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## **Introducing innovative precision farming techniques in agriculture to decrease carbon emissions.**

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## Abstract

Nowadays, agricultural systems are asked to satisfy the increasing global demand for food and fiber for a growing population. The intensification of the current systems in term of inputs and outputs lead to raising the concerns about the impact on the environment. Considering the background found in literature and its highlighted gap, the hypothesis of this thesis are (1) to survey within-farm soil and yield variability in order to delineate the homogeneous zones and productive potential; (2) study the synergy between conservation agriculture and precision agriculture allowing the optimization in terms of crop yield, net energy and energy efficiency; (3) identify the best strategies, derived from the synergy between conservation agriculture and precision agriculture, able to decrease the CO<sub>2</sub> emissions of agricultural systems in the mid-term using SALUS simulations.

Data collection required to verify these hypotheses derived from different sources, and their analysis was performed using different approaches and tools. In fact, different soil and crop sensors were used to define site-specific crop management and enable processes to better understand land changes such as spatial variations or delineation of homogeneous zones at farm scale. Besides, simulation models, when suitably tested, provide a useful tool for finding the combination of management strategies to reach the multiple goals required for sustainable crop production. Simulation models also allow to increase inputs efficiency and to perform land management.

The homogeneous zones characterization derived from the interpolation of ARP data and historical crop-yield data. Incorporating this method, it is possible to efficiently perform the analysis with a larger set of data. Classification and definition of the homogeneous zones were fulfilled by inputting data into the MZA software. The optimum number of homogeneous classes was identified according to the study of indices provided by the software. Four homogeneous zones satisfying these requirements were then defined. Consequently, the productive potential was assigned to the homogeneous zones through ANOVA test of soil features and historical crop yield. Finally, the productive potential was validated comparing the average province yield of the considered crops.

Regarding crop yield, strip-tillage (ST) and no-tillage (NT) got a decrease of 20% and 15% compared to conventional tillage (CT). However, the contribution of precision agriculture allows mitigating crop yield reduction in every tested conservation tillage system. In fact, an increase in total crop yield higher than 10% was observed, leading minimum tillage (MT) to obtain the same response of CT. In the same way, MT supported by precision agriculture achieves the highest net energy values, 2% higher than CT. While precision agriculture enables to enhance of almost 20% net energy in ST and NT compared to the same techniques managed in uniform rate application. Moreover, precision agriculture contributes to increasing energy efficiency in MT and NT with an increase with respect to CT of 10% and 2% respectively. Finally, ST supported by precision agriculture technologies shows an increase in energy efficiency of 15% compared to ST managed with a fixed rate of inputs.

On the other hand, the contribution of precision agriculture in term of carbon emissions mitigation was assessed in order to define the strategy with the lowest total annual CO<sub>2</sub> emissions under current climatic condition. SALUS simulation shown a general trend among the treatments characterized by a decrease in soil organic carbon (SOC) stock. However, a significant reduction in SOC losses was simulated in MT and NT, 17% and 63% respectively, compared to CT. Furthermore,

the adoption of conservation tillage techniques decreased carbon emissions related to farming operations, while precision agriculture technologies led to an optimization of the exhaustible sources such as fossil fuels and fertilizers. Finally, we showed that the synergy between conservation tillage systems, especially NT, and precision agriculture strategies represents a useful tool in terms of carbon emissions mitigation. With consideration of current climatic conditions and the studied field variability, NT supported by precision agriculture strategies demonstrated a reduction of 56% of total CO<sub>2</sub> as compared to CT.

## Sommario

Oggi, I sistemi agricoli sono chiamati a soddisfare la crescente domanda di cibo e fibre vegetali dovuto al continuo incremento demografico. L'intensificazione di questi sistemi in termini di utilizzo massiccio di fattori produttivi e relative asportazione porta ad aumentare le preoccupazioni in merito all'impatto ambientale. Il principale obiettivo di questo lavoro di tesi è individuare, attraverso prove sperimentali combinate con simulazioni di medio-termine di diversi scenari, la miglior soluzione tecnica in grado di preservare la fertilità del suolo e ridurre l'impatto ambientale del settore agricolo studiando la sinergia tra l'agricoltura conservativa e l'agricoltura di precisione. Considerando i contributi scientifici che studiano i due principi, ed individuati i punti di approfondimento relativi alla gestione della variabilità e mitigazione dell'impatto ambientale, le ipotesi di questo lavoro di tesi sono (1) di mappare la variabilità a livello aziendale in termini di proprietà del suolo e resa in granella allo scopo di definire delle zone omogenee ed attribuirgli un potenziale produttivo; (2) studiare la sinergia tra l'agricoltura conservativa e l'agricoltura di precisione che permette di ottenere incrementi produttivi, energia netta ed efficienza energetica; (3) individuare le migliori strategie derivanti dalla sinergia tra agricoltura conservativa ed agricoltura di precisione, in grado di diminuire nel medio periodo le emissioni di CO<sub>2</sub> dei sistemi agricoli usando le simulazioni del modello SALUS.

Per verificare queste ipotesi la raccolta dati è stata effettuata utilizzando diverse fonti, approcci e strumenti. Infatti, strumenti per la mappatura del suolo ed il monitoraggio dello stato di vigore delle colture sono stati utilizzati per studiare la variabilità di campo e la sua evoluzione nel tempo per poter definire zone omogenee stabili nel tempo. Inoltre, i modelli di simulazione, quando opportunamente testati, rappresentano un utile strumento per poter definire la miglior strategia gestionale per ottenere delle produzioni sostenibili. Questi trovano diversi campi applicativi, dall'incremento dell'efficienza d'uso dei fattori produttivi alla gestione delle superfici coltivate.

La caratterizzazione delle zone omogenee è stata effettuata tramite interpolazione dei dati ARP e dati di resa storici derivanti da mappe di resa. Adottando questo metodo è possibile effettuare analisi su vasta scala. La classificazione e definizione delle zone omogenee è stata ottenuta alimentando un programma geostatistico chiamato MZA con i dati descritti in precedenza. Il numero ottimale di classi omogenee è stato selezionato sulla base di indici derivanti dall'analisi del programma, che per questo studio è risultato essere quattro. Successivamente, il potenziale produttivo di ogni classe omogenea è stato attribuito attraverso analisi della varianza dei dati relativi alle analisi del suolo puntuali e dati di resa storici. Infine, il potenziale produttivo assegnato è stato validato sulla base delle rese medie storiche a livello distrettuale.

Per quanto riguarda la resa in granella, nello strip-tillage (ST) e la non lavorazione (NT) si osservano cali del 20% e 15% rispetto alla tecnica convenzionale (CT). Tuttavia, il contributo dell'agricoltura di precisione permette di mitigare questo fenomeno in tutte le tecniche di lavorazione conservativa studiate in questo lavoro. Questo permette di ottenere incrementi produttivi superiori al 10%, che permettono alla minima lavorazione (MT) di eguagliare le rese di CT. Allo

stesso modo, MT supportata da agricoltura di precisione raggiunge i più alti valori di energia netta, 2% maggiori di CT. Mentre, l'agricoltura di precisione contribuisce ad aumentare di quasi il 20% l'energia netta in ST e NT rispetto al corrispettivo gestito in modo uniforme. Inoltre, Questa consente di aumentare l'efficienza energetica in MT e NT del 10% e 2% rispetto a CT. In ST invece, si osservano incrementi del 15% confrontato con la stessa tecnica senza supporto di agricoltura di precisione.

D'altronde, i possibili benefici dell'agricoltura di precisione sono stati calcolati in termini di emissioni di carbonio per poter definire le migliori strategie che pesano meno dal punto di vista delle emissioni di CO<sub>2</sub> in atmosfera nelle condizioni climatiche attuali. Dalle simulazioni del SALUS si evince che tutte le tesi studiate sono caratterizzate da perdite del contenuto di carbonio organico del suolo (SOC). Tuttavia, si sono registrate minori perdite in MT e NT del 17% e 63% rispetto a CT. Inoltre, l'adozione di tecniche di lavorazione conservativa mitiga anche le emissioni di carbonio legate alle agrotecniche, mentre l'agricoltura di precisione porta ad una ottimizzazione delle risorse esauribili come combustibile fossile e fertilizzanti. Infine, è stato dimostrato che la sinergia tra agricoltura conservativa, specialmente NT, e agricoltura di precisione rappresenta un utile strumento per mitigare le emissioni di carbonio in atmosfera legate all'attività agricola. Infatti, considerando le attuali condizioni climatiche e la variabilità di campo caratterizzante l'area di studio, NT supportata da principi e tecnologie di agricoltura di precisione è in grado di ridurre le emissioni totali annue di CO<sub>2</sub> del 56% rispetto a CT.

# 1 Introduction

## 1.1 Soil tillage systems

Soil tillage operations are important to provide the correct conditions for crop establishment and growth, and in general, requires mechanical manipulation of the soil by equipment that either cut, shatters, inverts or mixes the soil (Cannell, 1985; Gajri et al., 2002). Current tillage systems can be divided into two broad categories: conventional tillage and conservation agriculture tillage systems. In conventional tillage (CT) whereby a sequence of operations used to prepare a seedbed including complete soil inversion to bury or incorporate crop residue and is usually accompanied by additional cultivation to create a seedbed (Carter et al., 2003). Conservation agriculture (CA) includes systems that involve fewer passes than conventional tillage but incorporate crop residue into the surface (upper 10 cm) whilst still leaving at least 30% of crop residue on the soil surface (Davies and Finney, 2002). Recent pressure on farm incomes has led to tillage systems being developed that minimize the costs associated with cultivation and improve the timeliness of cultivation, leading to improved crop establishment. The selection of a particular tillage method depends upon many factors that influence successful crop establishment (Carter et al., 2003). CA can be classified in relation to soil tillage intensity, so the decreasing order is: Minimum tillage (MT), Strip-tillage (ST) and No-tillage (NT) (Fig. 1.1.).

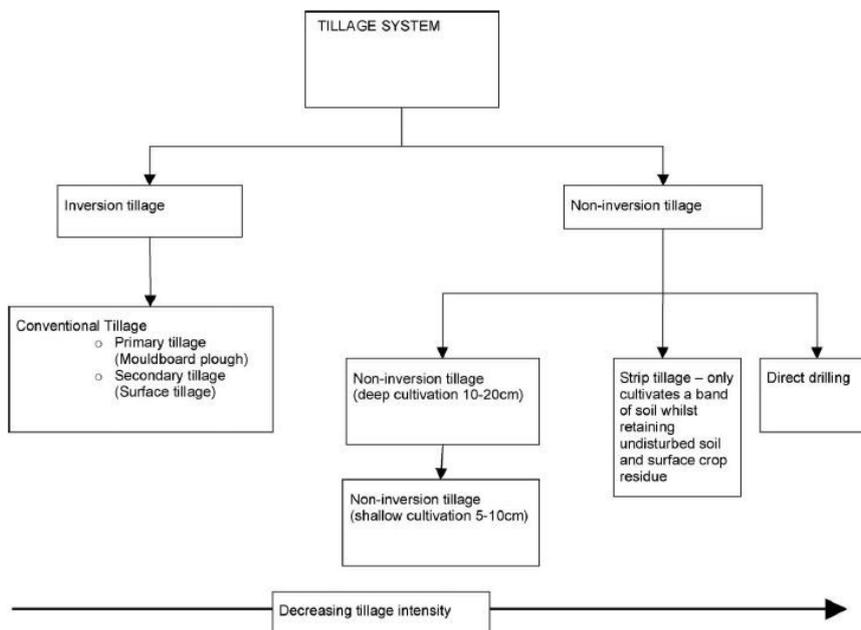


Figure 1.1: Classification of tillage systems in relation to tillage intensity (Morris et al., 2007). Non-inversion tillage=MT, Strip tillage=ST and Direct drilling =NT.

MT is a cultivation system that usually involves fewer passes than conventional tillage with implements working at shallow depths (5–20 cm) (Fig. 1.2.) whereby much of the crop residue remains on the soil surface or to deeper depths (20–40 cm) (Fig. 1.3.) whereby crop residues are mixed into the topsoil but leave a proportion on the soil surface (Carter et al., 2003).



Figure 1.2: Combined cultivator for shallow cultivation.

Deeper operations are useful to remove soil compaction (Batey, 2009) caused by heavy machinery or other cultivation damage such as soil smearing. MT is based on the use of tine and disc implements that do not invert the soil (Morris et al., 2007). The role of tines is to lift and shatter the soil removing any shallow compaction layers, discs then follow to cut and mix the straw and other residues to leave a fine tilth.



Figure 1.3: Combined cultivator for deep cultivation.

It is usual for press wheels to be fitted at the rear of the cultivator that firm and level the surface ready to sowing. In a non-inversion tillage system, the entire field area is disturbed for seedbed preparation (Gajri et al., 2002). Weed control is accomplished with the use of herbicides and cultivation. MT requires less energy when operated at shallower depths than CT, and facilitates faster land preparation allowing a large area to be sown within the optimum time frame for successful crop establishment (Cannell, 1985; Ball, 1989).

ST has been defined as a modification to an NT system where disturbance of less than one-third of the total field is cultivated (Reeder, 2000). Crop residue is removed from the cultivated strips and placed between rows with the seed being drilled into the strips (Fig. 1.4.).



Figure 1.4: Soil surface after strip tiller passage.

ST has a number of potential benefits over conventional tillage, within including its improvements to soil physical properties and the enhancement of in-field biodiversity (Reeder, 2000). ST is a kind of conservation tillage that conserves soil moisture and uses crop residue to protect against soil erosion and increase the environmental benefits for wildlife (Reeder, 2002). In the USA, ST creates narrow tilled strips which are typically 100–300 mm wide and raised 80–200mm above the surrounding undisturbed ground. The major benefits being that a high proportion of crop residue (60–75%) is left undisturbed on the soil surface protecting the soil from erosion and by removing crop residue from within row allows for early spring soil evaporation and warmer soil temperatures (Al-Kaisi and Hanna, 2002). ST can be used in growing many crops including wheat, corn, soybean, peppers, sugar beet, rice and cotton (Lee et al., 2003; Luna and Staben, 2003; Khalilian et al., 2004), with the row spacing varied according to the crop grown. Current strip tillers are based on a tine and disc combination that ensures soil disturbance is limited to a narrow strip thus retaining surface straw residue between rows (Fig. 1.5.). A number of tine designs are available for ST allowing for greater or lesser soil disturbance depending on the required effect (Overstreet, 2009).



Figure 1.5: Strip tiller implemented for fertilizer distribution at works (a), typical strip tiller's element (b).

A study by Morris et al. (2007) reported that a winged tine produced greater soil disturbance at a given depth compared to a knife tine within a narrow zone whilst maintaining an area of undisturbed soil.

Finally, NT refers to the sowing of crops directly into the previous crop stubble with no prior cultivation since harvesting the previous crop and with all crop residue left on the soil surface (Carter et al., 2003). NT implements consist of a series of tines or discs that cultivates a narrow band of soil that creates an environment suitable for the seed which is then placed behind the coulter and firmed by a rear roller or harrow (Fig. 1.6.). The soil profile remains undisturbed from year to year leaving crop residues covering the soil surface with a change in the microenvironment influencing crop growth patterns (Sprague and Triplett, 1986).



Figure 1.6: Pneumatic (a) and volumetric (b) seeders used in NT technique.

Timeliness of the operation is critical for good results and direct drilling tends to work best on stable, well-drained soils (Shepherd, 2002). The feasibility of CA methods can be observed under three point of view: economic, crop yield and quality and the effects that a particular tillage system will have on the environment and biodiversity.

Recent volatility in grain prices and expanding farm sizes means that improving production efficiency is a priority for many farmers. Reducing production costs can be a major contributor to maximising output per unit area and savings made during the crop establishment phase can be a vital part in cost reduction (Knight, 2004). Cultivation costs are directly correlated to the type, working depth and number of operations to produce a seedbed. Conventional tillage is more expensive than CA systems because of several reasons (Millar et al., 2001). Firstly, conventional tillage requires more passes with a machine and require several implements to create a satisfactory seedbed and, secondly, each pass costs time, labor and fuel (Reeder, 2000; Bullock, 2004). On heavy soils, Knight (2004) reported energy use for conventional tillage was 2826 MJ/ha compared to 1191 MJ/ha and 770 MJ/ha for non-inversion tillage and direct drilling respectively. This was because of the greater power requirement and a slower forward speed required when plowing (Knight, 2004), particularly on the heavy clay loam soils. On the other hand, under CA systems weed control has proved more difficult compared to a conventional system whereby weed seeds are buried when the soil is inverted by the plow. In some situations under CA techniques, more herbicides were needed to control weeds and this increased costs, although the

reductions in fuel and labor were found to outweigh the increased use of herbicides (Fawcett and Towery, 2002). But this problem can be mitigated through the use of stale seedbeds and crop rotations (Bullock, 2004). Besides, there is also evidence to suggest that retaining crop residue on the soil surface when using CT techniques can increase disease incidence. This is largely influenced on pathogens that remain on or near the soil surface and can cause re-infection from splash dispersal of inoculums onto new plant material (Conway, 1996; El Titi, 2003). NT and ST have the potential to improve the economic efficiency of crop establishment because there are fewer field operations, thus saving time and fuel. A farmer in Texas has found that growing cotton using ST resulted in great savings with typical fuel use having halved under ST (Deterling, 2004).

Fear of reduced yields using CA techniques is seen as a primary constraint to the uptake of such systems in Europe (Jones et al., 2006). Yield is determined by many interacting factors and effects of tillage systems are neither consistent nor predictable, but generally, crops established using MT yield slightly lower than those established after plowing (Jones et al., 2006). The research found that yields were affected when comparing different tillage systems on light, medium and heavy soils (Knight, 2004). Indeed, the study found that NT was 25–40% lower yielding in two out of three years compared to MT or conventional tillage on a clay soil, on the other hand, MT was found to give the highest yields in all years on the light soil (Knight, 2004).

The retention of crop residues in CT methods has helped to increase the build-up of organic matter and hence maintain the surface stability of the soil (Mullins, 2004). Increasing surface stability has helped to reduce the incidence of crusting, soil erosion and runoff. A study on a silt-clay loam found that MT reduced runoff by 48% and sediment loss by 68% compared to plowing (Holland, 2004). Besides, CA techniques increase invertebrate populations allowing a build-up in populations from year to year (Fawcett and Towery, 2002). Studies have found that carabid beetles are predators of slugs and therefore help to reduce slug damage to crops (El Titi, 2003). Research shows that residue influences soil temperature in three ways; residue acts as an insulating layer on the soil surface, residue reflects more solar radiation than bare soil and residue reduces evaporation rates causing the soil to warm more slowly (Shinners et al., 1994). These are NT features that lead to a reduction in crops germinations (Azooz et al., 1997). Licht and Al-Kaisi (2005) reported that ST increased soil temperature in a row by 1.2–1.4 C° compared to NT, whilst retaining residue cover between rows conserved soil moisture for plant growth. The increase in soil temperature within a row was primarily associated with the removal of straw residue increasing the absorption of solar radiation and the effect of soil disturbance on soil heat flux that alters the heat capacity and thermal conductivity of the soil (Licht and Al-Kaisi, 2005). Finally, a reduction in the intensity of cultivation is known to affect the accumulation and mineralization of nitrogen (N) within the soil. Therefore, using CA techniques that disturb less soil compared to plow based systems may suffer transitory N limitation because soil organic matter decomposes more slowly, thus decreasing the rate of nitrogen mineralization (Blevins and Frye, 1993).

## 1.2 Precision Agriculture

### 1.2.1 Introduction and definition

Precision Agriculture (PA) can be defined as the application of technologies, principles and strategies for the management in space and time variability, in order to increase crop performance and environmental quality (Pierce and Nowak, 1999). Therefore, implementing machines with sensors and electronic devices, and adopting PA concepts is possible to manage spatial and temporal variability (Bocchi e Castrignanò, 2007). Besides, the main goal of PA, through the study of the variability, is to define the best soil and crop managing strategies in order to achieve economic and environmental benefits (Aubert et al., 2012). Spatial and temporal variability is a component characterizing arable land, even if those are influenced by different variables. In fact, soil fertility is spatially distributed with different degrees of temporal stability within the fields (Pierce and Nowak, 1999).

In order to reach these goals, PA strategies can be divided into three phases. The first one is characterized by data collection derived from different sources, in the second phase data are processed and interpolated to study field variability and then in the third one variable rate applications (VRA) are defined to manage field variability. Finally, collecting data about the different managing operations allow assessing the efficiency and the liability of the adopted strategies (Bocchi e Castrignanò, 2007). In this regard, to consider all the variables composing field variability, which affects crop yield, data collection is provided by different sources and approaches (Aubert et al., 2012). Therefore, data collection represents one of the most important phases of PA, which leads to a correct study of field variability and to define the optimal managing strategies.

### 1.2.2 Evolution over the time

Studying and managing field variability requires data collection showing the distribution and evolution within the field. In this regard, georeferenced data gave a helpful contribution in term of data collection, study and management of field variability. It is provided by Global Navigation Satellite Systems (GNSS). Several missions were launched during the time, such as the American system NAVSTAR-GPS (NAVigation System Time And Ranging Global Positioning System), the Russian one GLONASS and the European system called GALILEO which will be available in 2020 (Fig. 1.7.).

