20 m or 60 m according to spectral bands.

From the spectral signature captured by sensors it is possible to discriminate different elements such as water, soil or vegetation.

In particular, vegetation is mainly affected by two factors: plant chemical and physical properties (chlorophyll and water content, cellular structure etc…) and plant structure (leaf coverage, phenology and plant health). Definitively, canopy behavior is mainly related to chlorophyll pigments concentration as result of pigments concentration in leaf area and leaf abundance expressed through Leaf Area Index (LAI) (Casa *et al.*, 2018).

As shown in figure 2.1, vegetation seems to be green to human sight, that is because foliar pigments absorb in blue and red wavelength, while they reflect in the green and NIR ones.

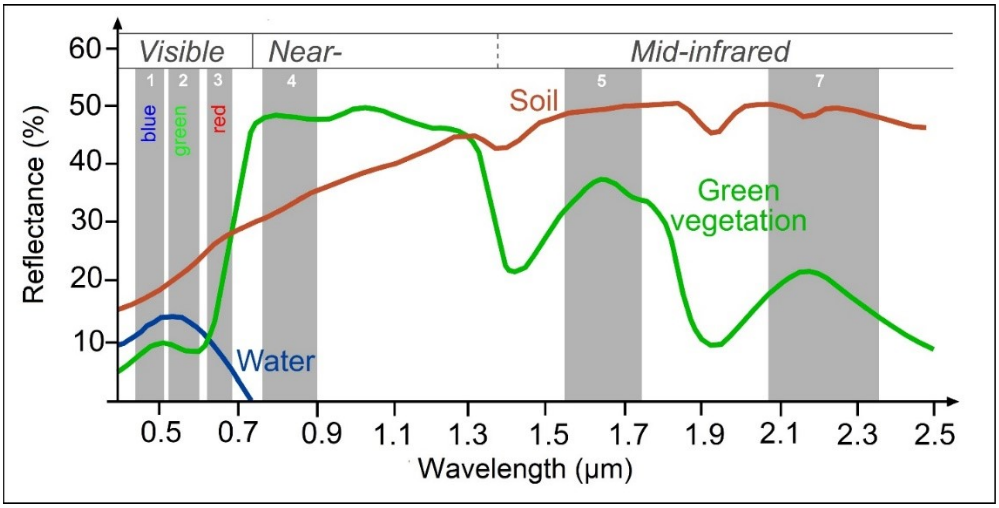

Figure 2.4 Spectral signatures

Chlorophyll concentration is particularly useful to monitor nitrogen nutrition status while NIR region, in particular red edge, is mainly used to collect data about structural parameters as LAI or green biomass. Foliar pigments and cellulose are invisible to NIR wavelength, so leaf absorbance is quite low. However, reflectance can reach high level over 60% due to multiple reflection between air and water contained respectively in leaf spaces and cell walls. This sudden increase in reflectance is called red edge (Casa *et al.*, 2018).

Starting from optical data and variable of agricultural interest, it is possible mathematic model describing interaction between solar radiation and vegetation generation (Casa *et al.*, 2018).

Following the main vegetation index used in precision agriculture:

- NDVI (Normalized Difference Vegetation Index): it is used to estimate crop vigor, its value varies from 0 (bare soil) to 1 (maximum plant cover);

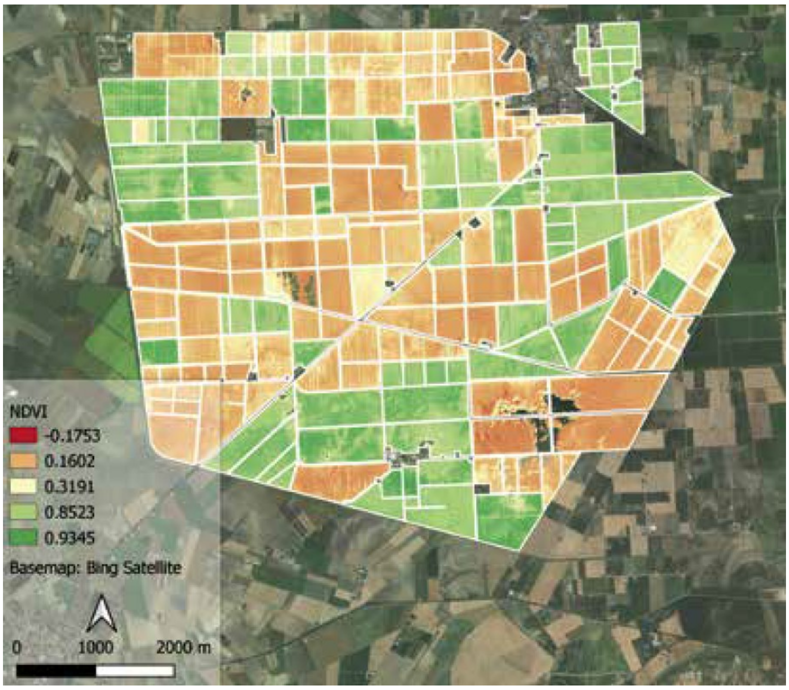

Figure 2.5 NDVI use for crop monitoring

NDVI index is quite sensible to variations in soil reflection, illumination and atmospheric effect. Also, it is more efficient if there is low or medium leaf coverage, on the contrary, if LAI has a high value, NDVI can't perceive variations. To solve those critical issues, the following vegetation index has been created.

- MSAVI (Modified Soil Adjusted Vegetation Index) has a higher discrimination power on the soil (Qi, et al., 1994) and OSAVI (Optimized Soil Adjusted Vegetation Index) optimized for agricultural uses (Rondeaux *et al.*, 1996).
- MCARI (Modified Chlorophyll Absorption Reflectance Index) measure absorption compare to reflectance (Daughtry, et al., 2000) TCARI (Transformed Chlorophyll Absorption Reflectance Index) that estimate chlorophyll concentration (Haboudane *et al.*, 2002).
- Indices combination and prediction models to estimate biophysical parameters as LAI or chlorophyll content (IBF Servizi S.p.A., 2021)

The output of the analysis is a georeferenced map illustrating crop vigor:

Figure 2.6 Satellite image representing crop vigor

Through the maps, farmers and technicians can individuate critical areas and, consequently identify causes and possible solutions through proximal sensing and smart scouting (IBF Servizi S.p.A., 2021).