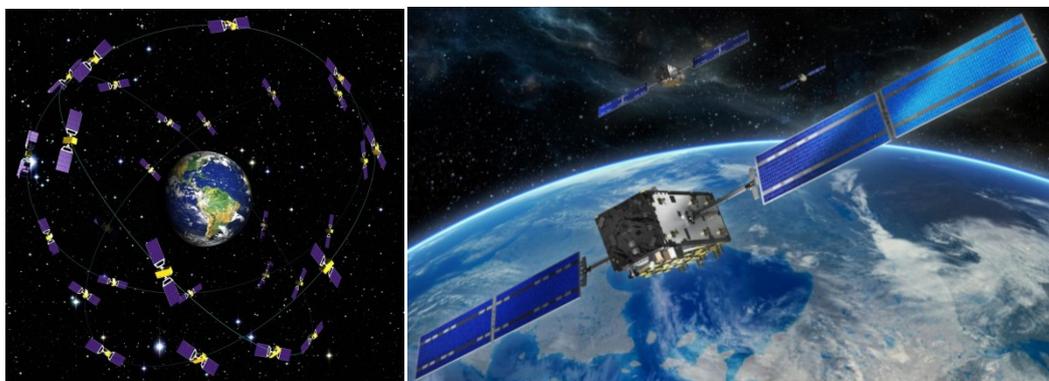


Figure 1.7: NAVSTAR satellites constellation.

Satellites carry out two complete turns of the world with an orbit ranging from 19.000 to 23.000 km distance. Besides, each satellite has atomic clocks which provide information about the position. Satellites signal is sent to control unit through radio waves which give information about time, longitude, latitude and elevation. Therefore, at least the information derived from four satellites is required in order to get a georeferenced data. On the other hand, the number of available satellites does not influence the precision of the data, which is provided by techniques to correct the error (Heege, 2013). One of the most used systems is the Differential Global Positioning System (DGPS). It is composed of a fixed station called base which corrects the positioning data sent from the satellites. Consequently, the corrected signal is sent to a geostationary satellite that gives the right position to the station mounted on the machine called rover. This correction system has 10-20 cm precision and it is also provided by the company.

Another more accurate method is the Real Time Kinematic (RTK-GPS) system. In this case, the correction signal is directly sent to the base station, through radio waves, to the rover one working in a diameter no longer than 11 km. To this end, RTK correction is the most accurate system with an error ranging from 1 to 3 cm. It is widely used for those managing operation requiring high precision such as planting or when there is the necessity to recur on the same lines such as in strip-tillage or controlled traffic farming.

In this regard, Global Positioning System (GPS) can be understood as the starting point of PA. In fact, PA got great evolution over the time in term of variability management (Fig. 1.8.).

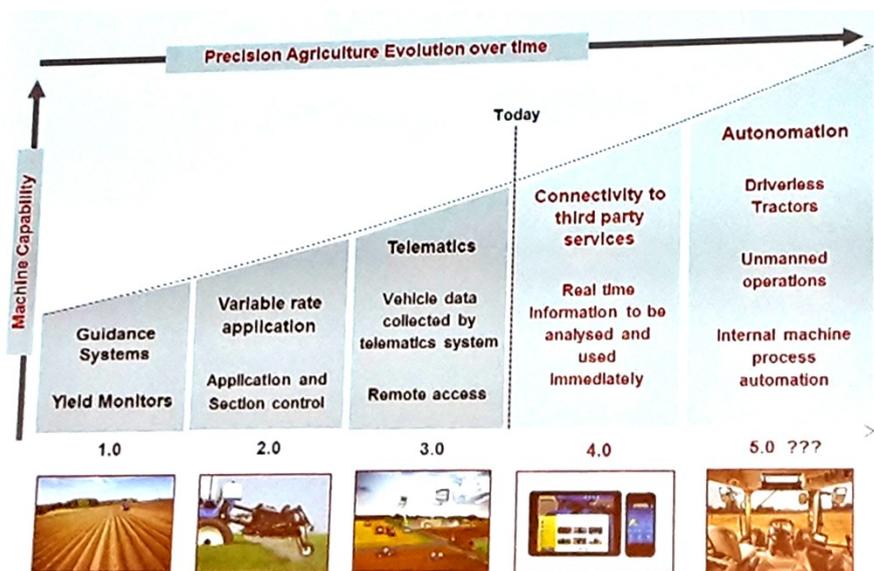


Figure 1.8: Evolution of Precision Agriculture over the time (CNH source).

The first step is characterized by the introduction of automatic steering guidance systems and yield mapping system. Then, the development in electronic sector allowed to implement machines able to modulate inputs application or the intensity of working tools depending on field variability. Thanks to section control technologies, it is possible to perform VRT to the single row. Nowadays, data derived from proximal and remote sensing represent a new layer useful to better study field variability and define more precise managing strategies. Finally, following this trend, in the next future will be developed technologies able to perform managing operations in a completely automated way.

Indeed, guidance systems are characterized by a different degree of accuracy and automation. They can be divided in assisted guidance system, semi-automatic steering guidance system and automatic steering guidance system. In the first one, the operator follows the working lines supported by a led bar showing the correction to apply with an error of 20 cm. While in the other two systems satellites signal is converted into positioning data by a unit control that performs line correction through electronic or hydraulic tools. Besides, automatic steering guidance system has the possibility to automate the turning operation at the end of the field and the successively positioning over the next line. Finally, implementing the automatic steering guidance system with an RTK error correction leads to achieve the highest level of accuracy, allowing to perform sensitive managing operations such as planting operation or soil tillage operations in strip-tillage.

Guidance systems are composed of different components: Satellite receiver to catch the signal; monitor able to process data and show the position of the machine in the field. It also allows to follow the right line and the led bar; electronic or hydraulic tools useful in automatic steering guidance systems (Fig. 1.9.).

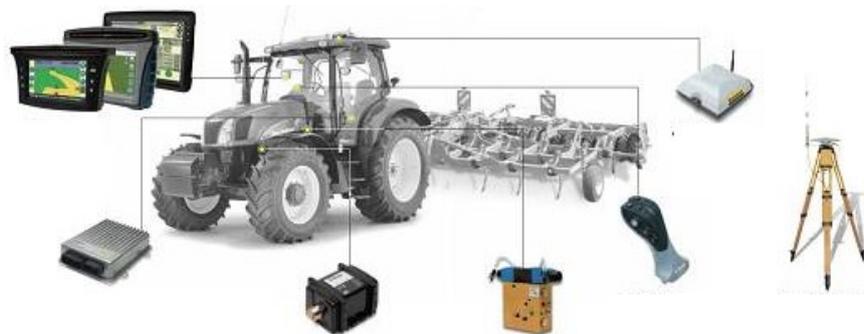


Figure 1.9: Automatic steering guidance system components with RTK-GPS correction.

Moreover, these components are also the basic devices required to manage field variability. In fact, a monitor properly implemented recognizes the position of the machine in the field and provide to modulate the treatment that is carrying out on the basis of the previously set information. To this end, it is most important to detect and study the field variability in order to define a managing strategy.

### 1.2.3 Components of the variability

Field variability derived from the interaction of different components: spatial variability; temporal variability; crop variability; management variability.

Spatial variability is characterized by different soil features within the field, strongly influenced by pedogenesis processes (Bocchi e Castrignanò, 2007) that define static features such as texture, soil organic matter content (SOM), cation exchange capacity (CEC). The presence of spatial variability within the field influences crop yield, showing field zones with different productive performances (McBratney et al., 2005). Besides, observing crop yield variation during the time is possible to investigate the temporal variability. It is meant as a number of factors limiting crop production and their evolution across the years. Therefore, some factors such as soil moisture and nitrogen content change within the same year, influenced by weather condition and soil biochemistry interactions (Bocchi e Castrignanò, 2007). While, it is possible to detect the evolution of some

features under different field zones across the years independently by their behavior within the year (Blackmore et al., 2003). On the other hand, crop variability represents the different crop productive suitability of the field, influenced by the interaction between the crop and soil features (Zhang et al., 2002). Finally, management variability includes the effects caused by managing operations on the different zones of the field, including: Tillage practice; crop hybrid; crop seeding rate; crop rotation; fertilizer application; pesticide application; and irrigation pattern (Zhang et al., 2002).

#### 1.2.4 Study of the variability: yield maps

Yield map is one of the most important sources of data representing a liable layer useful to study field variability (Bocchi e Castrignanò, 2007). Information about crop yield show differences within the field and their evolution over the years (Basso et al., 2007; 2011b). Yield maps derive from combine implemented with yield mapping system provided by the different company (Fig. 1.10.).



Figure 1.10: Combine implemented with yield mapping system.

Yield mapping systems are generally composed of a GPS receiver to georeferenced data and a unit control to process and store data. Besides, grain moisture is assessed using a sensor that measures electrical conductivity. While yield data is detected through flow sensor measuring grain volume or the impact on a plate.

On the other hand, studying yield maps is possible to obtain supplementary information about field variability. Indeed, it is possible to get preliminary information about the crop residue and the total biomass knowing the harvest index of the considered crop.

However, information derived from yield maps can be implemented and validated using multispectral images recorded by proximal or remote sensing (Basso et al., 2007). In fact, monitoring the crop in a specific stage of its cycle allows obtaining information about the productive response within the field (Basso et al., 2012). Using the reflectance values to different wavelength bands is possible to assess vegetation indexes such as normalized differential vegetation index (NDVI) ratio vegetation index (RVI) (Batchelor et al., 2002). In this regard, information deriving from yield maps, proximal or remote sensing and soil features can represent

the layers with which their interpolation enable to study field variability and characterize stable homogeneous zones over the years.

### 1.2.5 Study of the variability: soil features and data collection

Crop-yield response is influenced by spatial and temporal soil variability (Basso et al., 2016; Pezzuolo et al., 2017). Despite recognition of the heterogeneous nature of soil features, the lack of sensitive tools to detect subtle shifts among soil properties has a limited spatial characterization of such variability. In fact, the implementation of traditional sampling methods is inadequate for assessing the interrelated physical, chemical, and biological soil properties responsible for variations in crop yield (Cillis et al., 2017).

Over the last decade, non-destructive geophysical sensors designed to measure the soil electrical conductivity (or its inverse resistivity) have been extensively used to map the complex patterns in soil conditions that contribute to agronomic yield potential (Peralta and Costa, 2013; Marinello et al., 2017). The increasing number of soil and crop sensors provides an opportunity for definition of a site-specific crop management plan, and enables the synergistic use of observations from different sensors for a better understanding of land processes (Marinello et al., 2016) such as spatial variations or delineation of homogeneous zones at farm scale (Tucker et al., 2005).

The purpose of Electrical Resistivity (ER) surveys is to determine the resistivity distribution of the surrounding soil volume (Johnson et al., 2001). Artificially generated electric currents are applied to the soil and the resulting potential differences are measured (Fig. 1.11.). Potential difference patterns provide information on the form of subsurface heterogeneities and their electrical properties (Kearey et al., 2002; Lardo et al., 2012).

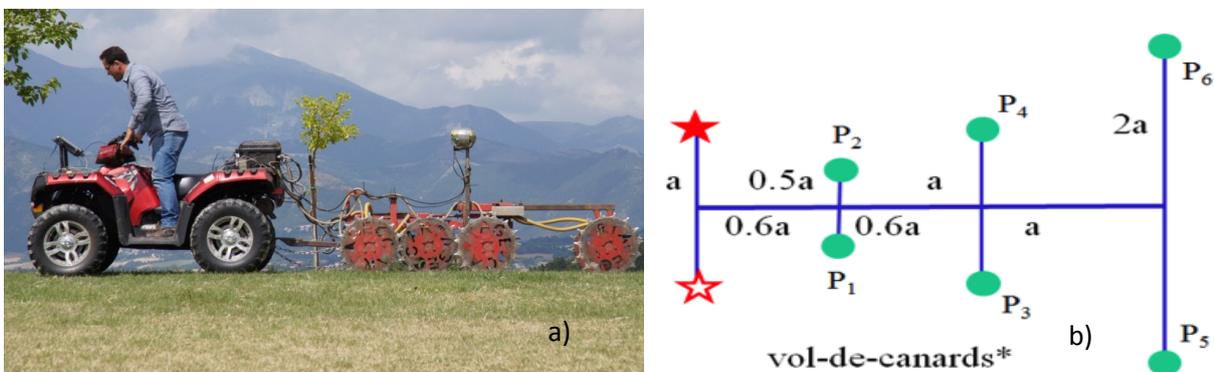


Figure 1.11: ARP system during data collection (a). ARP scheme and current interception.

High level of soil matrix heterogeneity leads to a change in ER detection that allows to better investigate soil-spatial variability. ER of the soil can be considered as a proxy for the variability of a soil's physical properties (Banton et al., 1997; Samouelian et al., 2005; Basso et al., 2010) including texture (Brus et al., 1992; James et al., 2003; Saey et al., 2009), type (Anderson-Cook et al., 2002), and moisture (Reedy and Scanlon, 2003; Sherlock and McDonnell, 2003; Zhu et al., 2010). These advantages may include lower cost, increased capacity and efficiency, and more timely results (Marinello et al., 2015). Moreover, the ability of a sensor to provide high-resolution characterization, as compared to sampling and removal methods, allows for an increase of overall spatial estimation accuracy even if the accuracy of individual measurements is lower (Valckx et al.,

2009; Sudduth et al., 2013). Furthermore, ER can be implemented as an indirect measure of other soil properties (Jaynes, 1996) and thus used as an indicator of crop production.

### 1.2.6 Study of the variability: homogeneous zones classification

Collecting field data and information, regarding soil and crops features represent the first step to get an objective management of the variability. The collection of data has to be performed by a non-random pattern, but it has to be representative of the whole field. In this regard, it is important not to concentrate the analysis in prevalent areas or where it is easier to highlight the differences with respect to close areas in a way that does not affect the sampling correspondence with the reality of the field.

A homogeneous zone to be defined homogeneous must be the more stable than lower is the temporal variability, and it is much more manageable as is defined in space, so the greater is its spatial variability in comparison with the other zones. Therefore, in order to detect a defined and stable homogenous zone, it is necessary to obtain data relating to the physical-chemical characteristics of the soil and their evolution in the time. Then, as described in the previous paragraphs, an analysis of the soil obtained by not-invasive tools that can scan the entire surface of the field is able to provide information on the spatial variability of the field (1.12.). Besides, it is also possible to get more information on the spatial variability of the field in a single passage, for example, exploring different layers of soil profile or collecting information about altitude and slope.

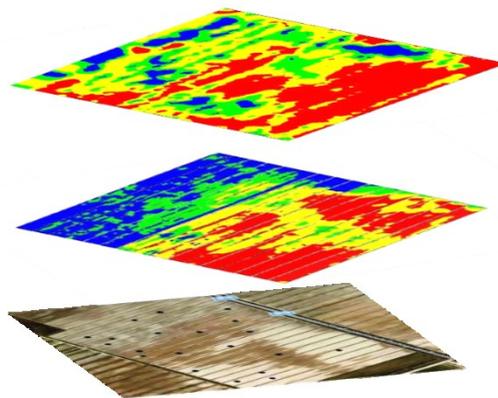


Figure 1.12: Field information layers derived from different sources.

Instead, the historical yield maps give information about the spatial variability evolution over the time. It is evident that a great availability of data related to the field allows to a more accurate definition of homogeneous zones. To this end, the difficulty remains to interpolate the data from different sources and to identify the right number of homogeneous zones that characterize the field, taking into consideration the feasibility to manage that. In this regard, the precise definition of homogeneous zones is weighted and calculated using software able to interpolate and perform a statistical analysis of data, returning as output the classification and the optimal number of homogeneous zones that characterize the field. These type of software uses the fuzzy c-means unsupervised classification algorithm. This algorithm involves the task of dividing data points into

homogeneous classes or clusters so that items in the same class are as similar as possible and items in different classes are as dissimilar as possible.

Therefore, applying this algorithm to the georeferenced points with different attributes values is possible to group into classes the points with similar characteristics. The type of matrix to use for data interpolation is chosen on the basis of the number of variables selected for the classification and the result deriving from the statistical analysis. Finally, indexes are calculated which indicate the optimal number of homogeneous classes to be taken. Uploading the new file in a GIS software it is possible to display the geographic position of the classes, and finally, assign their productive potential considering soil features and crop yield. To this end, the defined homogeneous zones can be managed through VRA.

### **1.2.7 Precision Agriculture application**

Knowing the entity and the distribution of the field variability, and the consequently study and homogeneous zones characterization represent the starting point for variable rate applications (VRA). Over the last years, VRA increased their feasibility and accuracy taking advantage of variable rate technologies, meant as all the technological implementation allowing the modulation of the different treatments. Nowadays, VRA can be divided into two categories: VRA based on maps; VRA based on sensors.

In the first one treatments modulation is performed on the basis of a previously built prescription map. The prescription map is a georeferenced map having one or more information about the treatments for every homogeneous zones characterizing the fields. Therefore, the machine recognizes its position within the field using a GPS receiver and performs the considered treatment on the basis of the information given by the prescription map uploaded on the monitor. Finally, the unit control modulates the working elements through electronic or hydraulic tools.

On the other hand, VRA based on sensors do not require the use of GPS receiver. In fact, changes in the intensity of the treatments are provided by sensors that collect data on-the-go. A unit control processes the information and successively modulates the treatments considering previously set parameters.

In this regard, VRA can be adopted to carry out managing operations such as soil tillage operations, planting operation, fertilizers and pesticides application and irrigation.

#### **1.2.7.1 Soil tillage operations**

Soil tillage operations provide a suitable environment for plant growth. Tillage systems are characterized by different soil tillage intensity. But, tillage intensity is also influenced by soil features and other parameters. In fact, studying soil variability is possible to define the suitable tillage system to adopt. It is useful to mitigate energy consumption and soil degradation. Besides, additional information derives from the assessment of soil compaction and the amount of crop residue over the field surface, which allows defining the optimal working depth increasing plant growth suitability and residue mixing.

### **1.2.7.2 Planting operation**

Soil conditions strictly affect planting operation and consequently seeds germination and plants grow. Therefore, studying stable soil features and its condition at sowing time allows to define the best strategy leading to an optimal seeds deposition. In fact, considering the productive potential of the different homogeneous zones is possible to define the right seed density and reference hybrid. Different hybrids are uploaded in separate tanks and seed density is modulated using electrical or hydraulic tools on the basis of the information given by prescription maps.

Seed deposition also is an important parameter to consider. Keeping a constant seed depth deposition allows achieving regular and uniform plants emergence. The definition of the optimal seed depth deposition is due to soil bulk density and moisture, which is modulated using hydraulic or pneumatic tools that regulate the strength of the planting elements on the soil surface.

### **1.2.7.3 Fertilizers application**

The first advantage of PA related to fertilizer application is the adoption of supported or automatic steering guidance systems, which allow limiting the overlapping problem and fertilizers wasting. In addition, variable rate fertilization leads to apply the optimal amount of fertilizer increasing its efficiency. It is widely used in nitrogen application due to the sensitivity of such crops to this element and its dynamic in the soil. Variable rate nitrogen application can be provided using prescription maps or sensors. In the first case, the amount of fertilizer to apply to each homogeneous zone is defined considering the previously studied soil variability. Even in this case, specific tools modulate the nitrogen rate on the basis of the information given by the prescription map and the position within the field detected by the GPS receiver.

Variable rate nitrogen application based on sensors utilizes information about crops status collected on-the-go. During fertilize application the rate is modulated considering the information collected by the sensor and processed by the unit control. It does not require GPS receiver but only the tools to modify the application rate. Several sensors were developed, investigating crops status using light reflectance or plant fluorescence. In this way is possible to define plants chlorophyll content and aboveground biomass at the fertilization time. Consequently, the unit control uses an algorithm that automatically translates this information into the optimal nitrogen rate considering previously set parameter.

### **1.2.7.4 Pesticides applications: herbicides and fungicides**

Variable rate pesticides application follows the same principles of fertilizers one. In fact, the adoption of supported or automatic steering guidance systems allows to decrease overlapping with product saving and reducing the negative effect of herbicides on sensitive crops such as soybean. In addition, technological progress leads to develop sprayers implemented with section control able to separately manage the single nozzle. The highest efficiency is reached in those sprayers implemented with separated tanks keeping split water and products which are mixed at the end of pipes system based on need.

However, the same approaches are used to modulate the inputs as well. Regarding pre-sowing herbicide application, prescription maps are built using information deriving from remote sensing. Multispectral cameras mounted on drones, aircrafts or satellites detect the side of the field

covered by weeds thanks to the different reflectance compared to bare soil. Other information is provided during the harvesting operation of the previous crop validated by scouting at the application time.

On the other hand, sensors mounted on the machine such as digital cameras and spectrometer are widely used to detect the presence of weeds within the field taking advantage of different shape and reflectance differences. Consequently, site-specific input application is performed. In the same way, fungicides application is carried out identifying the presence of leaf fungal damages expressed as spot or stripe (Heege, 2013).

#### **1.2.7.5 Irrigation**

The efficient use of water in agriculture is one of the most important agricultural challenges that modern technologies are helping to achieve. Variable rate irrigation combines information related to soil features, topography, climate model and crops water requirement to manage field variability. Nowadays, these technologies are implemented on big irrigation systems such as pivot and rainger. A GPS receiver is mounted on the irrigation system which recognizes its spatial position in the field and modulates the water amount on the basis of a prescription map uploaded in a unit control.

Regarding the tools used to modulate the application rate, different solutions were developed differing the degree of the precision and accuracy. Some systems change the amount of water applied modifying their speed across different homogeneous zones of the field. In other ones, spans system is divided into sectors managed by different unit control which modulates water flow rate depending on the information given by the prescription map.

#### **1.2.8 Economic and environmental benefits**

The adoption of precision agriculture technologies and principles lead to achieving economic and environmental benefits. Some of them can be directly observed since the first year of adoption, while others can be appreciated over the years. One of the most immediate advantages is the related to the installation of the automatic steering guidance system, which allows reducing overlapping, especially in fertilizer and pesticide application, and stress factor for the operator. It also allows increasing the working speed from 13% to 25% enhancing operating working capacity with the possibility to carry out the managing operations during the night. Besides, the possibility to manage the single working element gives the possibility to reduce inputs waste, especially in not regular shape fields.