2.2.2 Unmanned Aerial Vehicle (UAV)

Traditional platforms used in remote sensing, such satellites or airplanes, present some critical points: they lack in versatility, operational flexibility and spatial and temporal resolution (Matese *et al.*, 2018). In the last decades, UAV (Unmanned Aerial Vehicle) have become popular in Precision Agriculture and, with them, also many sensors pluggable on UAVs are available. They can provide centimeter spatial resolution data, possibility of timely intervention due to reduced planning time (Matese *et al.*, 2018).

UAVs can use remote control or they can fly autonomously following a waypoint defined by the user through a complex system of control sensors as gyroscopes, magnetic compass, GNSS, pressure sensor and triaxial accelerometers controlled by a microprocessor (Matese *et al.*, 2018).

They are particularly suitable for small and medium farm, with fragmented cultivated surface or high level of heterogeneity in plots (Matese *et al.*, 2013).

Among other benefits, UAVs have a relatively low investment cost, high maneuverability, the possibility to autonomously collect data and, if necessary to repeat the flight (Matese *et al.*, 2015); on the contrary, satellite images are available every five days and, in case of cloud cover, they can't be used (IBF Servizi S.p.A., 2021)

UAVs can be classified in two categories by flight mode: flapping wing or propeller, the last one in largely used in precision agriculture (Matese *et al.*, 2018).

Figure 2.7 Hexacopter UAV

Even sensors have been adapted to be used on UAVs in terms of weight, dimension and power consumption. Nowadays multispectral sensors are widely used in agriculture, while hyperspectral ones are used in research and development contexts because of their high cost and difficult management (Matese *et al.*, 2018).

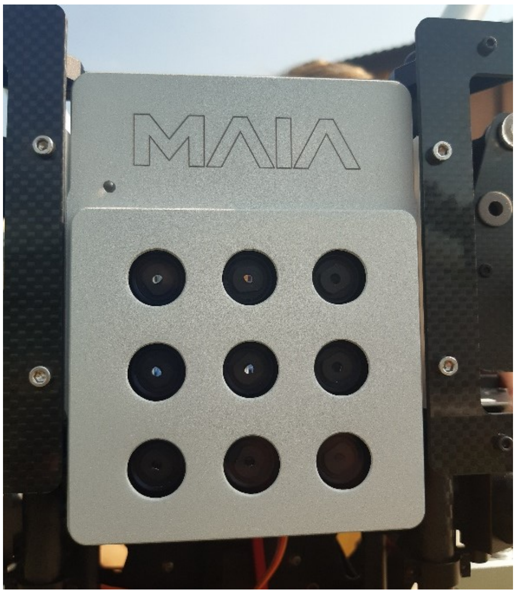

Figure 2.8 Multispectral camera

Nowadays, remote sensing data collection is mainly about vigor and water stress. Data collection passes through several steps, from flight planning to post-processing to obtain maps representing calculated indices (Matese *et al.*, 2018).

The first step is flight planning and it is the most important operation because it is useful to reduce flight preparation in the field and, consequently, operational risks. According to camera characteristics, the Field Of View (FOV) must be define and it give back information on the dimension of the captured images in relation to flight altitude. Then waypoints, flight speed and acquisition frequency must be scheduled. Even overlapping is a fundamental parameter because it guarantees quality images for mosaicking: higher is the overlapping level, more accurate will be the quality of the mosaic. Overall, if the objective is a high detailed image, high overlap and low flight altitude are necessary; on the other hand, if wide areas have to be monitored, it is fundamental higher flight altitude and less overlap in order to be able to monitor all the area in similar atmospheric conditions (Matese *et al.*, 2018).

Then, it is possible to fly: the flight can be remote controlled by the user or it can autonomously fly following waypoints. The last operating mode relies on GPS system to take off, to navigate and to land, but also to manage images acquisition. Obviously, some factor cannot be predicted during the planning phase and they are mainly due to weather conditions: light conditions should be optimal and homogeneous, cloud can produce anomalies that cannot be corrected in the following steps. Also, wind can create problems, but recently, high performance UAVs have been developed (Matese *et al.*, 2018).

To obtain a correct acquisition, radiometric calibration is necessary for each sensor first in the laboratory, then in the field. This calibration is useful to obtain a singular response to same light condition. Considering that the air between the sensor and the surface can affect the signal by absorbance and scattering, also atmospheric correction is necessary. Geometric correction allows the elimination of spatial deformations due to the sensor acquisition, generating a new image with correct scale and projection (Matese *et al.*, 2018).

After sensor calibration and image correction, mosaic orthoimages realization occurs. From the output, generally a point cloud, algorithms can define object geometries. Those images are mainly used to estimate yield or crop biomass through vegetation indices (Matese *et al.*, 2018).

2.3 Decision support system (DSS)

One of the main objectives of Precision Agriculture is to provide to farmers and stakeholders the right instruments to evaluate a specific condition and, therefore make decisions about management or problem resolution. The instrument to reach this objective is the Decision Support System defined by Zhai *et al*. as a "human-computer system which utilizes data from various sources, aiming at providing farmers with a list of advice for supporting their decision-making under different circumstances" after they say: "One of the most representative characteristics of an ADSS (Agricultural Decision Support System) is that it does not give direct instructions or commands to farmers. Because farmers are in the position of taking the final decisions." (Zhai *et al.*, 2020).

Generally, DSS are constituted by conclusions drawn by the analysis of several data collected with different methods (mainly attributable to remote and proximal sensing) and they can be carried out through models, one of the most innovative techniques or simply through data analysis.

Models can describe soil-plant-atmosphere interactions through mathematical equations (Basso *et al.*, 2015) and they can significantly represent and interpretate dynamic processes related to water movement along soil profile, soil nutrients content and plant growth. To obtain a reliable simulation, genetic features, soil characteristics, weather data and historical climate data should be implemented (Basso *et al.*, 2018). This technology can increase income through costs reduction and unit production increase also, they are useful to reduce environmental impact and to conservate natural resources (Basso *et al.*, 2005). The integration with GIS allows to have georeferenced data, defining homogeneous areas that can be managed in similar ways (Basso *et al.*, 2018).

Additionally, DSS can be predictive or final according to its objective: preventive DSS can help decision makers to adopt the right management strategy while final DSS allow the evaluation of a specific analyzed factor.

In this study DSS could be useful to choose the most suitable barley variety according to lodging resistance optimizing not only the use of productive factors, but also the yield increasing the sustainability of the whole productive process through soil efficiency and enhancement of genetic material.

Generally, DSS are particularly useful to manage agronomic operations that requires material input such as irrigation, plant protection treatments or fertilization.