On the other hand, managing the field variability with VRA reaches advantages from different points of view. In fact, modulating soil tillage intensity on the basis of soil features and crop residue allows decreasing energy consumption related to fuel consumption. In addition, variable rate inputs applications, especially nitrogen applications, get an increase in inputs efficiency from 17% to 25% (McBratney et al., 2005). Therefore, the optimization of the nitrogen rate applied for each homogenous zones allows to reduce production costs and mitigate nitrogen leached into the groundwater. However, the total costs expected for the adoption of precision agriculture can be divided into technologies used for data collection and VRA and the knowledge required for data

interpolation, the study of field variability and definition of the best managing strategies. Finally, an interesting precision agriculture application able to gain an economic benefit is the possibility to monitor crops using remote sensing and define the best harvesting period (McBratney et al., 2005), or to perform differential harvesting on the basis of defined qualitative standard (Cillis et al., 2016).

### 1.3 Precision agriculture and soil tillage systems

#### 1.3.1 Conservation precision agriculture

The development of precision agriculture technologies leads to an increase in machines implementation which allows performing more precise managing operations in different agricultural systems. In fact, the high accuracy automatic steering guidance systems with RTK correction are a useful tool in those tillage techniques where all the managing operation should be performed following the same lines. Strip tillage, which provides less than 50% of field surface tilled, takes advantage from the high level of repeatability and recur the same lines during the planting operation. In order to amplify the positive effects on the of this tillage system, tilled strips have to remain fixed over the years. Besides, the deposition of the seeds in the middle of the tilled strips allows better seed germination and emergence uniformity, with a positive influence in term of yield performance (Fig. 1.13.).



Figure 1.13: The automatic steering guidance system with RTK-GPS correction allows to an optimal seed deposition in the middle of the tilled strip (a). The high precision and data repeatability leads to enhance the agronomic benefits of strip-tillage (b).

On the other hand, changing the position of the sowing lines in no-tillage technique leads to the seeds deposition in the inter-row of the previous crop (Heege, 2013), with positive production response in wheat and canola (Mccallum, 2007). In this regard, the adoption of the suitable tillage system is strictly related to weather condition, soil features and crop rotation. Therefore, soil tillage intensity modulation can be performed using the previously cited approach: site-specific soil tillage based on maps and site-specific tillage based on sensors.

#### 1.3.2 Site-specific soil tillage based on maps

Homogeneous zones characterization allows defining the right tillage technique and its intensity across the field, which gets an advantage in term of gross revenue (Basso et al., 2011b). The same study reported that the adoption of the site-specific no-tillage system obtained higher economic benefits than the uniform one. The main parameters considered to define the best tillage technique and its tillage intensity are soil features, soil compaction, the presence of crop residue

and slope. Therefore, a new information layer useful to define the best strategies is defined after data interpolation. In fact, crop residue monitoring gives additional information about crop growth within the field. The degree of the covered surface by residue can be detected using remote sensing. A widely used remote sensing tool used to survey field crop residue is satellite. Several missions such as Landsat 7 and 8 TM and Sentinel2 were launched over the year, which provide for taking periodically multispectral images with a resolution ranging from 10 to 60 m. In this regard, crop residue is detected taking advantage of the residue reflectance to bands of the electromagnetic spectrum close to 2100 nm due to the presence of lignin fraction (Daughtry et al., 2006), or using soil indices that discriminate bare soil. Getting this information gives the possibility to build prescription maps for planter element modulation. Finally, it is possible to manage the working intensity of specific tool such as row cleaner depending on the previously studied presence of crop residue (Heege, 2013). On the other hand, nowadays the application these technologies have an interesting room for improvement but it is still inserted in research programs (Zheng et al., 2012).

### 1.3.3 Site-specific soil tillage based on sensors

Implementing operating machines with on-the-go sensors allows collecting information about soil condition, soil moisture, tillage pan and crop residue covering the surface. Regarding soil tillage machines, the implementation of the working elements with sensors enables to measure the strength of the soil to the tillage. A unit control elaborates the information and define the clumps size and modulate the working intensity through electrical or hydraulic tools. The speed of the tractor is modulated for power harrow machines as well. Besides, a multispectral camera using near-infrared bands define soil moisture, and the tillage intensity is modulated in order to obtain the optimal seedbed preparation. In the same way, seed deposition is modulated considering the site-specific soil moisture during planting operation in order to allow the suitable condition for seeds germination and uniform emergence. Finally, electromagnetic induction sensors mounted on the front of the tractors survey soil condition and modulate tillage intensity in order to manage tillage pan.

Considering minimum tillage technique, information about the amount of crop residue represent a source of information useful to modulate tillage intensity in order to get agronomic and energetic advantages. A high-resolution camera mounted on the front of the tractor enables to distinguish the presence of residue over the surface (Fig 1.14.). The information is processed by the unit control that automatically modulates tillage intensity (Pforte and Hensel, 2010).

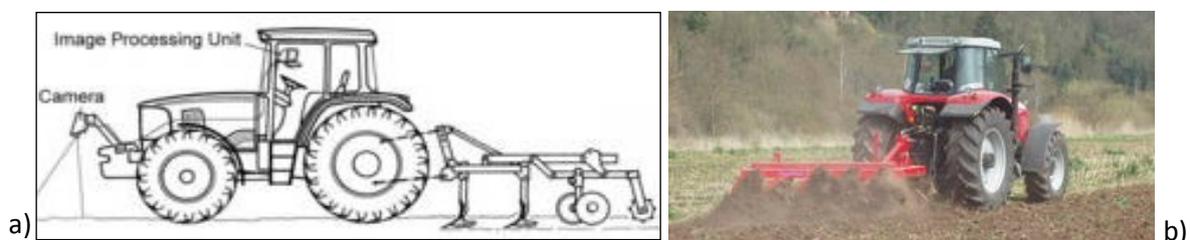


Figure 1.14: Soil tillage depth modulation components (a). Minimum tillage cultivator implemented with tillage depth modulation system.

An alternative approach measures the amount of crop residue through the difference in reflectance between bare soil and residue to different electromagnetic spectrum band or indices, using the multispectral camera (Daughtry et al., 2001). Site-specific soil tillage intensity based on residue also achieves agronomic benefits in term of the optimization of the residue mixing and degradation of organic fraction.

In this regard, crop residue management strategy has to be planned since the harvesting operation. The basic requirements to an optimal residue management are a uniform distribution over the field and a straw size that does not affect the next managing operations. Specific tools and sensors, which monitor the straw size, the combine position within the field and the wind intensity, provide for a permanently uniform distribution of the residue across the field.

### 1.3.4 Site-specific management tools

In order to get fast germination and uniform plants emergence the optimal seeds deposition is the first goal to achieve. Considering conservation tillage systems, seedbed could be affected by the presence of big size clumps and crop residue. This condition can negatively influence seeds deposition and their emergence. Therefore, studying seedbed condition and managing its variability allow to reach a high level of plants emergence in conservation tillage systems. In this regard, electrical, hydraulic and pneumatic tools were developed to constantly modulate planting element parameters on the basis of the information supplied by the unit control (1.15.).

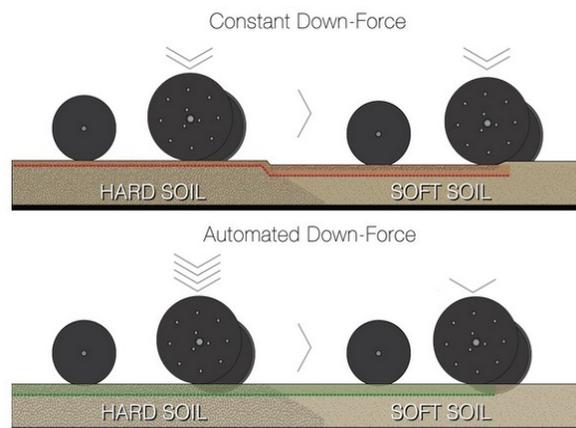


Figure 1.15: Effect of automated Down-Force on depth seeds deposition.

Unit control and mechanical tools are linked by the standardized communication protocol ISOBUS (ISO11783) or using Bluetooth and wireless technologies. The seed depth control is modulated through the information derived from a prescription maps or on-the-go soil data recorded by sensors. It is performed by hydraulic or pneumatic tools that maintain the previously set depth (Fig. 1.16.).



Figure 1.16: Hydraulic (a) and pneumatic (b) tools to constantly maintain seeds depth deposition.

It is reached applying the right pressure on every single planting element. In this way changes in soil moisture, soil texture and irregular seedbed condition are managed (Suomi e Oksanem, 2015). The same approach is followed in modulating the row cleaners working intensity in order to avoid crop residue over the seed deposition line or losses in fine soil useful to seed germination. Finally, the best managing strategies and the highest inputs efficiency levels are reached implementing seed depth controller with VRA enable to manage the productive potential of different homogeneous zones of the field.

### 1.3.5 Soil compaction management

Currently, agricultural systems are considered (analyzed and studied) from different points of view compared to the past. One is the protection of the environment in terms of carbon emission and soil features (López-Garrido et al., 2009; Pezzuolo et al., 2014). Soil features are negatively influenced by soil compaction, a side effect of modern agriculture experienced on soils in different parts of the world. Soil compaction is defined as “the process by which the soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby increasing the bulk density” (Kroulík et al., 2011). Soil compaction leads to negative consequences such as the reduction of soil porosity, a decrease of aeration (McHugh et al., 2009), reduction of saturated hydraulic conductivity and an increase in soil resistance to roots exploration (Balbuena et al., 2003; Valdes-Abellan et al., 2015). For this reason, such method was implemented for the present study. Machines crossing fields are the main source responsible for soil compaction (Chen & Yang, 2015), and their most influencing factors are tire dimension, wheel loads, and inflation pressure.

Several mechanical, agronomical, and management solutions are available to mitigate soil compaction. Implementation of low ground pressure tires can allow a reduction of soil compaction on topsoil for about one third of the pressure in comparison with conventional practices (50-80 kPa) (Chamen et al., 1990), and in equipping machines with rubber tracks (Fig. 1.17.), a reduction in soil compaction on subsoil is observed (Ansorge & Godwin 2007, 2008).



Figure 1.17: Tractor and combine implemented with rubber tracks to mitigate soil compaction.

It is possible to use lighter machines and reduce passages in the fields adopting minimum tillage or no-tillage techniques. Subsoiling allows enhancing soil porosity and water drainage. In addition, compaction is reduced adding organic carbon on soil, depending on soil texture (Kumar et al., 2009; Martín-Lammerding et al., 2013).

Generally, soil compaction leads to negative growth conditions for crops due to high mechanical impedance for roots, decrease in soil aeration, and decrease in water storage (Da Silva & Kay, 1996). There are crops more susceptible to soil compaction than others, as suggested by Koch et al., (2008). Sugar beet (*Beta vulgaris* L.) is accounted as a susceptible crop to compaction (Tijink & Maerlaender, 1998). Reduced emergence, initial growth, final yields, and root quality parameters are reported in compacted soils (Chancellor, 1976; Gemtos & Lellis, 1997; Tolon-Becerra et al., 2011). Compaction can reduce leaf area, dry matter accumulation, and plant population in sugar beet. Furthermore, the total length and distribution of roots in the soil profile can be reduced by topsoil compaction up to 50% (Brereton et al., 1986). Controlled traffic farming (CTF) is one of the most interesting and often efficient ways to mitigate soil compaction. In CTF, all or most of operations are performed on well -defined traffic lanes (Fig. 1.18.). Machines are equipped with satellite guidance systems which permit crossing repeatedly the same lanes; additionally, machine widths are closely matched with standardized track widths >3m and narrow tires are implemented (Holpp et al., 2011).

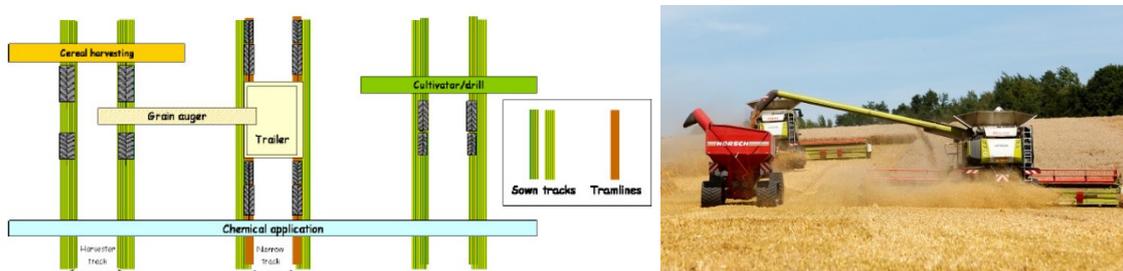


Figure 1.18: Controlled traffic farming (CTF) considers the working width of the machines used for every managing operation in order to cross the field in the same lines.

Machines never exit defined traffic lanes, therefore, topsoil is only marginally affected by compaction (Hamza & Anderson, 2005; Chamen, 2006). CTF has demonstrated an increase in crop yield related to random traffic farming. Advantages can be significant in root and bulb crop systems for instance potatoes, onions and sugar beet (Gasso et al., 2013; McPhee et al., 2015).

### 1.3.6 Management information systems and predictive models

Precision agriculture technologies provided the opportunity to study within field variability and to manage efficiently a large amount of information (Fountas et al., 2006; Aubert et al., 2012). The technological development of on-board tractor performance monitoring systems allows the acquisition of tractor and implement status data through the ISOBUS protocol. It collects useful information to optimize the managing operations and field productivity (Scarlett, 2001; Backman et al., 2013). The combination with the DGPS systems could be used for spatial mapping of tractor-implement field performances (Taylor et al., 2002) (Fig. 1.19.).



Figure 1.19: On-board tractor monitors enable to monitor machine parameters and to get information about the performance of the carrying out managing operations.

These goals can be reached studying field variability adding several information layers derived from extensive databases as the basis for decision support and control actions. Besides, on-the-go sensors mounted on agricultural machinery provide site-specific analytical information of soil and crop conditions (Adamchuk et al., 2004). In this regard, the development of autonomous vehicles adopted to field activities will gradually change the role of the tractor. The ISOBUS protocol plays an important role in the development of precision agriculture by helping information to be exchanged and stored more efficiently among sensors, processors, controllers and software packages from different brands within the same tractor or operating machine (Stafford, 2000).

Once studied the field variability and adopted VRT enabling site-specific management, defining the best strategies to manage the homogeneous zones represent one of the precision agriculture phases which can significantly increase agronomic, economic and environmental benefits. In this regard, crop modeling, when suitably tested, could be a useful tool for defining combinations of management strategies in order to achieve the objectives required for sustainable crop production (Basso and Ritchie, 2015). It is also necessary to identify the best in space and time approaches for sustainable production across different agricultural systems, which cannot be reliably obtained with field experiments. Crop simulation models can be divided into simple models and complex ones. Simple models are based on statistical information and historical yield to predict crop production of large range areas. On the other hand, complex models simulate the evolution of soil-plant-atmosphere interaction using more detailed information that may be unavailable in several situations. However, crop models are also divided in deterministic and stochastic. The first

group provides information on the basis of set condition under uniform soil and crop growth conditions, while stochastic models consider the uncertainty due to spatial and temporal variability, abiotic and biotic factor influencing crop growth. But, it is possible to get the same accuracy using deterministic models too. It is made possible running the models for different years and knowing the soil spatial variability divided into homogeneous zones (Basso et al. 2007).

Moreover, deterministic models are divided into statistical, mechanistic, or functional ones (Addiscott and Wagenet 1985, Ritchie and Alagarswamy 2002). Because of a lack regarding variation in soil features and weather conditions, statistical models outcomes cannot be exported over places and time. For these reasons, statistical models are used to determine past yields and historical influences (Gage et al., 2015).

Mechanistic models simulate soil-plant-atmosphere interaction considering physical, chemical and biological processes. Processes are investigated at fine scale time, which require a large amount of input parameters. For this reason, mechanistic models outcomes get a high level of uncertainties, which make them less reliable to those outside of the model development group (Basso et al., 2012a). Finally, functional models are based on empirical functions, such as crop's interception of energy using plant leaf area and radiation use efficiency, to simulate complex processes. As a result, simulated data reasonably explain the observed ones. Simulation is performed starting from daily time inputs for weather and management operations such as temperature, precipitation, solar radiation and fertilizer inputs. To this end, these models, when properly tested, provide an appropriate level of accuracy of crop production. Simulation models are widely used to simulate soil organic matter, soil water balance and biochemical fluxes affecting crop growth and land management.

CENTURY is one of the most used models to simulate soil organic matter (SOM), plant production and nutrient cycling over long-term (Parton et al., 1988). It uses a monthly time step with monthly average maximum air temperature (at 2 m height), monthly precipitation, soil texture, nutrient and lignin content of dead plant material, and atmospheric and soil inputs of N. However, CENTURY lacks short-term input data. A daily incrementing modification of CENTURY called NGAS-DAYCENT simulates trace gas fluxes of nitric oxide (NO), nitrous oxide (N<sub>2</sub>O), and dinitrogen (N<sub>2</sub>) from soils as well as methane (CH<sub>4</sub>) formation and oxidation (Parton et al. 1996, 1998, 2001; Del Grosso et al. 2000a, b). Another mechanistic SOM and gas emission model is the DeNitrification-DeComposition (DNDC) model, which was used to simulate N<sub>2</sub>O and CH<sub>4</sub> emissions from agricultural lands (Li 1995, 2000), but it requires a lot of input detail than other models.

Regarding crop growth and biogeochemical fluxes simulation models, the Decision Support System for Agrotechnology Transfer (DSSAT) represents one of the more reliable and user-friendly models (Tsuji et al. 1998). It is composed of a suite of modules to predict crop yield of the most cultivated legumes (CROPGRO), cereal crops (CERES), crops with belowground storage (SUBSTOR). They are based on empirical functions to estimate the soil water balance (runoff, drainage, evapotranspiration, soil storage) and biomass production. Besides, simulations are executed on a daily time step using solar radiation, temperatures (maximum and minimum), and precipitation, thereby accounting for day-to-day variation that can be substantial. Another well-established

model is the Systems Approach to Land Use Sustainability (SALUS) model. SALUS is a process-based model developed to simulate the interactions soil, between climate, crop genotypes and management strategies on crop growth, water and nutrient cycles during growing seasons. It implements the well-established CERES model with modifications in the nitrogen cycle, water balance and tillage (Basso et al., 2006; Albarenque et al., 2016). SALUS model uses soil parameters by layer, daily weather parameters, management decisions, leaf development coefficients and crop coefficients as inputs to determine crop growth, nutrient cycle and water balance at daily step.

Soil features include silt, clay and sand content, pH, bulk density and soil organic carbon content. Regarding weather input parameters, it considers solar radiation, minimum and maximum temperature and precipitation. The SALUS model predicts crop germination and duration based on thermal time to germination and duration respectively.

Consequently, Radiation-use efficiency, characterizing each crop, and leaf area index (LAI) are used to assess biomass accumulation at daytime (Dzotsi et al., 2013).

It is also implemented with a soil nitrogen (N) and soil organic matter (SOM) modules, derived from modification carried out to CENTURY (Parton et al. 1988). SALUS model has been tested for cereal crop phenology and yield (Basso et al., 2011a, 2012), nutrient cycling (Senthilkumar et al., 2009; Giola et al., 2012; Basso & Ritchie, 2015) and soil water balance (Basso et al., 2010). Finally, the Environmental Policy Integrated Climate (EPIC) and The Agricultural Production Simulator (APSIM) models use processes similar to CENTURY and DSSAT (Williams et al. 1984; Keating et al. 2003).

## 1.4 Research synopsis and objectives

Agricultural systems are asked to satisfy the increasing global demand for food and fibre for a growing population. The intensification of the current systems in term of inputs and outputs lead to raise the concerns about the impact on the environment. The continued use of tillage with inversion layers has led over the years to change the physical, chemical and biological features of the soil that involves the degradation of the structure leading to a general deterioration of water retention and infiltration, phenomena of intense compaction and a reduced content of organic matter with strong depressions of biological and microbiological activity. These negative effects lead to a reduction in food production in the world.

Conservation tillage techniques, have been adopted to reduce these negative impacts even if sometimes characterized by lower crop yields. However, the potential for these techniques to mitigate these problems is strictly related to the soil features and climatic conditions. Therefore, the presence of field scale variability represents the first requirement in adopting precision agriculture. Managing spatial and temporal field variability is one of the main advantages of precision agriculture. In this regard, variable rate applications (VRA) on stable homogeneous zones promote an increase in crop yield reducing negative environmental consequences.

The main objective of this thesis is to identify, through experimental tests combined with mid-term simulation of different scenarios, the best technical solutions enable to preserve soil fertility and reduce pollution linked to agriculture studying the synergy between conservation agriculture and precision agriculture. In this regard, considering the background described above and its highlighted gap, the hypothesis of this thesis are (1) to survey within-farm soil and yield variability in order to delineate the homogeneous zones and productive potential; (2) study the synergy between conservation agriculture and precision agriculture allowing the optimization in terms of crop yield, net energy and energy efficiency; (3) Identify the best strategies, derived from the synergy between conservation agriculture and precision agriculture, able to decrease the CO<sub>2</sub> emissions of agricultural systems in the mid-term using SALUS simulations.

Chapter 2 deals with the study of spatial and temporal variability. In order to get a reliable homogeneous zones characterization, several levels of information derived from different sources were used to perform a cluster analysis. Besides, the productive potential was assigned to each homogeneous class defined by the analysis. Successively, starting from the homogeneous zones characterization, the optimal inputs rate to apply to each zone were assessed using SALUS model simulation. In chapter 3 different treatments were studied in term of crop yield, net energy and energy efficiency. Conventional tillage and conservation tillage systems were tested, and the contribution of precision agriculture under conservation tillage techniques was studied as well. Finally, chapter 4 aims to study the effects of the same treatments on carbon emissions. This chapter focus the attention on soil carbon losses under different tillage systems and the CO<sub>2</sub> emissions related to managing operations. To this end, converting each item in kg CO<sub>2</sub> eq., the best strategies able to decrease the total carbon emission were defined.

## **2 Field-scale electrical resistivity profiling mapping for delineating soil condition in a Nitrate Vulnerable Zone.**

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Applied Soil Ecology.

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Venice Lagoon is an extremely heterogeneous environment conditioned by natural changes and anthropogenic pressures. The area is a particularly vulnerable system characterized by high spatial geomorphological variability. Site-specific crop management, defined as the best strategies to manage heterogeneous farmlands, has the potential to maximize agricultural production while preserving soil and water resources. This work was aimed at identifying and characterizing spatial variability within the fields in terms of soil fertility and productive potential using precision agriculture principles. Automatic resistivity profiling (ARP) was implemented to study spatial variability of the field and to define the best localization of twenty soil sampling points. Three years' historical yield maps were used to determine homogeneous zones within the study area. The application of a fuzzy c-means clustering algorithm led to classification of four homogeneous zones, which were assigned with productive potentials using an ANOVA test of soil features and historical yield data. Such classification was validated by a comparison of the homogeneous zone's productive potential with five-year average production.

### **2.1 Introduction**

The Venice Lagoon (Italy, North-Adriatic Sea) is an extremely heterogeneous environment conditioned by natural and anthropogenic pressures (De Franco et al., 2009). The area is a particularly vulnerable system characterized by high spatial geomorphological variability (Scudiero et al., 2013).

Regarding arable lands, crop-yield response is influenced by spatial and temporal soil variability (Basso et al., 2016; Pezzuolo et al., 2017). Therefore, variability of soil features within a field cannot be managed using conventional farming practices (Robert, 2002). Site-specific crop management, defined as the best strategies to manage heterogeneous farmlands, has the potential to maximize agricultural production while preserving soil and water resources (Wallace, 1994; Pezzuolo et al., 2014).

Adoption of new technologies to investigate the field-scale variability (Pezzuolo et al., 2016; Dubbini et al., 2017) is the first step to achieve a successful site-specific management plan (Marinello et al., 2017a). Despite recognition of the heterogeneous nature of soil features, the lack of sensitive tools to detect subtle shifts among soil properties has limited spatial characterization of such variability. In fact, the implementation of traditional sampling methods is inadequate for assessing the interrelated physical, chemical, and biological soil properties responsible for variations in crop yield (Cillis et al., 2017).

Over the last decade, non-destructive geophysical sensors designed to measure the soil electrical conductivity (or its inverse resistivity) have been extensively used to map the complex patterns in soil conditions that contribute to agronomic yield potential (Peralta and Costa, 2013; Marinello et al., 2017b). The purpose of Electrical Resistivity (ER) surveys is to determine the resistivity distribution of the surrounding soil volume (Johnson et al., 2001). Artificially generated electric currents are applied to the soil and the resulting potential differences are measured.

Potential difference patterns provide information on the form of subsurface heterogeneities and their electrical properties (Kearey et al., 2002; Lardo et al., 2012). High level of soil matrix heterogeneity leads to a change in ER detection that allows to better investigate soil-spatial variability. ER of the soil can be considered as a proxy for the variability of a soil's physical properties (Banton et al., 1997; Samouelian et al., 2005; Basso et al., 2010) including texture (Brus et al., 1992; James et al., 2003; Saey et al., 2009), type (Anderson-Cook et al., 2002), and moisture (Reedy and Scanlon, 2003; Sherlock and McDonnell, 2003; Zhu et al., 2010). These advantages may include lower cost, increased capacity and efficiency, and more timely results (Marinello et al., 2015). Moreover, the ability of a sensor to provide high resolution characterization, as compared to sampling and removal methods, allows for an increase of overall spatial estimation accuracy even if the accuracy of individual measurements is lower (Valckx et al., 2009; Sudduth et al., 2013). Furthermore, ER can be implemented as an indirect measure of other soil properties (Jaynes, 1996) and thus used as an indicator of crop production.

The increasing number of soil and crop sensors provides an opportunity for definition of a site-specific crop management plan, and enables the synergistic use of observations from different sensors for a better understanding of land processes (Marinello et al., 2016) such as spatial variations or delineation of homogeneous zones at farm scale (Tucker et al., 2005). In this regards, Precision Farming (PF) plays an important role in term of within field management variability. In fact, PF describes the application of technologies, principles and strategies that are variably managed over space and time to increase crop production and protect environmental resources. (McBratney et al., 2005). Independent management of spatial and temporal variability of different portion of a field is one of the primary advantages of PF (Basso et al., 2001; 2007). Besides, variable rate treatments (VRT) on stable homogenous zones promote high crop yields, improve economic returns and reduce negative environmental consequences (Bertocco et al., 2008; Basso et al., 2016).

The present work aims to study within-farm soil variability using a multi-depth automatic resistivity profiler (ARP©, Geocarta, France). The objective was to test the ability to delineate the homogeneous zones at farm scale and productive potential through an analysis of the relationship between resistivity and historical yield data.

## **2.2 Material and methods**

### **2.2.1 Experimental site and agronomic management**

The experimental study was carried out in the demonstrative farm of Vallevicchia (45.63° N, 12.95° E) within the AGRICARE LIFE<sup>+</sup> project (LIFE13 ENV IT AGRICARE 0583).

The study area covers a surface of 23.5 hectares (500 m long by 470 m wide). Soil type is mainly sandy-loam (Molli-Gleyic Cambisols, FAO, 2001). It belongs to the Venice-Lagoon district, and most of the surface is below average sea level (asl) (Fig.2.1.). This condition leads to high-spatial variability derived from saltwater intrusion affecting crop production (De Franco et al., 2009). From the agronomic point-of-view, the study area was managed with conventional tillage technique, provided by ploughing, in a specific crop rotation: corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], and wheat (*Triticum aestivum* L.).



Figure 2.1: Map of the study area showing the canal network of the study area side of Venice Lagoon (a), and the study area located in proximity of the sea (b).

The average annual rainfall ( $935 \text{ mm}\cdot\text{year}^{-1}$ ) and temperature ( $13.7^\circ\text{C}$ ) were determined from a 20-year dataset recorded at a nearby agro-meteorological station. Rainfall was distributed mostly in the Fall and the Spring, while a monthly maximum of  $23.8^\circ\text{C}$  in July and a minimum of  $3.6^\circ\text{C}$  in January.

### 2.2.2 Study of the field-variability

In order to get a quantitative characterization of variability, field-data regarding soil and crops features must be collected accurately. To collect data representative of the whole field, a non-random pattern of sampling was used. The definition of homogeneous zones can be achieved in different ways, taking advantage of proximal or remote sensors providing information on soil, vegetation, and yield. The study started in September 2014 before the new crop-cycle started.

The study of soil-variability includes information derived from aerial-image, yield-maps of previous years, and soil-analysis. Satellite image gave preliminary information about the field, and it was also useful to define the boundaries and select the yield and soil resistivity data belonging to the study area. Besides, it represents the first layer in which all the collected data were overlapped for their interpolation.

Technological developments in soil analysis have led to new, non-invasive analysis methods. Such methods are not based on collection of soil samples but, allow high-resolution characterization of the soil-surface and have the potential to provide information at different depths. Non-invasive methods don't replace classic soil sampling approaches but can enhance efficiency which allows for a reduction of the number of soil-samples. One of the most important non-invasive soil analysis methods is the Automatic Resistivity Profiling (ARP© GEOCARTA, Paris, France) (Tabbagh et al.,

2000). ARP is an on-the-go multi-depth resistivity technique able to rapidly develop an accurate resistivity profile of soils. It is composed by four pairs of toothed wheels that function as electrodes. The first pair of wheels inject current into the ground while the following three pairs of wheels, spaced at increasing distances, work as receiving electrodes (Fig.2.2.).

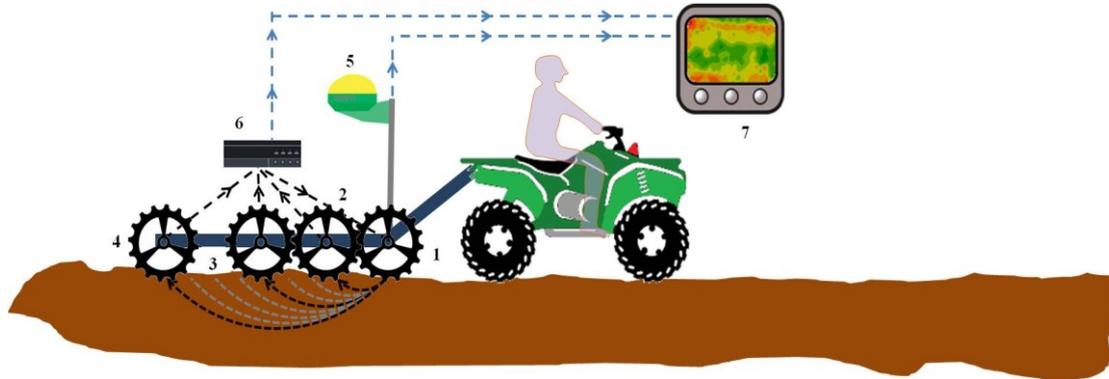


Figure 2.2: ARP system composed by current injector wheel (1), receiving wheels (2, 3, and 4), differential global positioning system (DGPS) (5), unit control (6) and monitor (7).

The equipment is pulled through the field to collect data at three different depths simultaneously (0-0.5; 0-1; 0-2 m) which is then referenced in real-time by the differential global positioning system (DGPS). Acquired spatial information and computation of a Digital-elevation-Model (DEM) provides topographic attributes as slope and position; generating complementary information that facilitates the interpretation of resistivity variation and the definition of homogeneous zones. The ARP system creates the ability to both analyze the variability of the entire fields' surface and collect information at three different depth levels. In addition, all data is geo-referenced, therefore, the ARP system can be used as an indicator for precise spatial recognition of soil characterizations. In this study, the resistivity measurement was taken on transects spaced 5 m apart. Twenty sampling points were selected to verify field variability, as depicted in Figure 2.3.

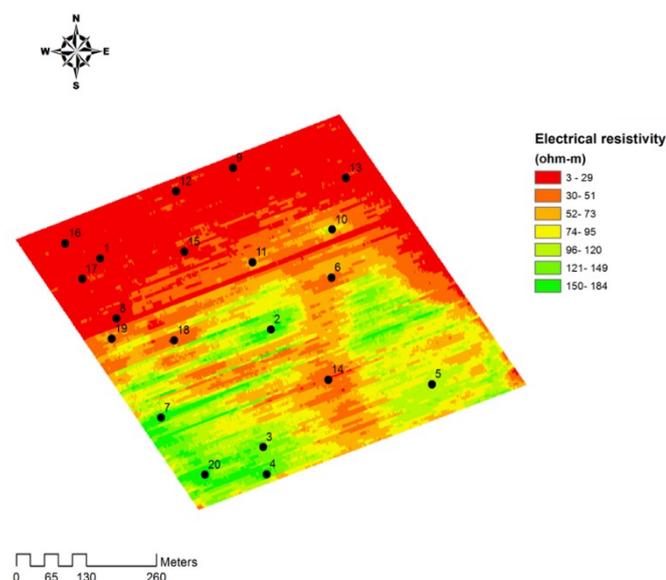


Figure 2.3: Thematic ARP map showing soil electrical resistivity of the 0-0.5m depth level expressed in ohm-meter and the defined soil sampling points.

For each-sample point, soil samples were collected at three depths (0-0.1; 0.1-0.3; 0.3-0.6 m) in order to assess pH, soil-organic-matter (SOM), texture, salinity, electrical-conductivity, nitrogen and phosphorus content. All of the sample points were geo-referenced for future analysis of changes in soil features. Crop-yield data was collected and geo-referenced by a combine equipped with sensors able to assess yield at a specific point (AgroCOM – Claas Agrosystems GmbH Germany) and a DGPS system that provides localization of yield-data. The study considered three years of historical yield-maps, specifically corn-2012, soybean-2013, and wheat-2014. To obtain a representative information of the real field crop production, the yield-mapping system was calibrated each year for the different crops following the instruction provided by the company. In addition, yield-maps were post-processed, filtered, and adjusted before starting the analysis. Yield-maps were interested by the insertion of the real crop specific weight recorded during the download operation and the real working width of each row. Besides, maps were filtered of out-layers recorded during the rows opening or technical problems of the combine. In this way, yield maps got an error less than 5% compared to the real field production (Robinson and Metternicht, 2005). Finally, the grain production values of the different crops were normalized. It led to define the field sides in which the crop-yield was higher or lesser than the average field yield. Data normalization allowed to obtain values describing the production within the field using the real yield information expressed as a percentage. In this way was possible to compare the yield-data derived from different crops and get a more accurate analysis (Fig.2.4.).

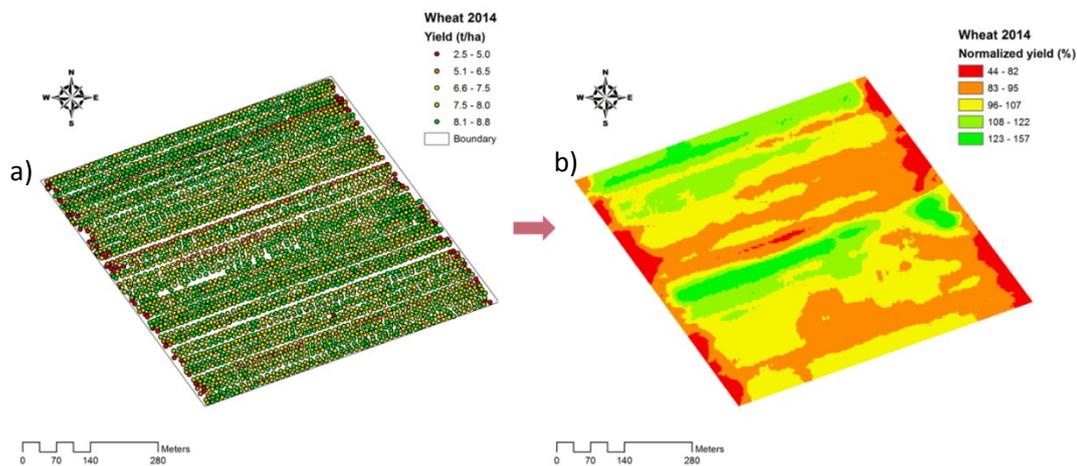


Figure 2.4: Example of raw yield map (a) and interpolated map after data processing (b).

### 2.2.3 Electrical resistivity, soil features, and crop yields

Soil-electrical-resistivity can be considered a proxy for the spatial and temporal variability of many other physical soil properties (Samouelian et al., 2005). In fact, it changes depending on soil-condition in terms of texture, structure, SOM, bulk density, and moisture.

In this study all of the previously described soil features were considered. In this regard, soil-resistivity can play an important role in the study of soil-spatial variability and in the definition of homogeneous zones. The most important advantage linked to the utilization of a non-invasive device is the potential to characterize the whole surface of the field. Then, the spatial soil variability could be explained due to the correlation between soil resistivity and soil-analysis derived from soil sample collections.

Furthermore, variation in yield is undeniably related to changes in soil properties (Corwin et al., 2003; Li et al., 2007; Savabi et al., 2013). So, to verify this principle, 2014 crop cycle yields were predicted using a multiple linear regression. Crop yield prediction was performed in retrospect with the purpose to obtain more information about characterization of homogeneous zones. Finally, ARP and historical yield data were used and combined in order to define homogeneous zones.

#### **2.2.4 Homogeneous zones characterization and yield potential definition**

The analysis was conducted using electrical resistivity and soil features relative only to the upper soil portion (0-0.5m), representing the soil profile most utilized by roots of the crops growing on the study area. With this assumption, only the first level ARP data were considered. The weighted average was calculated of the three levels (0-0.1; 0.1-0.3; 0.3-0.6 m) soil properties values derived from laboratory tests.

To aid analysis, yield data, ARP data, and soil features values were standardized to build a 20x20 m reference grid with a total of about 590 control points (pixels) using ArcMap 10.4 (ESRI, Redlands, CA, USA). Therefore, each pixel of the grid has an average value of yield and ARP as a singular mean value, while 20 of the 590 pixels have an additional information on soil features.

Homogeneous zones were characterized using a fuzzy c-means unsupervised clustering algorithm (Odeh et al., 1992). This algorithm was executed in the Management Zone Analyst (MZA) software (Fridgen et al., 2004). The statistical analysis concerning the correlation matrix, multiple linear regression, and the ANOVA test to define the productive potential of each homogeneous zone were performed using Statgraphics Centurion XVII (StatPoint, Inc., 2005). Finally, the productive potential derived from the study was tested comparing the productive response related to the 2015 crop cycle and the 2007-2011 average crop-yield of the Venice province (ISTAT, 2011).

### **2.3 Results and discussions**

#### **2.3.1 Relationship between crop yield and soil features**

At the end of data processing, each pixel of the grid had both the historical yield data and the electrical resistivity value. Not irrigated managing system and drought conditions caused low-production in corn and soybean cultivation, while wheat gained yield in-line with the average production characterizing the region. The maps give evidence of a similar distribution during the years analyzed. In fact, the southern part of the study area is closer to the coast and is systematically characterized by lower crop yield when compared to the northern side (Fig.2.5.).

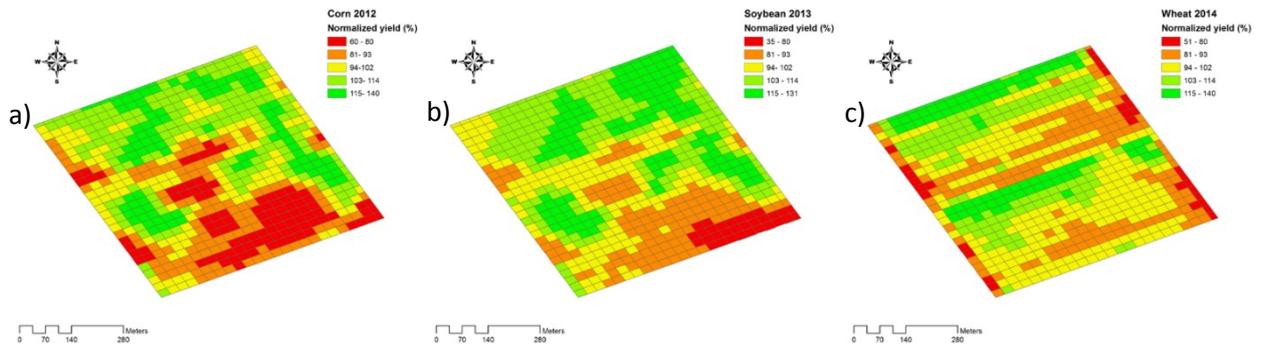


Figure 2.5: Historical yield maps interpolated with the reference grid. Yield values were normalized to compare 2012-corn yield (a), 2013-soybean yield (b), and 2014-wheat yield (c).

On the other hand, the same trend was observed for the electrical resistivity measurement. Specifically, resistivity values progressively decreased from the coastal side (i.e. from south to north). This trend was supported by the soil sample analysis. Indeed, those points located on the southern part of the field had different physic-chemical features compared to the points located farther from the coast (Fig. 2.6.).

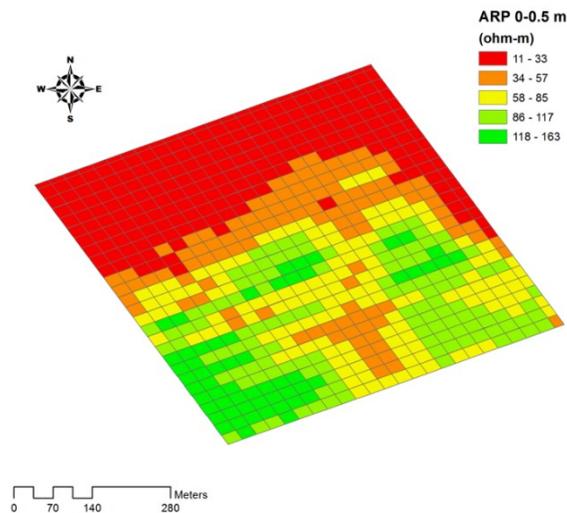


Figure 2.6: ARP map expressed in ohm-meter interpolated with the reference grid.

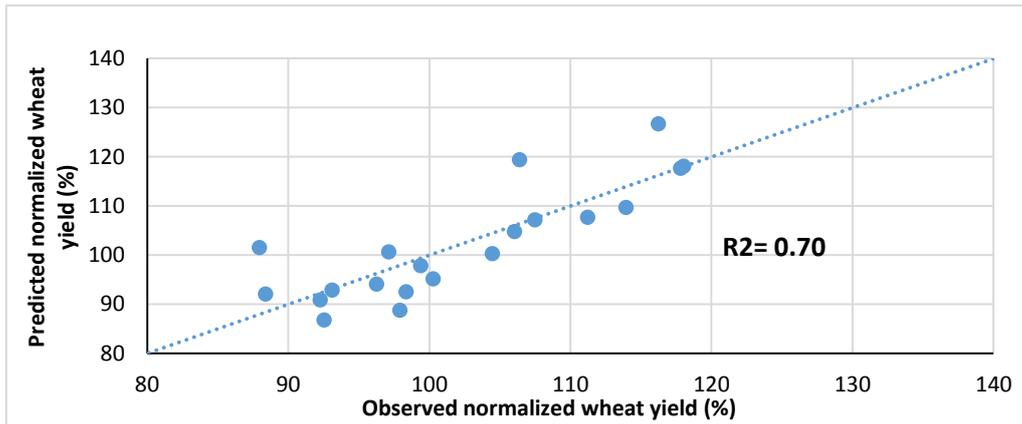
Generally, the first ones were characterized by high electrical resistivity, high percentage of sand, and low SOM. In addition, with the support of ARP analysis, some points were included in the areas influenced by saltwater intrusion, showing very low resistivity and high salinity. Significant correlation was observed between electrical resistivity and soil sampling features within the first depth level of ARP data. This is due to the similar depth level investigated by ARP data (0-0.5m) and soil sample collection (0-0.6m) (Tab. 2.1.).