2.3.1 Irrigation DSS

Variable Rate Irrigation (VRI) is one of Precision Agriculture applications and its objective is yield maximization through water sito-specific management: the amount of irrigation water should be the same of storage capacity (Vincini *et al.*, 2018). Also, they allow a better management of nitrogen if we consider that water percolation is one of the main causes of nitric nitrogen leaching (Evans *et al.*, 1994; Meisinger *et al.*, 2002).

In Italy, Sito Specific Variable Rate Sprinkler Irrigation (SS-VRI) technology is not common, but irrigation prescription is a valuable tool to manage waterings.

According to (Sadler *et al.*, 2005), there are five main criteria to prescribe waterings:

1. Some regions could be excluded from irrigation: it is the case of paths, headland etc…but also areas that, for example, are characterized by waterlogging;
2. Watering differentiation can help to solve problem as waterlogging and excess salinity since high water volumes can help salinity run-off;
3. Watering volumes can significantly affect crop quantity and quality production allowing resource use optimization;
4. Water volumes are determined on water balances and water availability for each Management Unit Zone;
5. Irrigation should vary according to species or variety watered by the same irrigation system.

Based on that, simulation models have been developed: they use weather data, soil data, groundwater data, general cultural parameters, irrigation system data and sito-specific cultural parameters (Vincini *et al.*, 2018). The model simulating water-soil-plant interaction is quite complex (Driessen, 1986) and the algorithm is based on complex physics-mathematic equations describing the variable dynamic (Vincini *et al.*, 2018).

Models can provide several estimates including effective infiltration calculated from rainfall data and soil characteristics, root growth and phenological phases through GDD, effects of water stress, groundwater supply, water movement along soil profile and the final DSS including water volume necessary to satisfy crop requirements and the irrigation date (Vincini *et al.*, 2018).

2.3.2 Plant protection DSS

Plant protection is one of the operations that mainly affect not only environment, but also farmers' incomes. Actually, it has been shown that over 70% of the pesticides could not reach the target (Balsari *et al.*, 2007); this is mainly due to sprayers wrong calibration or planning that does not consider pathogen evolution and its plant interaction (IBF Servizi S.p.A., 2021).

Pesticide differentiated distribution can be carried out with two main systems: one is based on real time techniques, the other involves georeferenced maps. In the first case, sensors plugged in sprayer bars can detect plant health status and, consequently real time application is possible; on the other hand, pathogen maps are generated by monitoring systems and, consequently, prescription maps can be produced (IBF Servizi S.p.A., 2021). Alternatively, farmers can decide to maintain fixed dose operating in a discontinuous way applying the product where it is necessary, that is define patch-spraying distribution (IBF Servizi S.p.A., 2021).

Nowadays, weed control is much more developed compared to pest control that is steel in experimental stage. Even in this case, forecast models can significantly help farmers and decision makers (IBF Servizi S.p.A., 2021).

In this case, models are useful to individuate phenological phases and pathogen evolution, predicting the infestation possibility. Those output should be integrated to define plant-pathogen interaction and, consequently, the possibility of pathogen attack. From this analysis and visual monitoring, the correct time frame for treatment can be defined and it allows the control of almost 98% of pathogen attacks on extensive crops (IBF Servizi S.p.A., 2021).

Obviously, the detail level of the agronomic board is influenced by the detail of the input data collected: for example, a farm weather station will provide more detailed data compared to regional service weather station data (IBF Servizi S.p.A., 2021).

Agronomic boards represent a helpful tool for farmers, but the final decision is demanded to decision makers (IBF Servizi S.p.A., 2021).

2.3.3 Nutrition DSS

The term “fertilization” includes all those operations aiming at improving soil physical, chemical and biological fertility. Those operations include mineral fertilization, pH correction and addition of organic soil improvers. Nowadays, mineral fertilization is widely spread, especially the nitrogen one. The main objective of fertilization operation is the nutrients supply that could limit plant growth to reach the maximal production potential. Also, crops, during their vegetation cycle, remove nutrients from the soil impoverishing and making unsustainable production process in the long term. Therefore, removed elements should be restored in the soil considering not only plant taken, but also input and output that naturally occurs in the system: this operation is called input-output balance (IBF Servizi S.p.A., 2021).

To apply Precision Agriculture nutrition principles, several methodologies are available but the best solution is always their integration: among these, removal quantification from previous years production mapping, monitoring of soil characteristics linked to fertility and crop nutrition status monitoring (IBF Servizi S.p.A., 2021).

The most difficult element to manage is nitrogen because of the high dynamism of its cycle. This involves several inefficiencies that mainly affect environment and economy. According to European Nitrogen Assessment, environmental costs for nitrogen losses are about 70-320 billion of euro per year, higher than nitrogen benefits in agriculture.

For this reason, one of the objectives of precision agriculture is the improvement of Nitrogen Use Efficiency (NUE) (the ratio between nitrogen used by crop and nitrogen deployed with fertilization) whose value at world level is about 33% due to leaching, admonishment and nitrous oxide transformation. Beyond that, even production improvement, costs reduction and environmental impact reduction are persecuted by PA (IBF Servizi S.p.A., 2021).

Nitrogen supply should be calculated trough balance method and, consequently, the dose should be split to provide nitric nitrogen, directly taken by the plant, in the periods where nutrients are higher demand. In particular, it is fundamental in specific phonologic phases such as tillering and stem elongation when lack of nutrients would lead to reduced vigor, chlorosis, reduced dimension and, consequently, decrease in yield (IBF Servizi S.p.A., 2021).

Currently, management strategies involve the study of the previous at least five years to obtain information about production potential. That information is useful to classify areas characterized by the same productivity, usually defined as “high”, “medium”, “low”. On this basis, the first fertilization dose can be defined (IBF Servizi S.p.A., 2021).

Then, crop monitoring is fundamental to define the dose for covering fertilizations. In addition to static balance, dynamic balance should be taken in account to update information on the interpretation of vigor maps. Alternatively, even in this case, simulation models can be profitably employed. They are able to predict crop production using historical weather data and soil data. Simulations can be run with different fertilization doses to individuate the best solution to optimize yield and profit reducing, at the same time, leaching losses (IBF Servizi S.p.A., 2021).

The practical application can be accomplished by prescription map or on-the-go systems. While maps are based on historical monitoring and yield data, integrated with information about soil properties that can affect plant nutrition, on-the-go systems employ sensors that can detect crop reflectance and, consequently, it can elaborate Vegetation Indices and define the optimal dose. Obviously, to apply differentiated distribution, suitable sprayers are required. Because of their complexity, that equipment is not widely spread and it represents 1% of fertilizer spreader used in Italy (IBF Servizi S.p.A., 2021).