Table 2.1: Correlation matrix for soil features and yield data of the study area. Bold numbers are significant at the  $p \leq 0.05$  level.

Soil features	ARP 0-0.5	ARP 0-1	ARP 0-2	EC	SAR index	CaCO <sub>3</sub>	pH	Clay	Sand	Silt	SOM	Total nitrogen	P <sub>2</sub> O <sub>5</sub>	K <sub>2</sub> O	Yield 2012	Yield 2013	Yield 2014
ARP 0-0.5	-																
ARP 0-1	<b>0.97</b>	-															
ARP 0-2	<b>0.78</b>	<b>0.90</b>	-														
EC	<b>-0.46</b>	<b>-0.44</b>	-0.33	-													
SAR index	0.02	0.02	0.03	<b>0.78</b>	-												
CaCO <sub>3</sub>	<b>0.57</b>	<b>0.50</b>	0.28	<b>-0.65</b>	-0.26	-											
pH	<b>-0.72</b>	<b>-0.67</b>	<b>-0.49</b>	0.21	-0.20	-0.30	-										
Clay	<b>-0.65</b>	<b>-0.57</b>	-0.33	0.15	-0.35	-0.40	<b>0.56</b>	-									
Sand	<b>0.70</b>	<b>0.61</b>	0.35	-0.29	0.25	<b>0.51</b>	<b>-0.73</b>	<b>-0.79</b>	-								
Silt	<b>-0.60</b>	<b>-0.52</b>	-0.30	0.31	-0.15	<b>-0.47</b>	<b>0.70</b>	<b>0.52</b>	<b>-0.93</b>	-							
SOM	<b>-0.72</b>	<b>-0.64</b>	-0.42	0.40	-0.14	<b>-0.53</b>	<b>0.80</b>	<b>0.80</b>	<b>-0.93</b>	<b>0.83</b>	-						
Total nitrogen	<b>-0.75</b>	<b>-0.67</b>	-0.44	0.29	-0.25	<b>-0.50</b>	<b>0.80</b>	<b>0.83</b>	<b>-0.96</b>	<b>0.85</b>	<b>0.97</b>	-					
P <sub>2</sub> O <sub>5</sub>	-0.22	-0.24	-0.25	0.21	-0.06	-0.08	0.12	0.40	-0.07	-0.14	0.22	0.18	-				
K <sub>2</sub> O	<b>-0.66</b>	<b>-0.64</b>	<b>-0.50</b>	<b>0.57</b>	0.05	<b>-0.76</b>	<b>0.46</b>	<b>0.60</b>	<b>-0.67</b>	<b>0.59</b>	<b>0.71</b>	<b>0.69</b>	0.33	-			
Yield 2012	<b>-0.60</b>	<b>-0.57</b>	-0.43	-0.12	<b>-0.53</b>	-0.28	<b>0.63</b>	<b>0.60</b>	<b>-0.71</b>	<b>0.64</b>	<b>0.56</b>	<b>0.68</b>	0.01	<b>0.47</b>	-		
Yield 2013	<b>-0.53</b>	<b>-0.53</b>	-0.43	-0.08	-0.42	-0.32	<b>0.54</b>	<b>0.49</b>	<b>-0.61</b>	<b>0.57</b>	<b>0.49</b>	<b>0.61</b>	-0.13	<b>0.46</b>	<b>0.94</b>	-	
Yield 2014	-0.25	-0.27	-0.29	0.04	-0.30	-0.02	0.39	<b>0.54</b>	<b>-0.56</b>	<b>0.46</b>	<b>0.60</b>	<b>0.59</b>	0.42	0.32	0.38	0.31	-

On the other hand, a significant correlation between 2014 crop-yield, texture, and SOM was found. Therefore, a multiple linear regression model to predict crop yield using soil features and historical yield data was applied. A backward stepwise function was used to obtain the simplest model with the lowest number of variables and highest correlation. As a result, eq.1 shows the best response between the wheat model and the variables most affecting crop yield in regards to soil features characterizing the study area. The model also includes a variable representing the electrical resistivity in the deep layer of soil profile (0-2m), even if this layer is not interested by the roots activity of the studied crops. This is due to the particular location in which the study area is located. In fact, the presence of belowground preferential canals allows saltwater intrusion which affects the crop yield. Therefore, the presence of this variable in the model means that ARP analysis represent a liable indirect non-destructive method to study soil variability.

The regression showed an  $R^2$  of 0.70 (Fig. 2.7.) and a mean absolute error (MAE) of 4.44. All soil parameters were significant at  $p < 0.05$  or below. The analysis of variance (ANOVA) provided a significant,  $F= 9.06$ .



$$\text{Eq.1 } Y = 112.81 + 0.25 \cdot \text{ARP } 0-0.5 - 0.98 \cdot \text{ARP } 0-2 - 0.63 \cdot \text{Sand} + 0.44 \cdot \text{P}_2\text{O}_5$$

Figure 2.7: Relationship between observed and predicted normalized wheat yield using eq.1. Dashed line represents a 1:1 relationship.

The model described about 70% of the total yield variability, suggesting that other factors affected wheat crop yield in 2014 (e.g. biological, meteorological, and anthropogenic factors).

### 2.3.2 Homogeneous zones characterization and yield potential definition

The homogeneous zones characterizations were derived from the interpolation of ARP and historical crop-yield data. Incorporating this method, it is possible to perform the analysis with a larger set of data (over 25 pixels/ha) efficiently. In addition, these two data sources represent spatial and temporal variability. Spatial variability is defined by electrical resistivity obtained by ARP device, strictly related to soil features affecting crop yield; and temporal variability is represented by the historical yield maps related to different crops.

Classification and definition of the homogeneous zone was fulfilled by inputting data into the MZA software. Then, the MZA's algorithm was set on the basis of the variance-covariance matrix response highlighted by the software. The optimum number of homogeneous zones was identified according to the minimization of the fuzziness performance index (FPI) and the normalized classification entropy index (NCE) (Odeh et al., 1992). Four homogeneous zones satisfying these requirements were then defined (Fig. 2.8.).

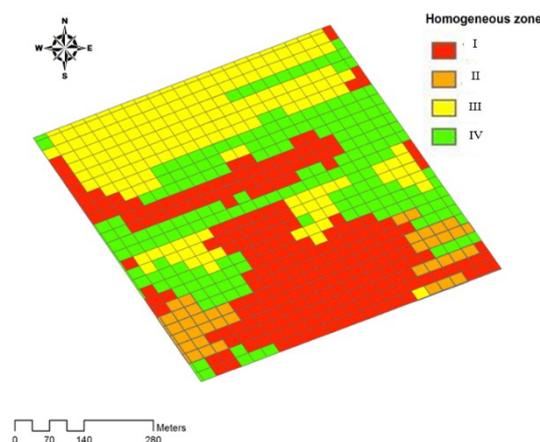


Figure 2.8: Study area divided in homogeneous zones derived from MZA analysis using ARP data and historical yield maps.

Finally, the identification of productive potential was attributed to the homogeneous zones. The ANOVA test of those soil sampling points belonging to the different homogeneous zones defined by MZA analysis was performed accordingly.

The ANOVA test took into consideration soil features (electrical resistivity, clay, sand, SOM) and three years yield data. As a result, the homogeneous zone III exhibited the highest levels of clay and SOM and lowest sand content compared to the other zones. Considering electrical resistivity, homogeneous zone IV belonged to a different class compared with zones I and II. These differences were stressed by historical yield response. In fact, the ANOVA test of 2013 yield shows that homogeneous zone II had the lowest yield, showing low production in the 2012 and 2014 crop cycles. To make the difference between zones more clear, the productive potential of the four homogeneous zones were renamed, attributing an increase in productive potential from A to D (Tab. 2).

Table 2.2: ANOVA test of soil features and yield data to define the homogeneous groups (HG) and assign the productive potential to the homogeneous zones.

Variable	Zone II	HG	Zone I	HG	Zone IV	HG	Zone III	HG
ARP ( $\Omega \cdot m$ )	134.6	a	91.3	a	68.3	Ab	21.2	b
SOM (%)	1.10	a	1.30	a	0.98	A	2.26	b
Clay (%)	15.1	a	14.8	a	17.2	A	29.9	b
Sand (%)	59.0	a	61.7	a	61.2	A	22.1	b
Yield 2012 (Normalized yield %)	75.3	a	82.2	a	101.1	B	115.7	c
Yield 2013 (Normalized yield %)	68.3	a	86.4	b	101.0	C	113.1	c
Yield 2014 (Normalized yield %)	92.3	a	102.2	ab	92.5	A	112.1	b
Productive potential	Zone A		Zone B		Zone C		Zone D	

In order to verify the predictive capacity of the model in practice, such productive potential was evaluated against a comparison between the average production of the Venice province and the experimental sites' 2015 crop yield. The analysis showed zones A and B's yields were about 24% and 12.2% lower, respectively, than reference production; while zones C and D's yields were about 9.6% and 14.2% higher, respectively, compared to the same reference productions in the Venice province.

## 2.4 Conclusions

Non-invasive soil analysis methods represent an important tool to better study soil variability and enhance the efficiency of traditional soil sampling. In addition, data derived from ARP analysis shows a correlation between soil resistivity and soil features such as texture, SOM, salinity etc.

In this work the spatial variability of wheat production is explained by soil features such as electrical resistivity, sand, and available phosphorous. Consequently, the application of a fuzzy c-means clustering algorithm led to the classification of the study area in four homogeneous zones, which implied the productive potential through the ANOVA test of the soil features and historical yield data. This trend was validated by the comparison of the homogeneous zone's productive potential with 5-year average production data. Moving forward, it is possible to consider precision agriculture technologies as useful tools to study and manage changing soil fertility within fields.

### **3 Conservative Precision Agriculture: an assessment of technical feasibility and energy efficiency within the LIFE+ AGRICARE project.**

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The integration of conservation agriculture with the benefits of precision farming represents an innovative feature aimed to achieve better economic and environmental sustainability.

The synergy between these principles was assessed through a technical feasibility and energy efficiency to define the best approach depending on different agricultural systems, spatial and temporal field variability.

The study compares three conservation tillage techniques supported by precision farming with conventional tillage in a specific crop rotation: wheat, canola, corn and soybean. The preliminary results show a positive response of precision farming in all the conservation tillage systems, increasing yields until 22%. The energy efficiency achieves highest level in those techniques supported by precision farming, gaining peak of 9% compared to conventional tillage.

#### **3.1 Introduction**

Nowadays, issues of primary importance are: food security, due to an increasing in world population, soil degradation by its mismanagement and anthropogenic increases in atmospheric greenhouse gases emission. All of these issues are linked to the sustainability of soil quality especially in relation to soil organic carbon (SOC) pool and its dynamics (Lal, 2001). Accordingly, the agricultural sector is asked to increase the use efficiency of arable land to meet the increase of world's population. It also needs to maintain economic feasibility in order to guarantee an income for farmers who face an increasingly competitive and fluctuating market. Finally, environment and preservation of biodiversity should not be neglected. To achieve these requirements, the agricultural sector can adopt principles and strategies derived from conservation agriculture (CA) and precision farming (PF). Indeed, the continued use of tillage over the years with inversion of layers has led to a change in physical, chemical and biological features of the soil, including a degradation of soil structure, a deterioration of water retention and infiltration, phenomena of intense compaction and decrease in soil organic matter leading to strong depressions of biological and microbiological activity (Holland, 2004).

CA, which does not include implementation of plow, maintains on the surface at least 30% of the crop residue allowing to preserve the physical, chemical and biological soil features (Derpsch *et al.*,

2010). Furthermore, CA can reduce the energy needed to carry out soil tillage operations with a decrease in gases emission into the atmosphere. For this reason, CA plays an important role in terms of mitigation of climate change that represent one of the most serious problems to sustainable global development. With reference to past experiments carried out in Italy, the use of CA allows a reduction in CO<sub>2</sub> emissions equal to 17-65% of the national rate reduction defined by the Kyoto Protocol. Besides, implementing CA with an appropriate crop rotation combined with the use of cover crops, allows to increase the content of organic carbon in the soil (Lal, 2004). Then, soil is seen as a carbon sink (C-sink), as opposed to traditional processes, where soil represent a carbon source (C-source) due to organic carbon mineralization (Nelson *et al.*, 2009).

The growing interest in CA techniques has led to the definition of different kinds of soil managing systems, which are different in terms of working intensity. Strip-tillage is one of the last interesting introduced techniques, focusing its characteristics on crop suitability, soil features preservation and environmental sustainability. With this technique, less than 50% of total surface is tilled, producing the typical strips where seeds are deposited (Celik *et al.*, 2013). Its correct exploitation necessarily involves the use of satellite guidance systems in order to carry out the sowing on the strips of soil previously tilled. In general, the benefits of CA could be enhanced by the contribution derived from PF. PF can be seen as the application of technologies, principles and strategies for the management of space and time variability, in order to increase the response of the crop production and protection of environmental resources (Marinello *et al.*, 2017). Indeed, the possibility of modulating the inputs rates on the basis of stable homogeneous zones (Zhang *et al.*, 2010) characterized by soil and crop features could lead to an increase of economic and environmental benefits (Basso *et al.*, 2016). Additionally, it is possible to enhance inputs and soil use efficiency (Licht *et al.*, 2016), and mitigate the yield gap characterizing CA related to conventional soil tillage technique. Finally, another tool belonging to precision agriculture strategies applicable to conservation tillage is the use of predictive models. A predictive model is capable to give a decisional support related to site-specific crop inputs management in order to increase their efficiency and to have an increase in economic, energetic and environmental sustainability (Pezzuolo *et al.*, 2014).

The aim of the present work is to investigate the synergy between CA and PF identifying, through experimental tests combined with simulation of different scenarios of medium and long-term, the best technical solutions allowing optimization in terms of energy efficiency and production.

## **3.2 Materials and methods**

### **3.2.1 Study area and agronomic management**

The experimentation was carried out in the pilot and demonstrative farm of Vallevicchia (45.63° N, 12.95° E) within the AGRICARE project (LIFE13 ENV IT AGRICARE 0583). The study specifically analyses data derived from the crop season 2014/2015.

The study area covers a surface of 23.4 hectares (500 m long and 470 m wide), divided into 16 plots with an area of about 1.5 hectares each, representing the experimental theses. The study considers three conservation soil tillage techniques characterized by a different working intensity

of soil, in decreasing order: minimum tillage (MT), strip tillage with 55cm spacing (ST) and no-tillage (NT), compared with the conventional tillage (CT) which is used as a reference.

The considered crop rotation included the most important crops present in the Po Valley: wheat, canola, corn and soybean. Since conservation tillage techniques are characterized by a permanently covered soil surface, after the main crop, a cover crop was sown, which was eventually devitalized before starting a new crop cycle.

In addition, with the exception of the CT witness, all of the other soil tillage techniques were integrated with the most modern PF technologies. Therefore, agricultural machines were equipped with satellite, radio antennas and automatic guidance systems, while the experimental farm was implemented with satellite and radio antennas allowing Real Time Kinematic (RTK) correction characterized by an error of 2.5cm and a repeatability of 5cm. Finally, all of the machines used for the inputs application were implemented with technologies providing section control and variable rate application. However, in order to evaluate the contribution of PF within the different conservation tillage techniques investigated, a central test bands managed with fixed rate of inputs were identified.

From a climate perspective, the average annual rainfall in 20 years recorded by an agrometeorological station located nearby was 935 mm year<sup>-1</sup>.

### **3.2.2 Study of the variability**

In order to get an objective characterization of variability, field data and information, regarding soil and crops features have to be accurately corrected. Data collection has to be performed through a non-random pattern: indeed, it has to be representative of the whole field. The definition of homogeneous zones is achieved in different ways using proximal or remote sensors providing information on soil, vegetation and yield. The experimentation started by studying soil variability using information derived from aerial images (giving basic information about the study area), Automatic Resistivity Profiling (ARP<sup>®</sup>, Geocarta) and soil samples analysis, and yield maps from previous years. Monitoring productions is effective information, useful to identify the field areas characterized by a more homogeneous trend. Indeed, the analysis of historical yield maps allows to identify the temporal stability of the spatial variability, thus helping characterization of repeatability in time domain of the zones having the same productive potential. Two years historical yield maps were used to define the homogeneous zones. Maps were derived from corn and soybean cultivation to obtain information about the suitability of different crops in the study area. Additionally, the ARP analysis allows to collect information on spatial variability of soil features. ARP is an on-the-go multi-depth resistivity device. It is a non-invasive soil sampling method allowing investigation of soil profile at three different depth levels (0-0.5, 0-1 and 0-2m). In this study the resistivity measurement was carried out with a transect of 5m apart, as shown in Figure 3.1.

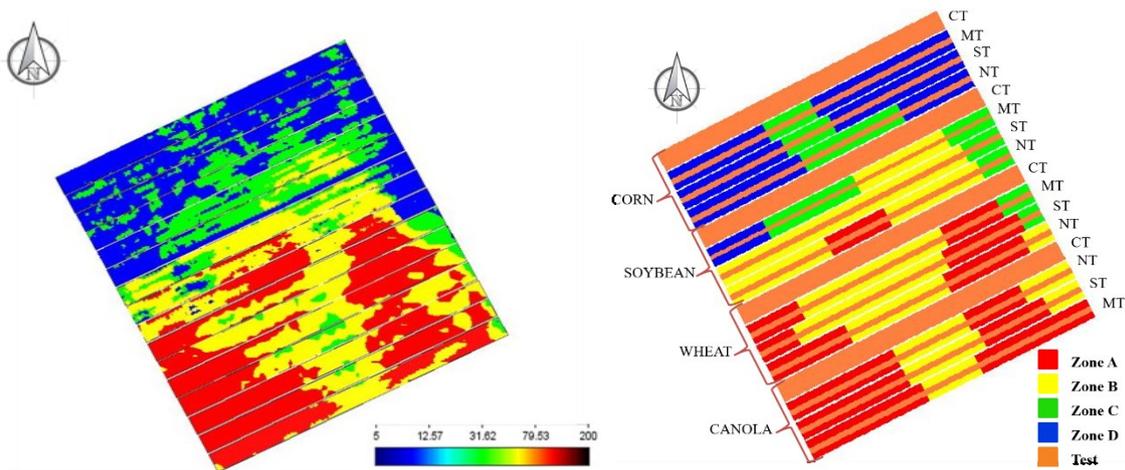


Figure 3.1: Interpolated ARP map expressed in ohm-meters (left) and experimental homogeneous zones characterization (right).

In order to support and complete ARP data, additional physic-chemical soil parameters analyses at three depth level (0-10cm, 10-30cm, 30-60cm) were carried out. 20 sampling position were defined taking advantage of ARP maps, thus allowing an optimization of samples localization.

The homogeneous zones characterization derived from the interpolation of all field collected data. Such operation was completed by means of dedicated statistical software, the MZA-Management Zone Analyst - University of Missouri-Columbia software (Fridgen *et al.*, 2004). Finally, the productive potential characterizing the different homogeneous classes derived from the MZA analysis was assigned. As a result, the study area was divided into 4 homogeneous zones with an increasing productive potential, namely from A to D (Figure 3.1.).

To assess the optimal rate of inputs to be applied to the different homogeneous zones, the predictive model SALUS (System Approach to Land Use Sustainability) was used. SALUS is a model designed to simulate the production response of herbaceous and woody crops under different agronomic management strategies (Dzotsi *et al.*, 2013). It simulates the dynamics of nutrients, soil and atmospheric carbon and the directly or indirectly connected environmental impact (Basso *et al.*, 2006).

Table 3.1: Optimal seed and nitrogen rates applied for each homogeneous zone in different crops and soil tillage techniques.

Crop	Soil tillage	Zone	Rate seed	Nitrogen application	
			[seeds·m <sup>-2</sup> ]	[kg·ha <sup>-1</sup> ]	
Canola	CT	-	50	128	
		A	50	140	
	MT	B	50	120	
		A	55	140	
	ST	B	55	120	
		A	55	150	
	NT	B	55	130	
		-	7.5	193	
	Corn	CT	C	8.5	180
			D	9.5	200
MT		C	8.5	170	
		D	9.5	190	
ST		C	8.5	200	
		D	9.5	220	
NT		C	8.5	200	
		D	9.5	220	
Wheat		CT	-	500	178
			A	500	150
	MT	B	500	190	
		C	500	140	
	ST	A	260	150	
		B	260	190	
	NT	C	260	130	
		A	550	150	
	NT	B	550	190	
		Soybean	CT	-	45
B	50			-	
MT	C		40	-	
	D		35	-	
ST	B		50	-	
	C		40	-	
NT	A		55	-	
	B		50	-	
NT	C		40	-	

Input data of the software tool are:

- soil characteristics (texture, depth, reaction, etc.);
- daily climate data (maximum and minimum temperature, rainfall, solar radiation);
- agronomic management (plan of crop rotation, type of tillage, sowing, seed rate, fertilization, irrigation management, etc.).