Phosphate fertilization is easier compared to the nitrogen one because of the lower mobility of phosphorus. This allows to not consider variability in time and permit the dose calculation on the basis of crop uptake. To correctly calculate phosphorus dose, some assumptions are necessary: the next crop should have similar needs, soil phosphorus can satisfy crop requirements and there are not other losses except crop uptake. To calculate phosphorus removal phosphorus product content should be multiply by yield including material taken off by the field (in cereal crops, for example, hay). If soil content is not enough, pre-sowing fertilization is necessary, then this value should be maintained. Alternatively, prescription maps based on assimilable phosphorus variability can be elaborated, but they require soil sampling and, consequently, high costs and long lead times (IBF Servizi S.p.A., 2021).

As phosphorus, even potassium fertilization is based on site-specific maintainment according to crop uptake. On the other hand, potassium il more susceptible to leaching, especially in soil characterized by clay values lower than 5%. In those condition, even crop uptake will be lower due to element lack. In addition, geo-electrical proximal sensing could detect areas characterized by low percentage of clay that could lead to potassium lack and, therefore to a higher dose (IBF Servizi S.p.A., 2021).

Despite there are not studies on variable rate organic fertilization, it is becoming more and more important. This is due to the fact that soil is the second carbon stock after oceans and a correct soil management could lead to climate change mitigation. Several studies demonstrate that manure distribution in areas less productive increase yield but economic and environment benefit analysis states that the best solution is the opposite one that is manure distribution in higher dose in most productive areas. Generally, in coarse texture soil, higher doses of manure are recommended to increase organic content and physical and chemical fertility; on the other hand, lower doses of slurry are recommended to reduce leaching losses. On the market are available technologies that allow manure and slurry dosage based on nutrients concentration.

2.4 Yield monitoring systems

Variability represents the starting point of each precision agriculture application and it can be carried out through several method but the best solution is represented by the integration of several information levels, among these, yield maps that give information about quality, quantity and heterogeneity of production (IBF Servizi S.p.A., 2021).

Through yield monitoring is possible identifying sub-areas set on the basis of production potential, calculate nutrients removal due to products and byproducts harvest and assess the effects of eventual variable rate management (Lazzari *et al.*, 2018).

Cereals are the main crops affected by those technologies and they represent the field where sensors are mainly spread and used (Lazzari *et al.*, 2018).

To monitor yield quantity, flow sensors are used to assess production mass or volume through indirect or impact measurements (Küzbach *et al.*, 1997). Currently, only sensors able to measure volume operating through impact are used. Volumetric sensors count “elementary volumes” moved by harvester elevator: the total volume corresponds to the product between elementary volumes and steps performed. To calculate elementary volumes that are not regular, optical sensors are necessary. After monochromatic light emission, they are able to detect light energy not absorbed by product determining chamber filling degree. Impact sensors transform grain kinetic energy detected by a platform in electric signal that will be the grater the grater will be grain flow (Lazzari *et al.*, 2018).

Volumetric values can be converted in mass values through density sensors: they compare a volume with known density with a box that has the same volume that is sequentially filled with grain. Often, those values are not accurate because the box is not totally filled Dry matter values are carried out by humidity sensors made by capacitors able to detect dielectric constant of air and grain nearby flow sensors (Lazzari *et al.*, 2018).

During harvest, it is even possible determine the quality of the grain through NIRs sensors that obtain information about humidity, protein content, fat content in non-destructive way. However, they are not widely spread mainly because of the difficult calibration (Lazzari *et al.*, 2018).

All those sensors require a correct calibration that usually consists in validate data input that modify calibration curve that makes collected measurement quite similar to estimated ones. After calibration, data collection occurs and it is visible on on-board monitor. After this operation, raw data are exported through the use of cloud or mobile memory support.

Data elaboration consists in error and non-significant data elimination where a correct data interpretation is fundamental. Then, punctual data will be interpolated generating an estimate of point where sampling did not occur. Finally, clustering operation allows the classification in productivity classes that define zones characterized by the same level of productivity. At this point, the map is easily interpretable for evaluations about agronomic management or variable rate applications assessment.

Chapter 3
EXPERIMENTAL STUDY

3.1 Barley

Barley (*Hordeum vulgare L.*) is a specie belonging to Graminaceae family cultivated since 7th millennium b.C, initially in Middle East, then worldwide. In 2023, in Italy it occupies around 300.000 ha, a higher value compared to the previous years: 268.000 ha in 2022 and 252.000 ha in 2021 (ISTAT, 2023) and the yield stands from 6 to 8 t/ha (L'Informatore Agrario, 2022). Barley is cultivated for grain but also as forage crop and, in regions where climate is not suitable for wheat cultivation, it represents a viable alternative to wheat which doesn't ensures high and constant yield. In the most developed countries, barley grain is mainly employed for animal feeding and secondly, in malt industry for beer and whisky production.

As all cereals, barley is subject to lodging that represent one of the main causes of quantity and quality yield reduction. Lodging can be defined as "a process which induced displacement of shoots from their vertical standpoint. This results in leaning or completely horizontal lying of plants on ground" (Jedel *et al.*, 1991) (Rutto *et al.*, 2013). Two types of lodging can be defined: stem lodging caused by weather conditions, in particular wind, rain and hail and root lodging that occurs when roots fail to maintain soil contact (Berry *et al.*, 2003). Losses severity depends on the duration and time of lodging: lodging at early development stage has less influence on yield reduction as compared to late development stage (Berry *et al.*, 2004). This is probably due to the fact that stem cannot be re-erected after lodging after anthesis or filling stage. The drop in quantity is due to reduced mineral translocation and carbon assimilation, loss of chlorophyll content and greater susceptibility to disease and pests attack that also affects grain quality (Foulkes *et al.*, 2011).

3.2 Experimental area

The experimental area is located in North-East Italy, in particular in Idice, province of Bologna.