Depending on site-specific soil features, climatic characteristics and management strategies, SALUS simulates the growth of plants and the soil conditions for each day having available climate data.

Taking advantage of SALUS simulations, the optimal seed and nitrogen rate for each homogeneous zone was defined considering their productive potential, the nitrogen curves efficiency, their expected leaching and economic sustainability in terms of marginal costs. This operation was performed for each crop and soil tillage technique; main results are reported in Table 3.1. The information about the inputs rates was transferred to the field by means of specific prescription maps. In order to achieve a technical and operating feasibility, prescription maps were built using a GIS software with a 3x5m grid for MT and NT theses, and 2.2x5m for ST.

### 3.2.3 Data collection

The harvesting operation was performed implementing a combine integrated with yield mapping system. The system allows to generate yield maps useful to monitor field distribution of crop production. Yield maps were utilized to assess the crop yield of each homogeneous zone, characterizing the different theses, and to compare areas managed with or without PF techniques.

Therefore, the energetic balance and energy efficiency assessment were performed for each soil tillage technique, crop and homogeneous zone. The energetic outputs were calculated considering the dry matter of the different crop yields and using energetic coefficients found in literature (Singh *et al.*, 2008; Unakitan *et al.*, 2010). A similar procedure was performed for all used inputs, assigning their energetic value through conversion coefficients found in literature. On the other hand, the total input's energetic values derived from the sum of different items represented by: direct and indirect mechanization energetic value (Sartori *et al.*, 2005; Bertocco *et al.*, 2008), man power energy consumption needed to carry out each operation (Canakci *et al.*, 2005; Mandal *et al.*, 2015) and all of the materials needed to produce those commodities (Barut *et al.*, 2011; Bilalis *et al.*, 2013).

## 3.3 Results

Yield data from the first experimentation year are here reported, processed in order to highlight crop productions from different homogeneous zones. The aim is to allow a comparison of crop-yield, inputs use efficiency and energy efficiency for each homogeneous zone belonging to different theses. Specifically, results from corn cultivation are reported in Table 2, showing the productive response of the soil managing methods supported by PF.

Corn undergoing uniform seed and nitrogen rates, was greatly influenced by simplified soil tillage methods, which led to a reduction in yield higher than 25% in ST and NT compared to CT. Such gap is strongly mitigated in those theses where CA techniques are managed with variable rate application of inputs: indeed, in this case, ST and NT feature production levels close to those of CT, while PF contribution allows MT to obtain higher crop yields compared to the reference CT.

The same approach was applied to all the four crops studied in this work (Corn, Soybean, Wheat and Canola), but with different observed trends, as shown in Figure 3.2. Indeed, soybean cultivation is characterized by an important gap in terms of crop yield only in specific homogeneous zones, and the implementation of PF practices allowed to get the highest production in MT.

Table 3.2: Corn yield response to different soil tillage techniques managed with uniform rate application (URA) and variable rate application of inputs (VRA).

Soil tillage	Zone	URA [t ha <sup>-1</sup> ]	VRA [t ha <sup>-1</sup> ]
CT	C	11.67	-
CT	D	11.70	-
MT	C	11.84	12.36
MT	D	11.46	11.88
ST	C	8.30	11.40
ST	D	8.35	10.83
NT	C	8.76	11.01
NT	D	8.40	11.45

On the other hand, PF benefits did not lead to an increase in crop yield in the case of wheat. However, considering the nitrogen application rates defined before, an increase in nitrogen use efficiency can be observed passing from soil tillage techniques managed with a fixed rate of input and the same methods implemented with PF technologies. Finally, canola cultivation had technical problems for some theses in the first year of experimentation. Specifically, the adoption of a new prototype machine designed to seed canola in strips (in the case of ST) partially failed with negative effects in final yield.

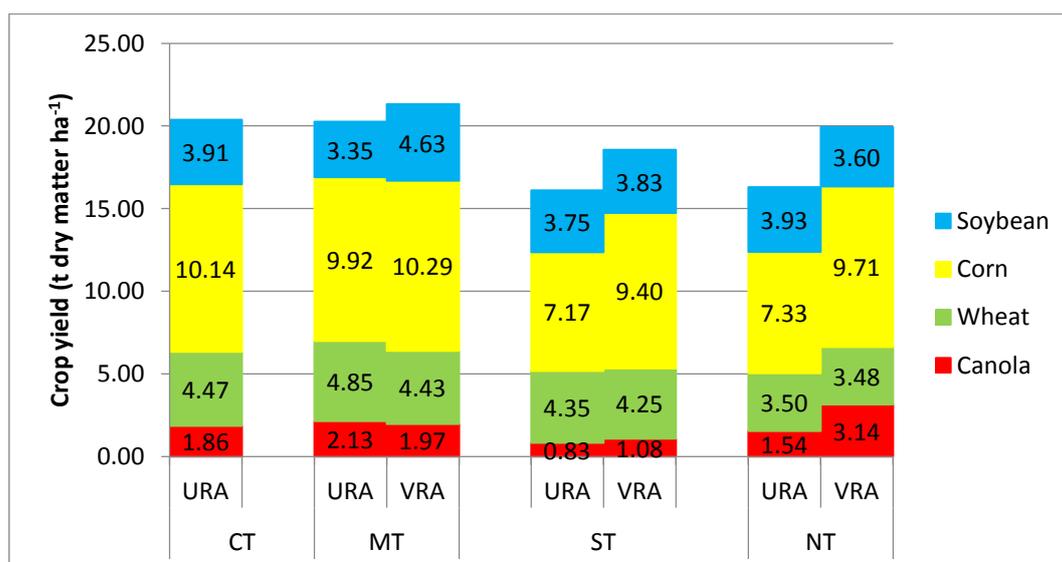


Figure 3.2: Sum of crop yield characterizing the experimentation for different soil tillage techniques managed with inputs uniform rate application (URA) and variable rate application (VRA).

From the energetic point of view, theses that reached highest crop yields got greatest amount of gross energy, while energy consumption differences are less evident. Therefore, the energy

efficiency was estimated as the ratio between the crops energetic content and the total input needed to their growth. Figure 3.3 shows the average energy efficiency gain achievable by each thesis considering the previously described crop rotation and spatial variability characterizing the study area.

In particular, PF contributes to increase energy efficiency in MT and NT with an increase with respect to CT, of 8% and 6% respectively. Finally, ST supported by PF technologies shows an increase in energy efficiency of 13% compared to ST managed with a fixed rate of inputs.

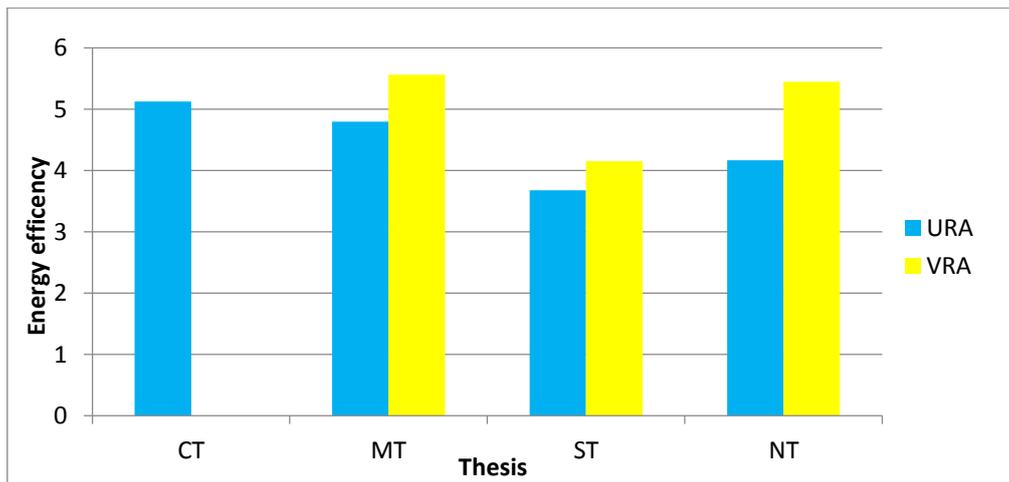


Figure 3.3: Energy efficiency for different soil tillage techniques managed with inputs uniform rate application (URA) and variable rate application (VRA).

### 3.4 Conclusions

This work is aimed to evaluate a technical feasibility and the energy efficiency derived from the synergy between conservation agriculture supported by precision farming principles, compared to conventional tillage technique and uniform inputs application. To this regard, it is important to consider the working width of the machines providing variable rate inputs application during the homogeneous zones characterization. Indeed, the homogeneous zones were shaped in order to allow an operating feasibility in terms of working width and change in inputs rate. In addition, the first year's experimentation results show an increase in crops production due to PF contribution in term of total yield derived from the four crops considered in this study. Especially in the simplified soil tillage techniques, it allows to gain a higher total production, respectively by 15% and 22% in ST and NT compared to the same techniques managed with uniform rate inputs application. Besides, MT supported by PF got the highest total crop yield, with a 5% increase with respect to CT. A similar trend is observed from the energy assessment point of view, in which the energy efficiency is at the highest level in those techniques supported by precision agriculture. In particular, it contributes to gain better energy efficiency in minimum tillage and no-tillage, with an increase of 8% and 6% compared to conventional tillage. Similarly, ST reported a 13% increase in energy efficiency when PF practices are implemented.

## **4 Modeling soil organic carbon and carbon dioxide emissions in different tillage systems supported by precision agriculture technologies under current climatic conditions.**

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Soil & Tillage Research. Under review, Ms. No. STILL-17-788.

Soil organic matter (SOM) is one of the most important factors affecting agricultural production. Its depletion may lead to soil degradation, which affects sustainable agricultural development and environmental health. SOM also represents the biggest pool of carbon within the biosphere and influences the flux of greenhouse gases between land surface and atmosphere, meant both as carbon sink and source. In this regard, conservation tillage systems have been adopted to reduce negative impacts of conventional tillage practices on greenhouse gases (GHG) emissions. But, the potential for these techniques to increase carbon sequestration also depends upon soil features and climatic conditions, which is studied and managed by precision agriculture (PA) principles and technologies. Besides, simulation models have shown to be useful tools to understand the interaction between soil, climate, genotypes and management practices to simulate the long-term effects of management approaches of different soils on crop yield, soil organic carbon (SOC) storage, and GHG emissions. The research goals of this study are (1) to study the mid-term (15 years) trajectory of SOC in the upper 0.4m of the soil profile under different tillage systems using the SALUS model; (2) determine the impact of PA on the inputs to the crop and CO<sub>2</sub> emissions; (3) Identify the strategies, derived from the synergy between conservation agriculture and precision agriculture, best able to decrease the CO<sub>2</sub> emissions of agricultural systems. The validated SALUS simulation shown a significant reduction in SOC losses in minimum tillage (MT) and no-tillage (NT), 17% and 63% respectively, compared to conventional tillage (CT). Furthermore, the adoption of conservation tillage techniques decreased carbon emissions related to farming operations, while PA technologies led to an optimization of the exhaustible sources such as fossil fuels and fertilizers. Finally, the synergy between conservation tillage systems, especially NT, and PA strategies represents a useful tool in terms of carbon emissions mitigation with a reduction of 56% of total CO<sub>2</sub> as compared to CT.

### **4.1 Introduction**

Agricultural systems are asked to satisfy the increasing global demand for food and fibre for a growing population. The intensification of the current systems in term of inputs and outputs lead to heightened concerns regarding the impact on the environment (Miller et al., 2007).

Soil organic matter (SOM) is one of the most important factors affecting agricultural production. SOM mediates nutrient cycling (Bolinder et al., 2010; Lal and Follett, 2009), soil aggregates, and water-holding capacity (Huntington, 2007). Therefore, SOM depletion may lead to soil degradation, which affects sustainable agricultural development and environmental health (Tang

et al., 2006). Also, the C contained in soil organic matter (soil organic carbon, SOC) represents the biggest carbon sink and source in the biosphere, and small changes in its mineralization rate may have a large impact on greenhouse gases (GHG) emissions (Wang et al., 2015). One option to mitigate increases in GHG concentrations in the atmosphere is the biological sequestration of CO<sub>2</sub> (Reicosky, 1997). Biological carbon sequestration in the soil represents the net removal of CO<sub>2</sub> from the atmosphere into long-lived sinks, or pools, of carbon (Lal, 2008).

Management practices such as conservation tillage systems, mulching, and cover crops have shown to increase the content of C in agricultural soils (Ludwig et al., 2011). Each tillage technique influences differently the amount of soil carbon sequestered and the distribution of C in the soil (Alvarez, 2005). Therefore, the combination of different management practices can contribute to mitigate climate change in different ways (Marraccini et al., 2012).

Conservation tillage techniques, such as minimum tillage (MT) and no-tillage (NT), have been adopted to reduce negative impacts of conventional tillage practices, even if sometimes characterized by lower crop yields (Van den Putte et al., 2010). Conventional tillage (CT), characterized by the inversion of soil layers through ploughing leads to a rapid mineralization of SOC, increases in soil erosion, creates a plough pan and increases energy demands for machinery (Bertolino et al., 2010; Rusu, 2014).

Over the last two decades numerous experiments supported the hypothesis that conservation tillage increases soil organic matter content (Kassam et al., 2008) however recent literature syntheses challenges the effectiveness of conservation tillage on the basis that results maybe often biased by a lack of equalization of soil mass between tillage practices (Powlson et al., 2016) and by recognizing that not all conservation practices are equally effective in reducing C emissions (González-Sánchez et al., 2012).

In addition to altering the SOC levels, conservation tillage also alters its distribution in the soil profile, in fact conservation tillage practices increase the C content in the upper soil layers whereas conventional tillage often result in an increment of SOC in the deeper soil profile, particularly, near or at the bottom of the tilled layer (Angers and Eriksen-Hamel, 2008; De Sanctis et al., 2012). The potential for these techniques to increase carbon sequestration also depends upon soil features and climatic conditions (Grace et al., 2006). The acknowledgement of soil spatial variability represents the first requirement to adopt precision agriculture technologies and spatially variable practices (PA) (Mulla and Schepers, 1997). PA can be defined as the application of technologies, principles, and strategies for management of space and time variability, in order to increase crop performance and environmental quality (Pierce and Nowak, 1999, Basso et al., 2001; 2007). In this regard, variable rate input (VRI) on stable homogeneous zones promote an increase in crop yield and reduce negative environmental consequences (Basso et al., 2016). Furthermore, simulation models have shown to be useful tools to understand the interaction between soil, climate, genotypes and management over space and time and to design best management practices required for sustainable crop production (Basso and Ritchie, 2015). Simulation models are also used to simulate the long-term effects of management approaches of different soils on crop yield, SOC storage, and GHG emissions (Pezzuolo et al., 2017; Manyowa et al., 2013). In this regard, Iocola et al. (2017) tested four different simulation models to determine the effects of different soil tillage techniques on crop yield and changes in SOC stock under current and future climate scenarios.

Here we use simulation models together with measured data of energy consumption to assess the energy efficiency of different management strategies. The strategies tested in this simulation experiment include three different tillage techniques and the adoption or not of precision agriculture technology and strategy (automatic steering and variable inputs rate).

Considering all the issues described above, the research goals of this study are (1) to study the the mid-term (15 years) trajectory of SOC in the upper 0.4m of the soil profile under different tillage systems using the SALUS model; (2) determine the impact of PA on the inputs to the crop and CO<sub>2</sub> emissions; (3) identify the strategies, derived from the synergy between conservation agriculture and precision agriculture, best able to decrease the CO<sub>2</sub> emissions of agricultural systems.

## 4.2 Material and Methods

### 4.2.1 Study area and climate data

This experiment was conducted at the Vallevicchia demonstration farm (45.63° N, 12.95° E), in the Venice Lagoon district, Italy. The study area is mainly characterized by sandy-loam soil (Molli-Gleyic Cambisols, FAO, 2001), and most of the surface is below average sea level. The farm is also affected by saltwater intrusion, a condition that leads to high spatial variability that affects crop production (De Franco et al., 2009) (Fig. 4.1.). The total study area encompasses about 18 ha, then divided into 12 plots with an area of about 1.5 ha each. Yield data from the 2014-2015 and 2015-2016 growing seasons were used for the SALUS calibration and validation. We considered grain yields derived from 76 of the 80 total treatments were considered in the study. Because of the high number of treatments planned, not all of the observed grain yields could be attained during the first two years of experimentation. On the other hand, the SALUS model has shown a high level of reliability in simulating grain yields.



Figure 4.1: Map of the study area that shows the canal network of the Venice Lagoon (a), and detail view of the study area (b).

The average annual rainfall (935 mm year<sup>-1</sup>) and temperature (13.7°C) were determined from a 23-year dataset recorded at a nearby agro-meteorological station. Rainfall was distributed mostly in the Fall and the Spring, while a monthly maximum temperature of 23.8°C in July and a minimum of 3.6°C in January was found. In the experimentation years, the annual rainfall was 708 mm and 1076 mm for the 2015 and 2016 seasons respectively. The average annual temperature was 13.9°C for 2015, and 13.6°C for 2016 (Fig. 4.2.).

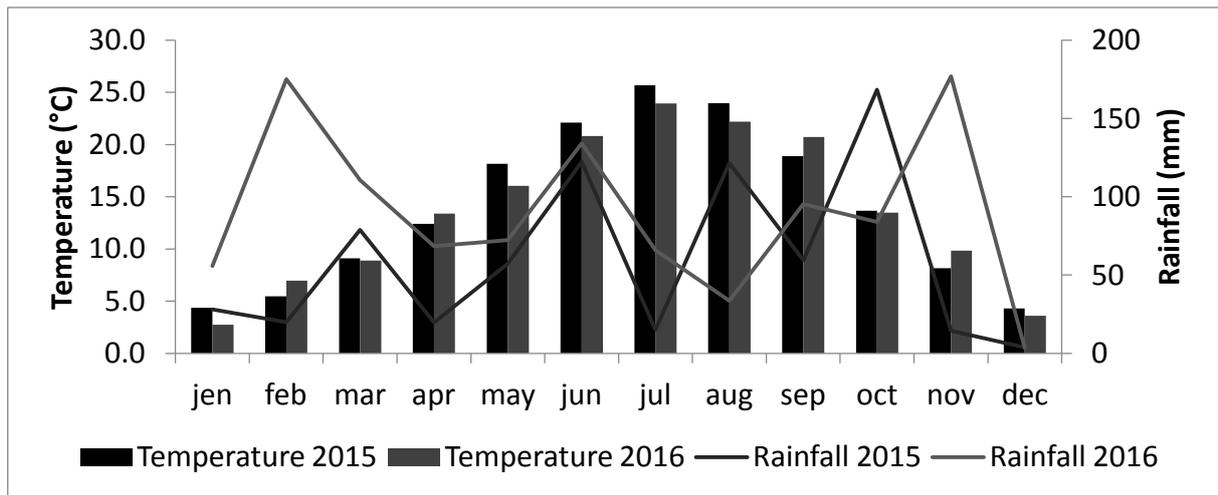


Figure 4.2: Average monthly temperature and total monthly rainfall for 2015, 2016.

#### 4.2.2 Tillage systems and agronomic management

Three soil tillage systems characterized by varying degrees of soil cultivation intensity were analyzed in the experimentation:

*Conventional tillage (CT)*: the soil was ploughed down to 35cm deep, leading to the inversion of soil layers. Soil ploughing was followed by seedbed preparation using a tine cultivator at 25cm and power-harrow at 10cm.

*Minimum tillage (MT)*: the initial technique conducted with a tine cultivator at 25cm depth without the inversion of soil layers. Seedbed preparation was carried out during planting operation using a combined power-harrow planter.

*No-tillage (NT)*: seeds were planted without working soil surface. Seeding was conducted by planters using special discs that make a narrow trough on the soil surface for seeds deposition.

Consequently, each tillage system was accompanied by a crop rotation including the most important crops present in the Po Valley: wheat, canola, corn and soybean. If not seeded with the main crops, the soil surface was permanently covered by sowing cover crops using conservation tillage techniques. In addition, MT and NT were integrated with PA technologies, consisting of an automatic steering guidance system, control units allowing automatic section control, and variable rate treatments (VRT). Finally, in order to evaluate the contribution of PA within the different conservation tillage techniques investigated, central test strips managed with fixed rates of inputs were identified (Tab. 4.1.).

Table 4.1: Precision agriculture techniques adopted in the study. Data collection and yield maps were used to compare the investigated treatments. MTv and NTv were implemented with automatic steering system and variable rate application.

Precision Agriculture technologies	CT	Conservation Agriculture			
		MT	MTv	NT	NTv
Automatic steering guidance system	✗	✗	✓	✗	✓
Data collection (historical yield maps, soil resistivity and analysis)	✓	✓	✓	✓	✓
Study of soil variability and homogeneous zone characterization	✗	✗	✓	✗	✓
Variable rate seed application	✗	✗	✓	✗	✓
Variable rate nitrogen application	✗	✗	✓	✗	✓
Yield maps collection	✓	✓	✓	✓	✓

### 4.2.3 Study of the variability and homogeneous zones management

To achieve an objective characterization of spatial variability, we collected the soil data for the definition of homogenous zones through a stratified selecting sampling points representative of the whole field. The definition of homogeneous zones at this site was previously established by analyzing data obtained from proximal or remote sensors that provide information on soil, vegetation and yield (Cillis et al., 2017a). The study area was divided into 4 zones characterized by an increasing productive potential from A to D (Fig. 4.3.).