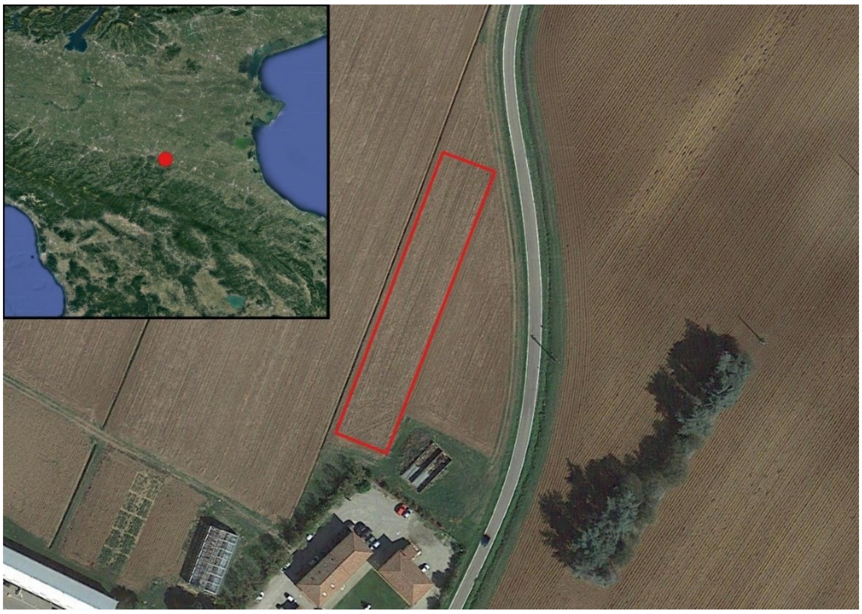

Figure 3.1 Experimental area

According to soil analysis, the designated area is characterized by sandy-clay-loam soil texture (64% sand, 15% loam and 21% clay). Clay presence provides moderate permeability and, consequently, a good water holding capacity. pH is 7,5, a sub-alkaline reaction, suitable for barley cultivation. Soil Organic Matter results in low quantity and it negatively affects physic and chemical fertility. About elements: magnesium and potassium results in medium quantity, phosphorus and calcium results in high quantity while total nitrogen quantity is low and its contribution to nutrition is limited.

In this area 195 plots were individuated. Their surface corresponds to 10 m^2 each.

3.3 Experimental design

As mentioned before, 0,2 ha area was individuated and split in 195 plots, 10 m^2 each. On those plots, 45 different experimental barley variety were tested for lodging in 3 replications.

After broad bean (*Vicia minor*), barley was sown at the beginning of November, on 05.11.2023 and the density is 300 germinable seed/m^2. About nitrogen fertilization: no pre-sowing fertilization occurred, while covering fertilization consists in the distribution of 60 kgN/ha on 14.02.2022. Plant protection against weeds was necessary to maintain crop health.

3.4 Analysis description

To collect data a hexacopter UAV was employed and a MAIA multispectral camera was plugged in.

Figure 3.2 Hexacopter UAV and MAIA multispectral camera

As mentioned before, the main drone advantages are the possibility to collect high-resolution data, even centimeter, in a timely manner avoiding satellite limits such as its lower resolution and atmosphere influence. Also, the use of a multispectral camera allows infrared band data collection, useful to obtain information about vegetation temperature.

Three main operational steps were followed:

1. Preliminary stage: in this stage the interested area should be investigated in order to individuate factors that should influence UAV flight and its planning (tree or cable presence, for example).

Figure 3.3 Flight planning and Ground Station Point

In this case some details were defined: flight height corresponds to 25 m and the flight time is scheduled at 12:00 to limit shadow influence. Image acquisition is characterized by 70% overlap and 50% overside. Those parameters influence mission's duration and the number of frames that will be analyzed but, at the same time, higher is their value, higher is the possibility to have better quality images;

2. The operational stage consists in the flight itself and in images acquisition;
3. Once data collection has been completed, specific software will elaborate images to reduce atmosphere influence and errors due to signal distortion and spatial deformations.

The output consists in an orthophoto that will be used to obtain and elaborate vegetation indices and the following analysis.

Chapter 4
ANALYSIS AND RESULTS

4.1 UAV analysis

After data collection and image elaboration, image analysis occurs.
From raw data, made up of point cloud, a Digital Elevation Model (DEM) can be designed to obtain an orthomosaic representing lodging level in barley crop.

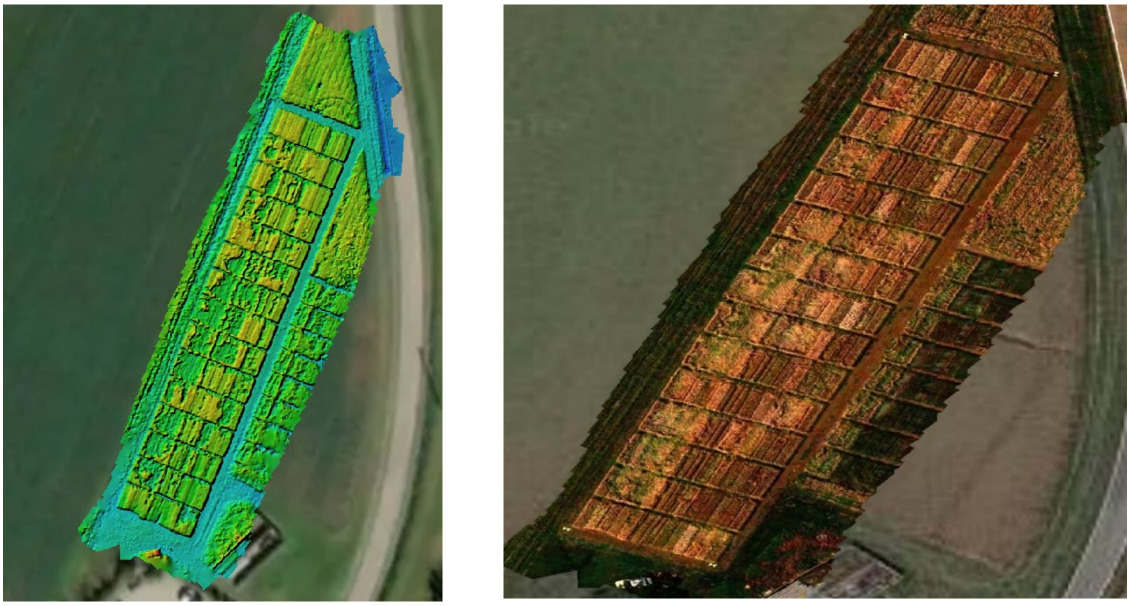

Figure 4.1 Digital Elevation Model and orthomosaic

The first step consists in K-means algorithm lodging evaluation to elaborate an index that can significantly represent lodging level. From this analysis 3 classes will be obtained: “Lodged”, “Partially lodged” “Not Lodged”.

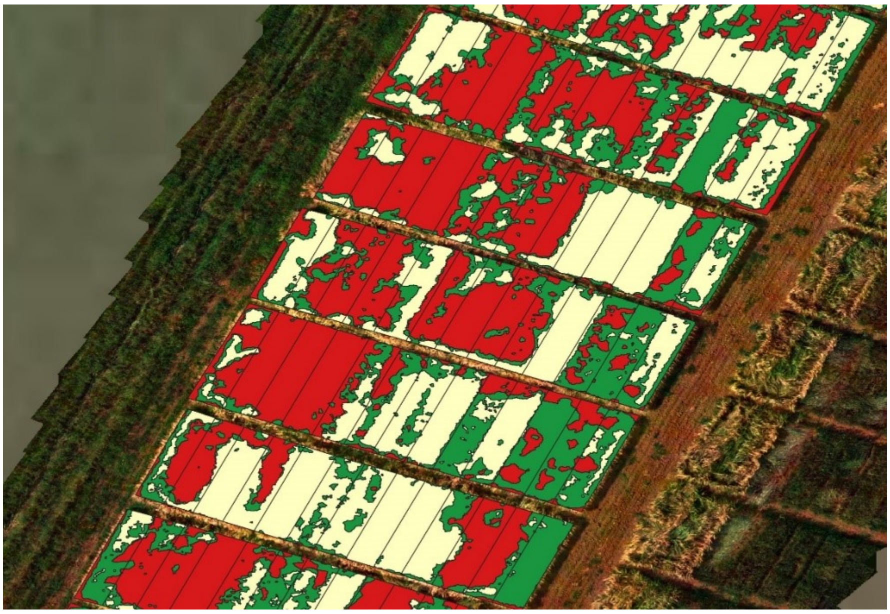

Figure 4.2 Cluster on DEM

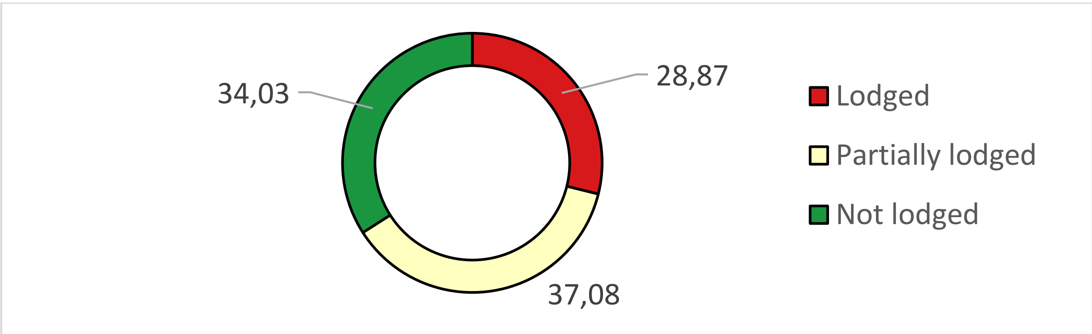

Figure 4.3 Surface lodge partition

This method highlights that data are classified in a homogenous way that do not allows discrimination of lodge from low size barley varieties that result “partially lodged”. So, a supervised method is necessary: it give the possibility to choose the thresholds that define those three levels limiting errors due to crop size according to measured data.

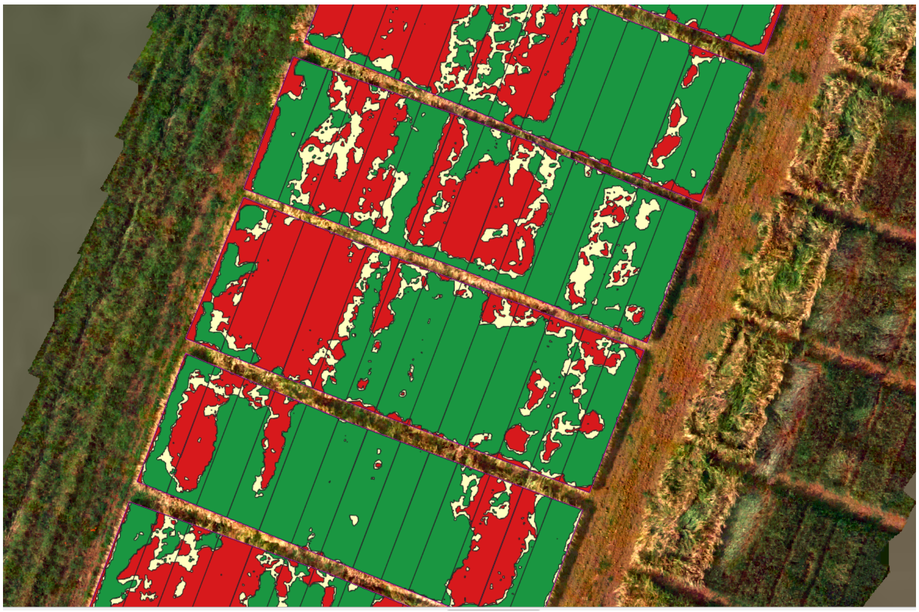

Figure 4.4 Supervised method cluster

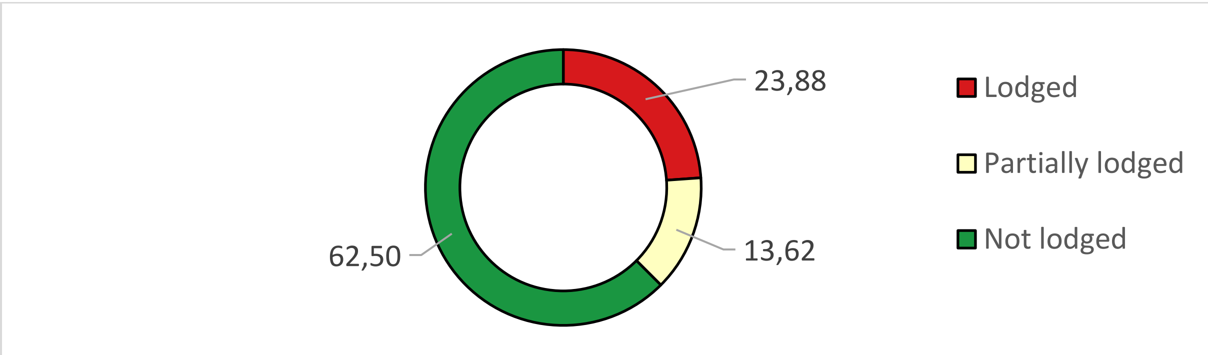

Figure 4.5 Surface lodge partition

Definitively, the supervised method, despite elaboration is more expensive in terms of time, allows a better definition of lodging level that, on the other hand is overestimated.