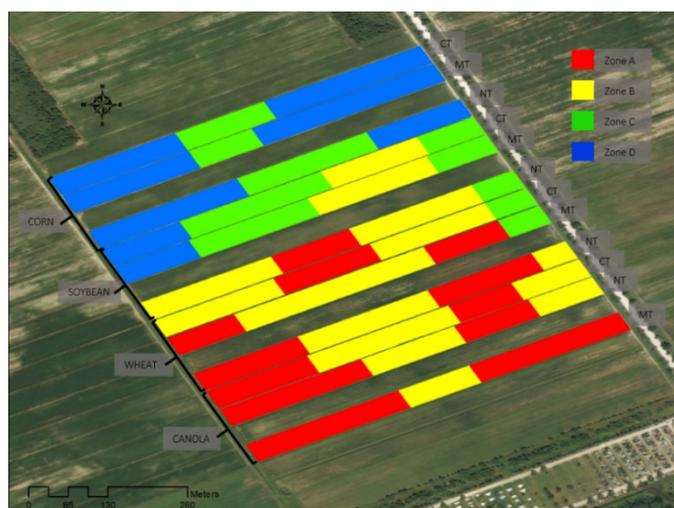


Figure 4.3: Study area divided in homogeneous zones identified by MZA analysis.

Successively, the optimal seed density and nitrogen fertilization rates for the different treatments were defined based on the SALUS model simulations (Cillis et al., 2017b). Table 4.2 shows optimal seed and nitrogen rates of the homogeneous zones managed with different tillage systems as identified from SALUS simulations. For this work, CT was considered as a reference to compare

different tillage systems and the contribution of variable rate application of the inputs. In this regard, CT and the test strips previously identified in those plots, characterized by conservation tillage systems, were always managed using uniform rate application considering the input rates adopted by the pilot farm.

Table 4.2: Optimal seed density and nitrogen rates applied in each homogeneous zone managed with different tillage systems.

Crop	Tillage system	Homogeneous zone	Seed density (kseed ha <sup>-1</sup> )	kgN ha <sup>-1</sup>	
Canola	CT	-	500	128	
		A	500	140	
	MT	B	500	120	
		C	500	100	
		D	500	110	
		A	550	150	
	NT	B	550	130	
		C	550	140	
		D	550	120	
		-	75	193	
	Corn	CT	A	60	180
			B	70	190
C			85	180	
D			95	200	
NT		A	65	200	
		B	75	210	
		C	85	200	
		D	95	220	
Soybean	CT	-	450	-	
		A	550	-	
	MT	B	500	-	
		C	400	-	
		D	350	-	
		A	550	-	
	NT	B	500	-	
		C	400	-	
D		350	-		
-		5000	178		
Wheat	CT	A	5000	150	
		B	5000	190	
		C	5000	140	
		D	5000	180	
	NT	A	5500	150	
		B	5500	190	
		C	5500	130	
		D	5500	170	

#### 4.2.4 Overview of Systems Approach to Land Use Sustainability (SALUS) model

SALUS is a process-based model developed to simulate the interactions between soil, climate, crop genotypes, and management strategies on crop growth, water, and nutrient cycles during growing seasons. It evolves from the well-established CERES model with modifications in the nitrogen cycle, water balance, and tillage (Basso et al., 2006; Albarenque et al., 2016). The SALUS model

requires information about the soil, climate, genotype characteristics and agronomic management to simulate yield, water and nutrient fluxes. at a daily step (Fig. 4.4.).

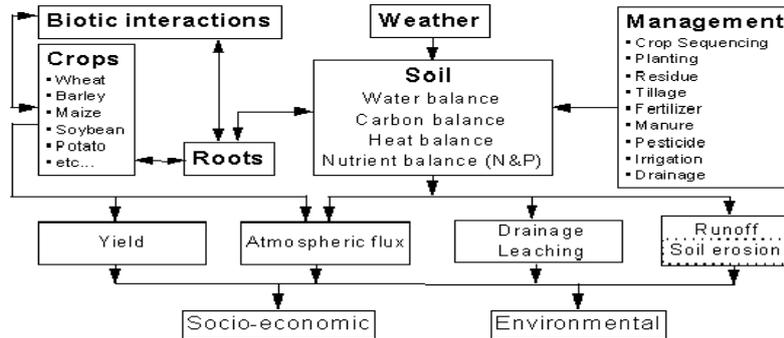


Figure 4.4: Overview of the SALUS model (Basso et al., 2006).

SALUS accounts for the impact on tillage practices on soil biophysical properties (bulk density, saturated hydraulic conductivity, soil organic matter turnover rates). A detailed description of tillage routines in SALUS has been reported in Basso et al. (2016). The model has been tested for crop phenology and yield (Basso et al., 2011a, 2012), nutrient cycling (Senthilkumar et al., 2009; Giola et al., 2012; Basso and Ritchie, 2015), and soil water balance (Basso et al., 2010, Hamilton et al 2015). It has also been widely used and successfully validated for Italian agricultural systems and environmental conditions by Basso et al. (2007, 2010, 2011a, 2011b, 2016a) (Dzotsi et al., 2013). Here, the SALUS model was used to define the best input rates and the SOC evolution under different management scenarios and field scale variability.

#### 4.2.5 Data collection

In order to test the SALUS model, specific input data regarding the study area was collected. A soil features dataset was built using soil sampling analysis derived from the study of field variability. Cillis et al. (2017a) employed a selective soil sampling method to define the sample points in the field; a total of 20 points were selected, where undisturbed soil samples were collected at three depth levels (0-0.1, 0.1-0.3, 0.3-0.6m). The same operation was performed in 2017 after three years of experimentation to validate the model for SOC simulation (Tab. 4.3.).

Table 4.3: Average soil organic matter (SOM) and bulk density of the different homogeneous zones at three depth levels. Data collection is related to the starting period (2014) and after three years of experimentation (2017).

Depth (m)	Homogeneous zone	Year 2014		Year 2017	
		SOM (%)	Bulk density	SOM (%)	Bulk density
0-0.1	A	1.22	1.66	1.14	1.67
	B	1.22	1.65	1.10	1.61
	C	1.92	1.55	1.79	1.64
	D	2.38	1.52	2.17	1.63
0.1-0.3	A	1.12	1.61	1.08	1.61
	B	1.18	1.52	1.05	1.59
	C	2.10	1.61	1.85	1.63
	D	2.38	1.62	1.94	1.62
0.3-0.6	A	0.92	1.67	1.11	1.64
	B	0.98	1.56	1.21	1.62
	C	1.80	1.67	1.82	1.68
	D	2.30	1.62	1.82	1.66

Historical weather data included a 23-year dataset recorded at a nearby agro-meteorological station. Weather parameter data at the daily time-step, required by SALUS, were obtained, then the model was calibrated and validated. The model validation was performed using 2015 and 2016 yield data on the basis of the productive response of each homogeneous zone determined by the previously cited crop rotation managed with different tillage systems. Yield data was provided by a combine implement equipped with a yield mapping system. Additionally, we collected total biomass samples at harvest (Fig. 4.5.) and we used the total aboveground biomass dataset as an additional validation representative of the studied treatments.

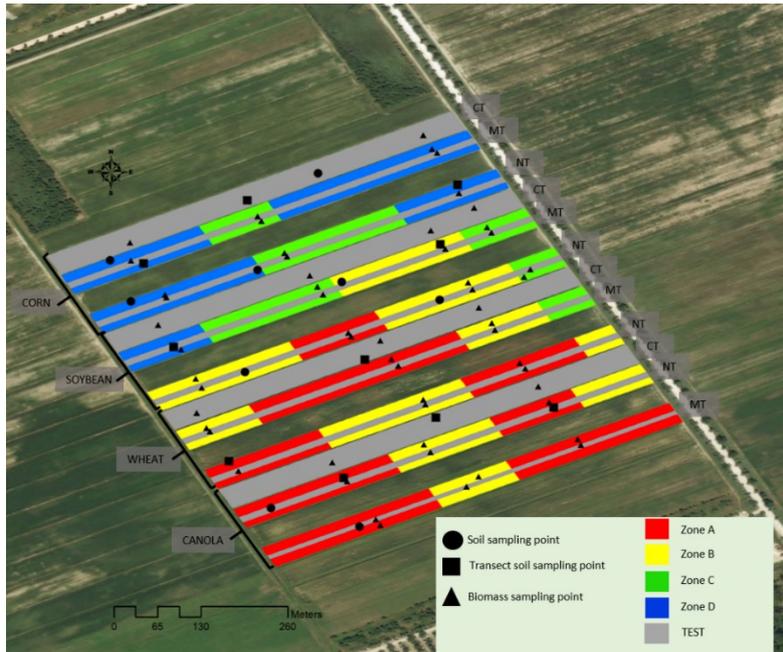


Figure 4.5: Final experimental plan showing the distribution of homogeneous zones, definition of the strip managed in uniform inputs application, and the selection of the soil sampling points used to build the transects for data collection.

Subsequently, we performed a 15 years simulation to study the SOC evolution in the upper 0.4m of the soil profile for each treatment. Additionally, all agricultural operations were monitored with regards to timing and fuel consumption, to assess the direct energy requirements; while the inputs rate and the utilized machines were used to define the indirect energy requirements for each treatment. The energy requirements ( $\text{GJ kg}^{-1}$ ) and  $\text{CO}_2$  emissions ( $\text{kg C kg}^{-1}$  product) of each farming operation and input were estimated using energy conversion coefficients as described in Pimentel and Pimentel, (1979), Clements et al., (1995), West and Post, (2002). Finally, an analysis of variance was performed, checking significant statistical differences between the means of the treatments using the LSD method considering a p value of  $\leq 0.05$ . Statistical analysis was performed using Statgraphics Centurion XVII (StatPoint, Inc., 2005).

## 4.3 Results

### 4.3.1 SALUS model validation

In this study, the SALUS model was validated in consideration of three variables: grain yield (Fig.4.6.), total aboveground biomass, and SOC content after three years of experimentation.

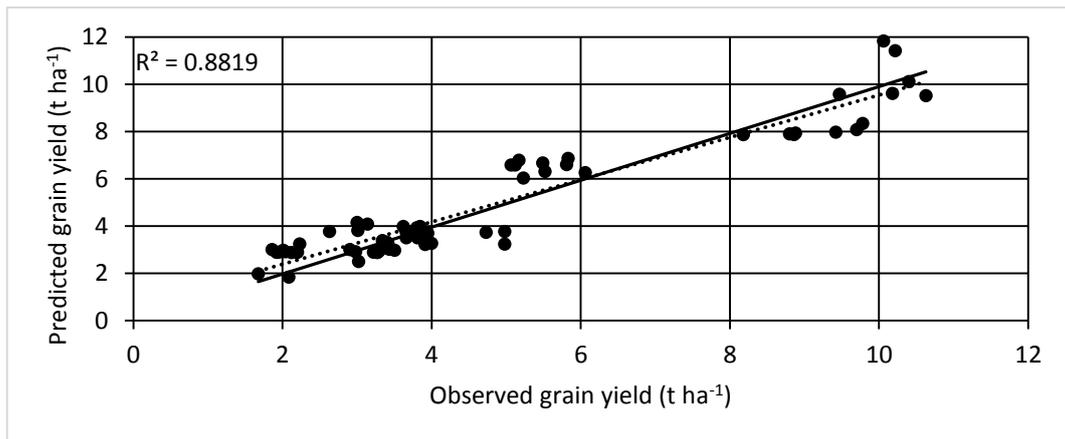


Figure 4.6: Predicted vs observed grain yield (expressed as dry matter) of the studied crops during the crop seasons 2015 and 2016 using the SALUS model.

Regression analysis showed an  $R^2$  of 0.90 and a RMSE of  $0.7 \text{ t ha}^{-1}$  significant at  $p < 0.05$  or below. However, the analysis highlighted a low predictive capacity for some treatment. In the first year of experimentation, canola and corn managed with NT achieved very low grain yield in homogeneous zones A, B, and C. This was due to the NT sensitivity during the first year of conversion and logistic problems. This led to low crops emergence in canola and corn stand reduction during all the crop cycle, which did not allow for precise calibration the model, especially in corn, considering its capacity to partially compensate stand reduction during the first stages of development (Coulter et al., 2011). Therefore, our analysis is affected by a failure of our model to account for the capacity of corn to compensate for stand reductions in the first stages of development.

The total aboveground biomass simulation was validated against 76 observed values. Approximately the same trend and reliability of grain yields was obtained (Fig. 4.7.).

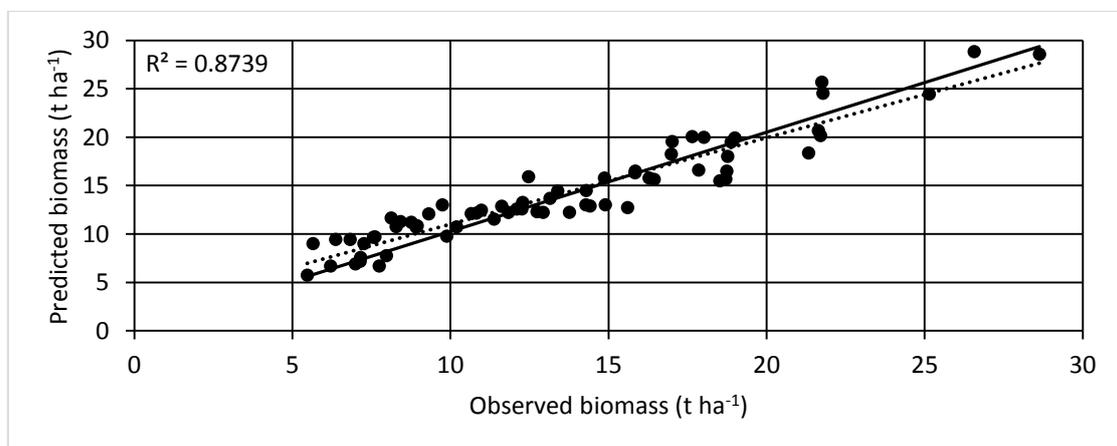


Figure 4.7: Predicted vs observed biomass yield (expressed as dry matter) of the studied crops during the crop seasons 2015 and 2016 using the SALUS model.

The regression analysis showed an  $R^2$  of 0.90 and a RMSE of  $1.3 \text{ t ha}^{-1}$  significant at  $p < 0.05$  or below. As for the predictions of grain yield, the total aboveground canola and corn biomass under NT system were overestimated in the first year of simulation, however we believe that the overestimation of the first year had a minimum effect on SOC simulation because it was a problem only related to the first year of experimentation.

Concerning SOC validation, the SALUS simulation was tested on the basis of the SOC analysis derived from the 20 soil samples collected in 2017. A total of 12 SOC values, representing the

homogenous zones managed with different soil tillage techniques, were defined. Therefore, the soil sampling points belonging to the different treatments were linked. Using this process it was possible to evaluate the evolution of SOC of the four homogeneous zones under different tillage systems after three years of experimentation (Fig. 4.8.).

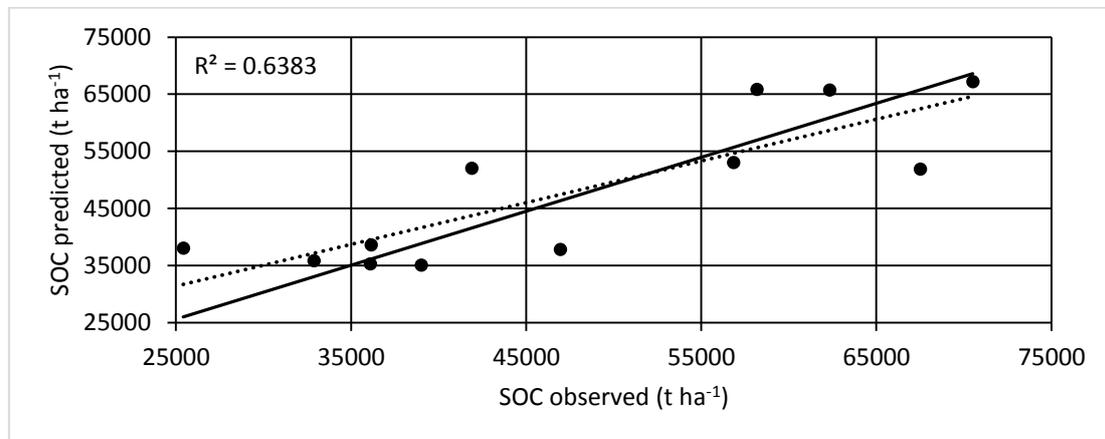


Figure 4.8: Predicted vs observed soil organic carbon (SOC) in the upper 0.4m of the soil profile of the homogeneous zones under different tillage systems after three years of experimentation using the SALUS model.

The regression analysis showed an  $R^2$  of 0.70 and a RMSE of 5770 kg ha<sup>-1</sup> significant at  $p < 0.05$  or below. Finally, considering that changes in SOC can occur slowly (Smith et al., 1997), the purpose of this validation was to monitor if the initial simulated trend was in line with the observed one. Coupling this validation with the total aboveground biomass, it is possible to perform a representative mid-term SOC simulation.

#### 4.3.2 SOC mid-term simulation

SALUS model simulations proved useful to study the evolution of SOC in the 0-0.4m soil layer in homogeneous zones characterized by different physical chemical features under the three tillage systems. Considering the different initial soil features, especially SOC, all the homogeneous zones followed the same trend (Fig. 4.9.).

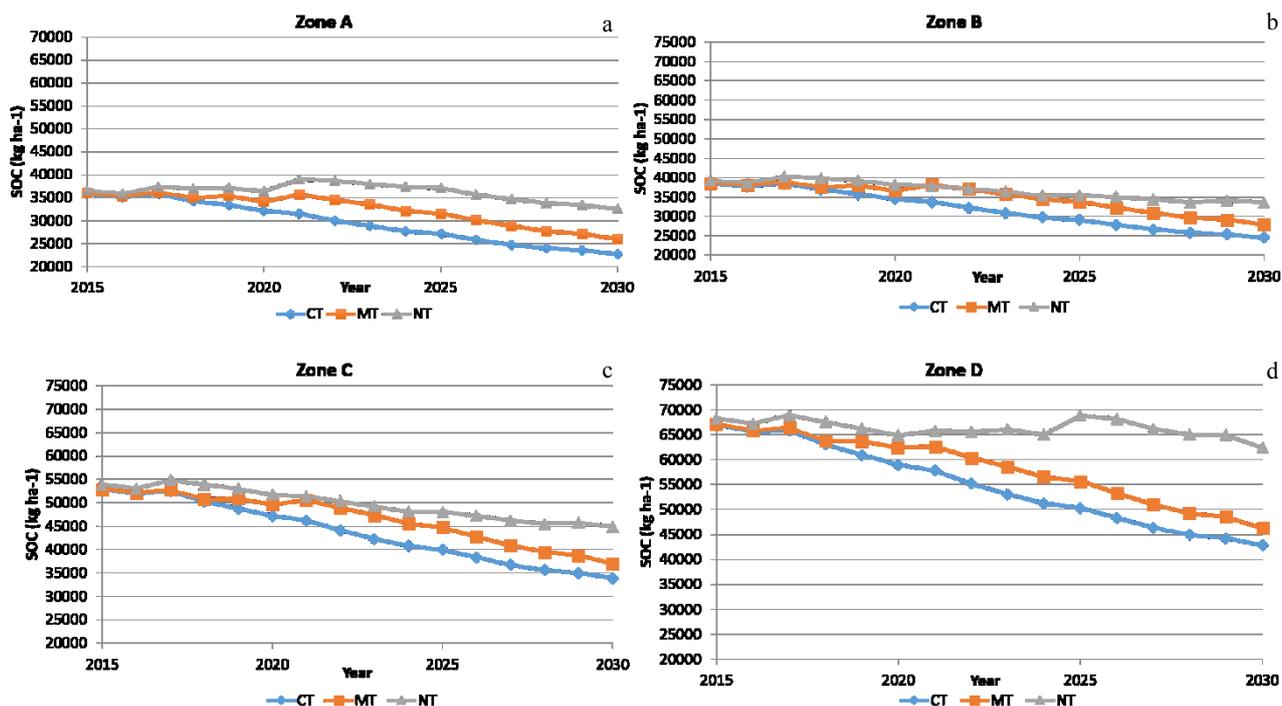


Figure 4.9: Evolution of SOC content in the 0-0.4m soil layer over 15 years (2015-2030) in the defined homogeneous zone (A, B, C, D) under CT, MT, and NT systems.

In fact, all of the cases highlight that CT loses the highest amount of SOC compared to MT and NT, while MT always fell between CT and NT. During the 15 year simulation, homogeneous zone A, characterized by the lowest SOC, lost an average of  $772 \text{ kgC ha}^{-1} \text{ year}^{-1}$  under the CT system, leading to a decrease in its productive potential and crops growth suitability. On the other hand, a reduction in SOC losses of 22% and 67% over 15 years was detected for MT and NT, respectively (Fig. 9a). Homogeneous zones B and C, having an intermediate SOC content, followed the same trend losing a higher SOC amount than zone A. In both cases, the capability of MT in mitigating SOC changes compared to CT decreased to 15%. This is most likely due to crop and cover-crop residue mixing in the soil, which allows high levels of SOC mineralization. NT, thanks to its features, lost in average of  $500 \text{ kgC ha}^{-1} \text{ year}^{-1}$ , 52% less than CT (Fig. 9b, c). Homogeneous zone D has the highest SOC content, but lost more than 30% of total SOC in the 15 years of simulations under the CT system, the largest amount of carbon lost in the homogeneous zones tested. Consequently, zone D represented the main contributor regarding carbon emissions in atmosphere. Even in this case, conservation tillage techniques can mitigate carbon fluxes to the atmosphere. NT reached the highest values of SOC, saving approximately 73% compared to CT (Fig. 9d). Finally, adopting conservation tillage techniques, especially NT, allowed for mitigation of soil fertility loss in zone A with low SOC and productive potential. In addition, NT was also able to decrease carbon changes in zone D, which is the main component affecting carbon flux to the atmosphere.