K-means lodging analysis constitutes the starting point for parcel lodging index elaboration: almost 6.000 sub-parcels were individuated and classified according to its lodging level (1 = Not lodged; 2 = Partially lodged; 3 = Lodged).

Figure 4.6 K-means lodging map

Then the ratio between the sub-parcel area and its parcel total area defined the weight of the sub-parcel on the parcel. Lodging index can be calculated by multiplication of its lodging level and its weight on the parcel. After the sum of each sub-parcel index, the parcel lodging index can be calculated. It is represented by continuous values from 1 = not lodged to 3 = completely lodged.

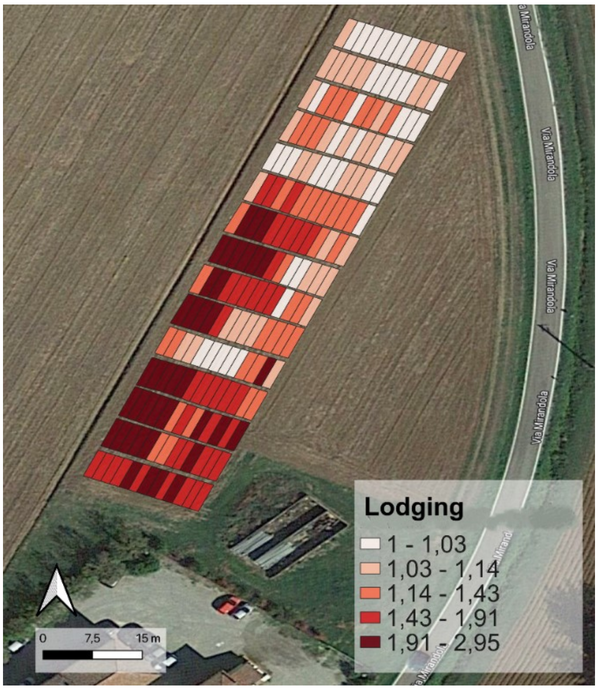

Figure 4.7 Parcel lodging Index

While with K-means algorithm the analysis refers to the total field, with this index every single parcel is taken in account through the assignment of an average lodging value.

Then, for each single parcel, through UAV's data, starting from DEM, medium height for each parcel have been calculated.

Figure 4.8 DEM map

Even NDRE, MSAVI and TCARI/OSAVI vegetation indices map have been generated.

NDRE represent crop biomass and, consequently, crop vigor in a better way compared with NDVI that tends to saturate with high value of leaf coverage; MSAVI has a higher discrimination power on the soil; TCARI/OSAVI, inversely related with chlorophyll content, combine the estimation of chlorophyll concentration (TCARI) with the soil discrimination power (OSAVI).

4.2 Correlation between lodging indices and mean height and vegetation indices

Therefore, data about DEM and vegetation indices have been exported to perform a comparison with lodging index. Simple linear regressions between lodging index and four variables (medium height, NDRE, MSAVI and TCARI/OSAVI) and $\log_{10}$ lodging index and the same four variables have been carried out.

The following tables show coefficients R-squared, Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Mean Squared Error (MSE) of both regressions:

Table 4.1 represents lodging index regression and its coefficients

X	R^2	RMSE	MAE	MSE
Mean height DEM	0.494	0.323	0.273	0.105
NDRE	0.012	0.455	0.399	0.207
MSAVI	0.081	0.436	0.369	0.199
T/O	0.440	0.340	0.268	0.116

Table 4.2 represents Log10 lodging index regression and its coefficients

X	R^2	RMSE	MAE	MSE
Mean height DEM	0.538	0.088	0.074	0.008
NDRE	0.031	0.128	0.117	0.016
MSAVI	0.087	0.122	0.110	0.015
T/O	0.409	0.098	0.081	0.009

Below, the evidence of the higher correlation between lodging index and mean height and TCARI/OSAVI. In the first case we can observe an inverse proportion: higher is the mean height, lower is the lodging level while in the second case the direct proportion evidence that higher is lodging index, higher is T/O that is inversely related with chlorophyll:

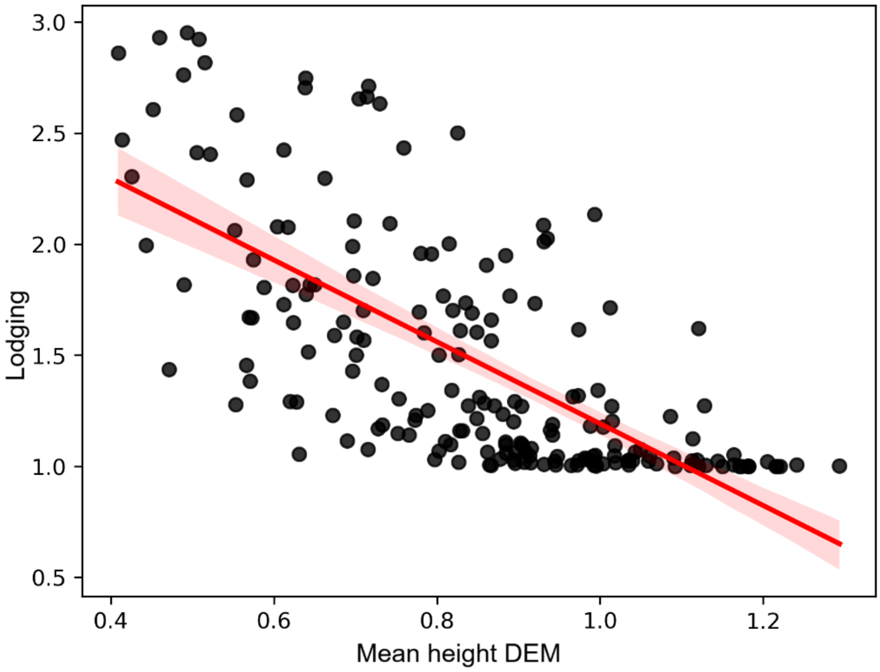

Figure 4.9 Lodging and mean height DEM regression graphic

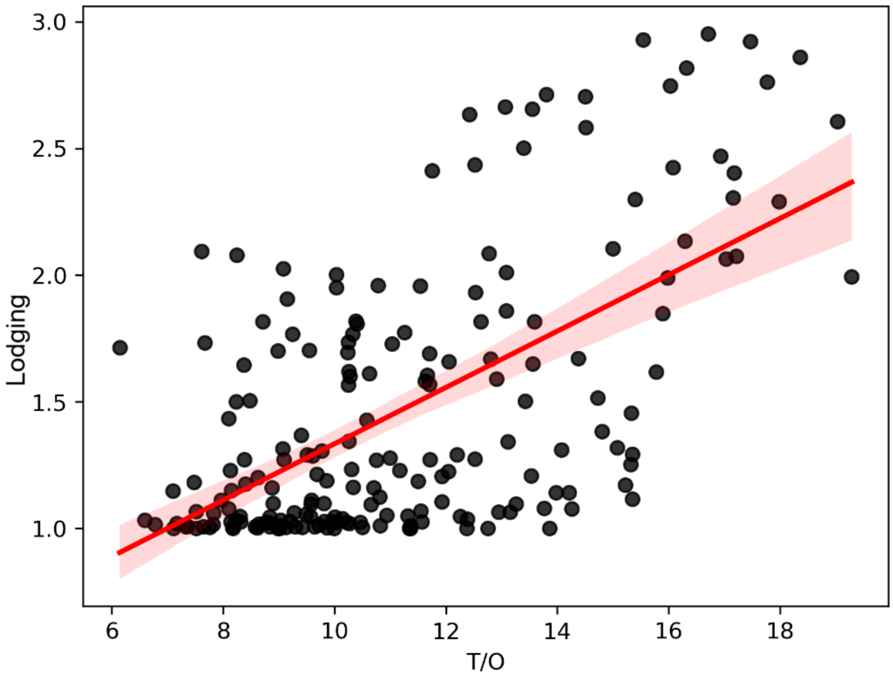

Figure 4.10 Lodging and mean TCARI/OSAVI regression graphic

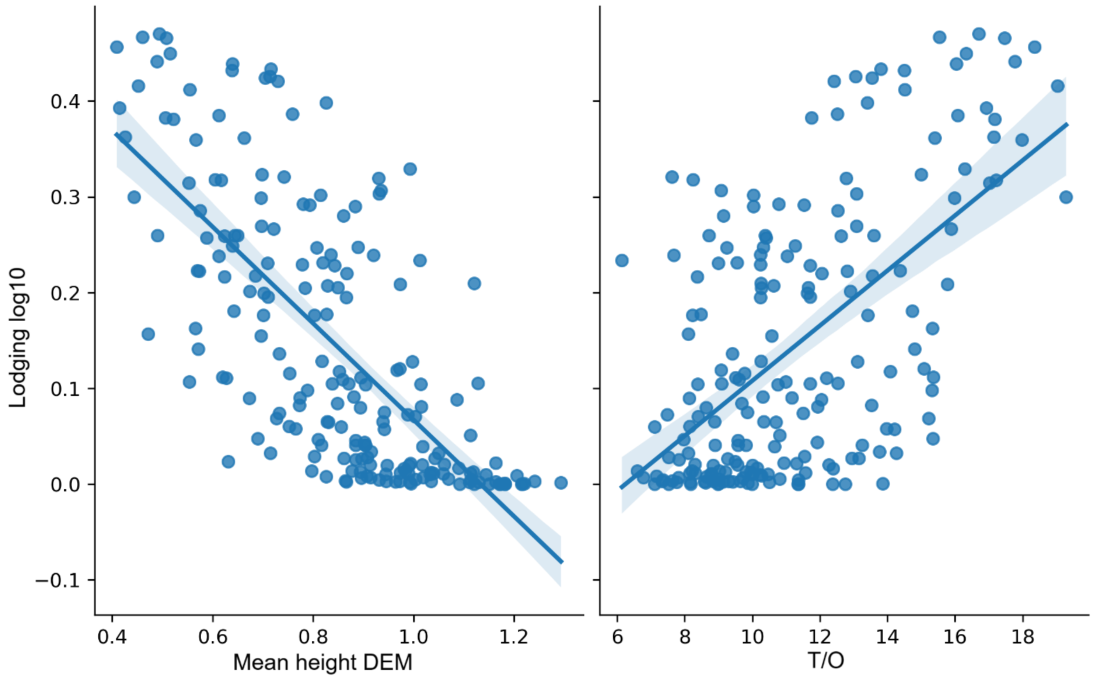

Figure 4.11 Comparison between mean height DEM and TCARI/OSAVI related to log10 lodging level graphic

In both cases it is possible to observe a flattening in the correlation. It occurs when there is a low lodging level; this is due to the low sensibility of correlation.

Chapter 5
CONCLUSIONS

In conclusion, it is possible to affirm that Precision Agriculture and, generally, new technologies can significantly help farmers and decision makers to achieve sustainability that, nowadays, constitutes a fundamental objective worldwide. In fact, agricultural sector is facing with production's sustainable intensification to satisfy consumer demand and, at the same time, should generate income for farmers optimizing natural resource use and reducing wastage through new technologies and good agricultural practices. The main topic of PA is space and time variability that, appropriately characterized, can help Variable Rate Applications implementation. Of course, several information layers integration, such as soil map, proximal and remote sensing, or yield map can clearly define the area of interest characteristics and, consequently the best way to manage it.

The aim of this dissertation is to find in correlations between barley lodging and mean height from DEM and vegetation indices processed from UAV images. The study evidences how remote sensing can help to process data otherwise hard to collect and how important can be correlation with other parameters easier to collect.

Starting from UAV images, DEM and orthomosaic can be realized. From orthomosaic, the mean value per parcel of three vegetation indices have been carried out: NDRE, MSAVI and TCARI/OSAVI while from DEM the mean height per parcel have been calculated. Those four parameters will be compared with lodging continuous index that is the result of K-mean algorithm sub-parcels and their weight on their belonging parcel.

The comparison evidence the best correlation with mean height DEM and the vegetation index TCARI/OSAVI respectively with indirectly and directly proportion. The flattening observed on chapter 4 graphics is due to the low sensibility of lodging index to low lodging values, probably due to the difficult of DEM reproduction starting from UAV images.

Once evaluated the possible correlations, this index may be used, as in this case, to discriminate lodging level of different genotypes or, in extensive cases, to evaluate, for example, how lodge can influence yield and grain quality.

To conclude, Precision Agriculture represent the near future despite farmers are reluctant to invest economic resources in technologies that don't apparently give back tangible benefits. The change of mindset could lead to innovative farm management and, consequently, new skills that can give added value to final production, generating qualitative and sustainable raw materials and, also, increasing farmer revenue.

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