The differences in the SOC pools among tillage techniques were reflected also in different  $\text{CO}_2$  emissions (Table 4.4.).

Table 4.4: Annual CO<sub>2</sub> soil emissions (t ha<sup>-1</sup>) of the different treatments. Bold values represent difference among the weighted average emissions related to the homogeneous zones under different tillage systems. Soft values highlight difference among the annual average CO<sub>2</sub> soil emissions of the different homogeneous zone managed with the same tillage system. Effects were considered significant if P ≤ 0.05.

Year	CT					MT					NT				
	A	B	C	D	Weighted mean	A	B	C	D	Weighted mean	A	B	C	D	Weighted mean
2015	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2016	1.97	1.84	2.62	3.48	<b>2.36</b>	1.58	1.47	2.35	3.33	<b>2.05</b>	1.68	1.63	2.28	2.92	<b>2.03</b>
2017	-1.76	-1.74	-1.61	-0.50	<b>-1.45</b>	-1.95	-1.93	-1.76	-1.37	<b>-1.78</b>	-4.18	-4.24	-4.65	-4.60	<b>-4.37</b>
2018	3.91	4.18	5.94	7.50	<b>5.12</b>	2.95	3.29	5.20	6.94	<b>4.31</b>	1.38	1.12	2.39	3.66	<b>1.95</b>
2019	2.57	3.06	4.06	5.73	<b>3.68</b>	-1.11	-1.03	-0.28	0.21	<b>-0.66</b>	-0.62	1.48	2.41	3.56	<b>1.53</b>
2020	3.11	3.46	4.22	5.28	<b>3.89</b>	3.40	3.42	3.29	3.50	<b>3.41</b>	1.85	2.88	3.35	3.36	<b>2.79</b>
2021	1.78	1.83	2.54	3.00	<b>2.19</b>	-4.29	-4.08	-2.48	-0.78	<b>-3.16</b>	-6.79	0.69	1.06	-2.18	<b>-1.85</b>
2022	3.99	4.19	5.67	6.93	<b>4.97</b>	3.02	3.14	4.43	6.06	<b>3.96</b>	1.05	1.91	2.75	0.50	<b>1.50</b>
2023	3.26	3.45	4.71	5.85	<b>4.13</b>	2.70	2.97	4.19	4.80	<b>3.50</b>	1.68	2.22	2.96	-1.34	<b>1.40</b>
2024	2.96	3.11	4.05	4.82	<b>3.60</b>	3.66	3.83	4.74	5.37	<b>4.27</b>	1.71	2.61	2.89	2.80	<b>2.46</b>
2025	1.59	1.63	2.12	2.49	<b>1.89</b>	1.60	1.67	2.07	2.39	<b>1.88</b>	0.80	-0.20	0.33	-10.19	<b>-2.07</b>
2026	3.25	3.40	4.33	5.18	<b>3.90</b>	4.02	4.22	5.31	6.24	<b>4.79</b>	3.69	1.16	2.06	1.87	<b>2.12</b>
2027	2.90	3.11	4.33	5.38	<b>3.75</b>	3.41	3.69	5.02	6.22	<b>4.39</b>	2.69	1.64	2.79	5.21	<b>2.89</b>
2028	2.20	2.31	3.03	3.64	<b>2.69</b>	3.00	3.15	3.81	4.59	<b>3.53</b>	2.34	2.24	1.87	3.09	<b>2.40</b>
2029	1.14	1.17	1.54	1.81	<b>1.36</b>	1.33	1.31	1.69	2.03	<b>1.53</b>	1.05	-1.38	-0.56	0.21	<b>-0.26</b>
2030	1.03	1.10	1.47	1.83	<b>1.30</b>	0.86	0.91	1.25	1.52	<b>1.09</b>	1.00	1.05	1.23	1.90	<b>1.25</b>
Mean	2.26 <sup>a</sup>	2.41 <sup>a</sup>	3.27 <sup>ab</sup>	4.16 <sup>b</sup>	<b>2.89<sup>a</sup></b>	1.61 <sup>a</sup>	1.74 <sup>a</sup>	2.59 <sup>a</sup>	3.40 <sup>a</sup>	<b>2.21<sup>ab</sup></b>	0.62 <sup>a</sup>	0.99 <sup>a</sup>	1.54 <sup>a</sup>	0.72 <sup>a</sup>	<b>0.92<sup>b</sup></b>

Significant statistical difference was found among the homogeneous zones under CT, with the highest level of carbon losses in zone D. Conversely, no significant difference was found in the same zones under MT and NT. These results confirmed the potential of conservation tillage systems to decrease carbon flux in atmosphere from soil characterized by different SOC content.

We that the CT average CO<sub>2</sub> emissions were higher than NT (p<0.05, table 4). Every zone managed by CT followed a cyclical pattern in regards to mitigation of carbon emissions. Throughout the simulated years, high biomass availability in the upper 0.4m of the soil layer was observed the year after a season of corn crop. This progression meant a reduction in carbon emissions. The effect of crop rotation was observed in MT and NT as well, however, due to their characteristics allowed for more carbon storage in the soil. In addition, conservation tillage systems were influenced by cover-crop practices. The additional amount of biomass derived from the cover-crops supplied to the soil amplified the carbon storage effect of MT and NT. Therefore, conservation tillage systems, especially NT, allowed mitigation of CO<sub>2</sub> emissions during all the considered crop rotations, achieving significant average annual carbon saving compared to CT. However, CT in the last years reached a steady layer with a consequent reduction in CO<sub>2</sub> emissions. This condition has not been observed in MT and NT because they were derived from a conversion period started in 2014.

### 4.3.3 CO<sub>2</sub> emissions related to farming operations.

CO<sub>2</sub> emissions due to farming operations are the second largest contributor of total carbon emissions to the atmosphere in the agricultural sector. Operations emissions are smaller than soil emissions, ranging from 25% to 50%, but it is still important to consider the potential to significantly decrease CO<sub>2</sub> emissions by adopting specific strategies. Figure 4.10 shows that CO<sub>2</sub> emissions related to mechanization (i.e. emissions due to fuel combustion) represents the main component for all of the treatments studied.

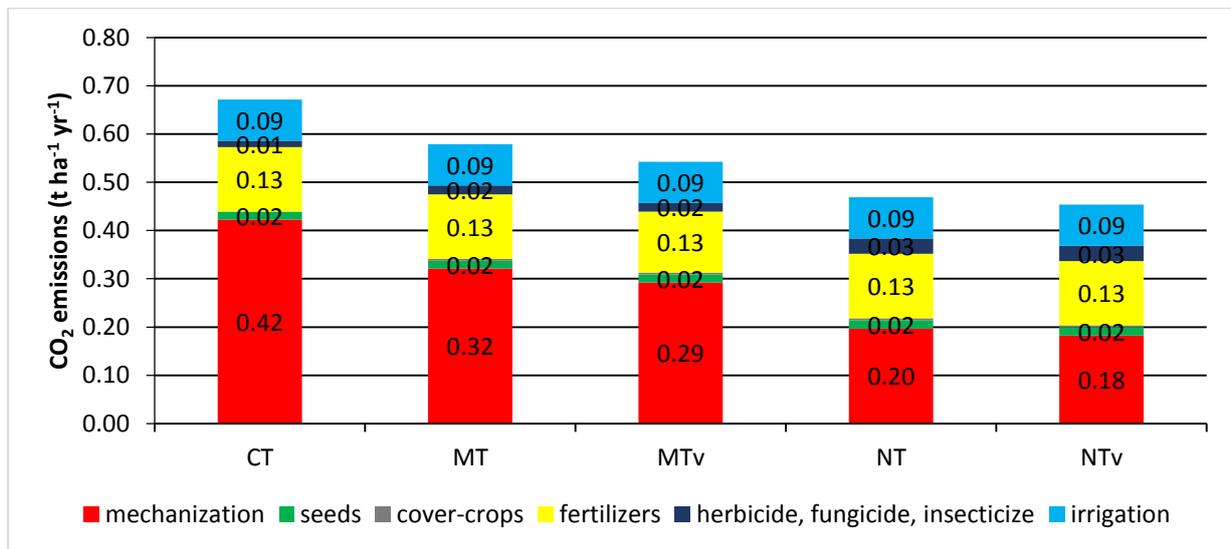


Figure 4.10: Total annual CO<sub>2</sub> emissions (t ha<sup>-1</sup> yr<sup>-1</sup>) of the considered crop rotation related to managing operations.

However, the adoption of conservation tillage practices and precision agriculture technologies drastically decreased carbon emissions related to operations. In fact, both MT and NT, due to the reduction of the intensive soil working passages, reduced CO<sub>2</sub> emissions by 24% and 53%, respectively, compared to CT. Moreover, the adoption of PA technologies, particularly the automatic steering system, led to an additional emissions saving of approximately 10% in MT and NT compared to the same treatments without PA implements. Conservation tillage techniques, especially NT, are very sensitive to herbicides application, which also affected CO<sub>2</sub> emissions. Considering the crop rotation adopted in this study, the carbon emissions related to herbicides application in MT are 42% higher than CT and almost three times higher than NT. Consequently, CO<sub>2</sub> emissions of the other considered factors did not highlight significant differences among the treatments. This can be seen as additional evidence regarding the liability of the SALUS model and determining the right approach used to define the appropriate inputs rate in MT and NT supported by PA. Finally, CT exhibited the highest average annual CO<sub>2</sub> emissions considering the aforementioned crop rotation. Therefore, MT and NT were able to decrease carbon emission related to farming operations by 20% and 33% respectively.

## 4.4 Discussion

Understanding the main factors affecting soil carbon fluxes in the atmosphere and their evolution during that time is a crucial topic for consideration. Adoption of strategies with the potential to make soil a carbon sink and mitigate the negative effects of global warming should be highlighted and considered (Lal, 2004). Nonetheless, it is also important to define the managing strategies leading to the optimization of the exhaustible inputs such as fossil fuels, fertilizers, and soil. In this regard, this study confirms the hypothesis that under current climatic conditions, conservation

tillage systems are a useful tool to mitigate SOC losses in the soil. Simulations using the SALUS model highlighted a SOC decreasing in the upper 0.4m of the soil profile in every homogeneous zone under different tillage systems during the 15 simulated years. Our results are in line with the trend obtained in other studies and climatic conditions (Senthilkumar et al., 2009; Bertocco et al., 2008; So et al., 2001). The results showed differences in the amount of SOC lost among the homogeneous zones. On the other hand, MT and NT allowed drastic reductions in farming operations' CO<sub>2</sub> emissions, optimizing the utilization of exhaustible inputs (Pezzuolo et al., 2017; West and Marland, 2002). This positive influence of conservation tillage techniques on CO<sub>2</sub> emissions was enhanced by the support of precision agriculture technologies. In fact, both MT and NT reduced carbon emissions related to fuel combustion thanks to the high working capacity achieved by the automatic steering system (Heraud and Lange, 2009). Additionally, variable rate application of inputs such as seeds and fertilizers enhanced their efficiency without affecting emissions (Fig. 4.11.).

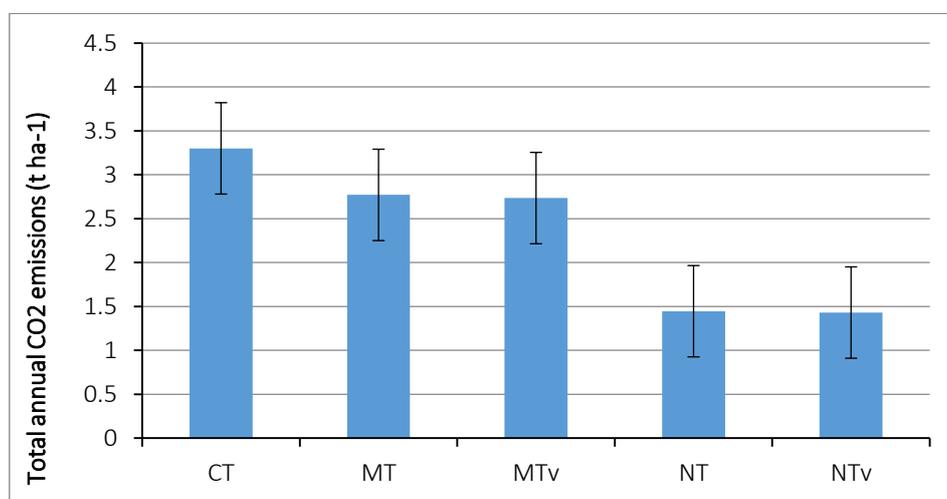


Figure 4.11: Weighted average annual soil carbon exchange and managing operation CO<sub>2</sub> emissions considering the study area variability and the defined crop rotation under the considered treatments.

In fact, no statistically significant difference was observed between conservation tillage managed in uniform rate application and the same techniques supported by PA considering the variability characterizing the study area.

CT has the highest average total annual emissions however no significant difference is observed compared to MT and MTv. Furthermore, NT decreased the total carbon emission by 56% compared to CT, but not it was not significantly different from MT and MTv. However, the synergy between NT and PA technologies reached the highest level of total annual emission saving under the current climatic condition during the mid-term simulations. PA produced higher inputs efficiency, reaching higher crop yields and lower emissions compared to the same techniques managed in uniform rate application (Fig. 4.12.).

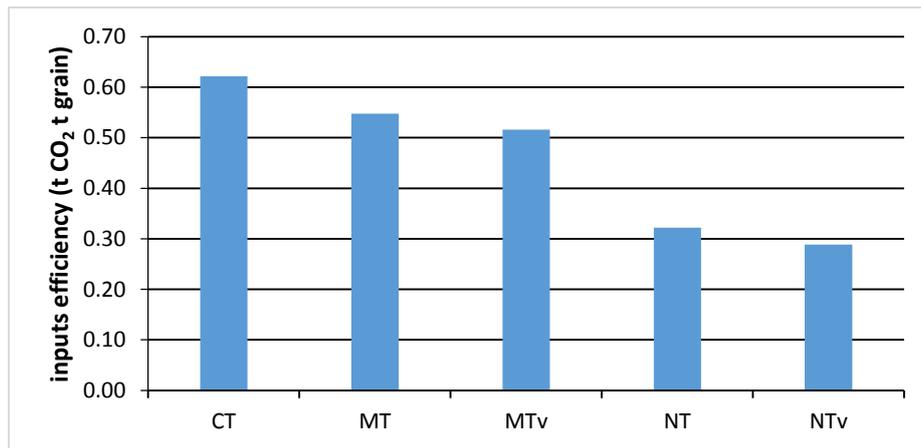


Figure 4.12: Inputs efficiency (t CO<sub>2</sub> t<sup>-1</sup> grains) of the studied treatments. It is referred to the average CO<sub>2</sub> emissions needed to produce 1 ton of average grains on the basis of the considered crop rotation and the study area variability.

Indeed, high working capacity reduced inputs waste due to overlapping and the application of the right inputs rate depending on the requirements of the different homogeneous zones are advantages when using PA strategies. Linking the reduced carbon emission with higher crop yields, an increase in input efficiency of about 10% in MT and NT compared to the same technique without PA technologies is observed. Finally, NTV spent in average 54% of CO<sub>2</sub> less than CT to produce 1 ton of grain, considering the cited crop rotation and variability.

#### 4.5 Conclusion

In this work, the SALUS model was used to study the evolution of SOC under different soil tillage systems considering field scale variability. In addition, the contribution of PA techniques in term of carbon emissions mitigation was assessed in order to define the strategy with the lowest total annual CO<sub>2</sub> emissions under current climatic condition. The validated simulation showed a general trend among the treatments characterized by a decrease in SOC stock. However, a significant reduction in SOC losses was simulated in MT and NT, 17% and 63% respectively, compared to CT. Furthermore, the adoption of conservation tillage techniques decreased carbon emissions related to farming operations, while PA technologies led to an optimization of the exhaustible sources such as fossil fuels and fertilizers. Finally, we showed that the synergy between conservation tillage systems, especially NT, and PA strategies represents a useful tool in terms of carbon emissions mitigation. With consideration of current climatic conditions and the studied field variability, NTV demonstrated a reduction of 56% of total CO<sub>2</sub> as compared to CT.

## 5 Discussion and conclusion

Agricultural systems are asked to satisfy the increasing global demand for food and fiber for a growing population. The intensification of the current systems in term of inputs and outputs lead to raising the concerns about the impact on the environment. In this regard, the hypothesis of the thesis are (1) to survey within-farm soil and yield variability in order to delineate the homogeneous zones and productive potential; (2) study the synergy between conservation agriculture and precision agriculture allowing the optimization in terms of crop yield, net energy and energy efficiency; (3) Identify the best strategies, derived from the synergy between conservation agriculture and precision agriculture, able to decrease the CO<sub>2</sub> emissions of agricultural systems in the mid-term using SALUS simulations.

The homogeneous zones characterization derived from the interpolation of ARP and historical crop-yield data. Incorporating this method, it is possible to perform the analysis with a larger set of data (over 25 pixels/ha) efficiently. In addition, these two data sources represent spatial and temporal variability. Spatial variability is defined by electrical resistivity obtained by ARP device, strictly related to soil features affecting crop yield; and temporal variability is represented by the historical yield maps related to different crops. Classification and definition of the homogeneous zones were fulfilled by inputting data into the MZA software. Then, the MZA's algorithm was set on the basis of the variance-covariance matrix response highlighted by the software. The optimum number of homogeneous zones was identified according to the minimization of the fuzziness performance index (FPI) and the normalized classification entropy index (NCE). Four homogeneous zones satisfying these requirements were then defined. Consequently, the productive potential was assigned to the homogeneous zones through ANOVA test of soil features and historical crop yield. Finally, the productive potential was validated comparing the average province yield of the considered crops.

Consequently, data derived from each homogeneous zone was separately considered in order to study the effects in term of crop yield and energy efficiency of soil tillage techniques and precision agriculture technologies. The average yield data from the two years of experimentation are here reported, weighted on the field variability in order to highlight crop productions from different homogeneous zones. The aim is to allow a comparison of crop yield, inputs use efficiency end energy efficiency for each homogeneous zone belonging to different treatments (fig. 5.1.).

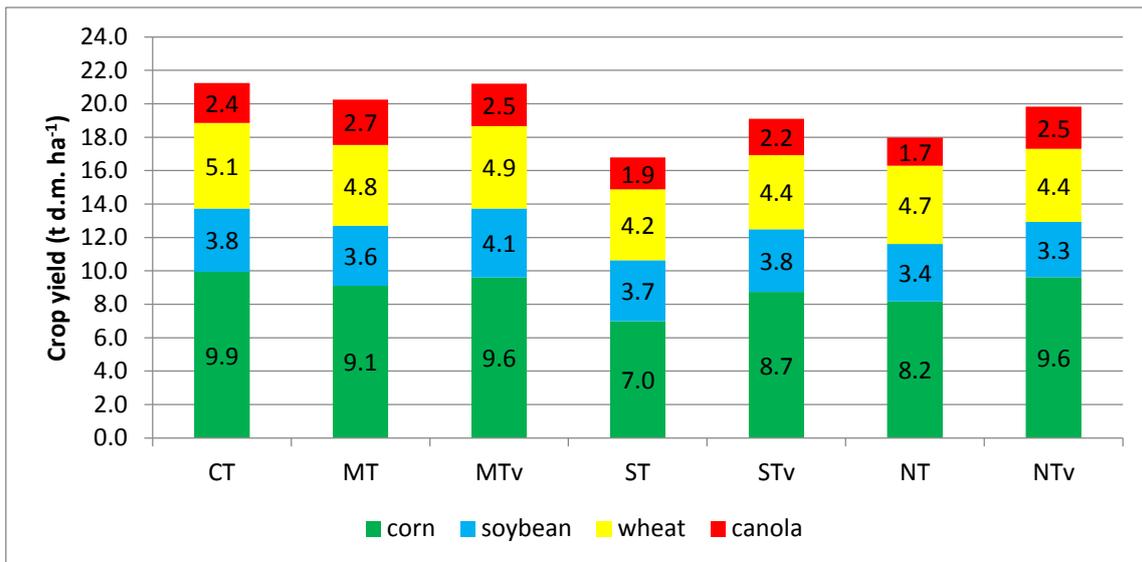


Figure 5.1: Average crop yield characterizing the experimentation for different soil tillage techniques derived from two years of experimentation. MTv, STv and NTv were implemented with precision agriculture technologies.

Corn undergoing uniform seed and nitrogen rates was greatly influenced by simplified soil tillage methods, which led to a reduction in yield higher than 25% in ST and 18% in NT compared to CT. Such gap is strongly mitigated in those treatments where conservation tillage techniques are managed with variable rate application of inputs: indeed, in this case, ST and NT partly lacked the gap compared to CT, while PF contribution allows MT to obtain the same crop yield compared to the reference CT. Soybean cultivation is characterized by an important gap in terms of crop yield only in specific homogeneous zones and the implementation of PF practices allowed to get the highest production in MT. On the other hand, PF benefits did not lead to an increase in crop yield in the case of wheat. However, considering the nitrogen application rates defined before, an increase in nitrogen use efficiency can be observed passing from soil tillage techniques managed with a fixed rate of input and the same methods implemented with PF technologies. Finally, canola cultivation had technical problems for some treatments in the first year of experimentation, which affected the final production. Specifically, the adoption of a new prototype machine designed to seed canola in strips (in the case of ST) and the unsuitable climatic condition partially failed with negative effects on crop development. However, a new strategy was adopted during the second year, which led to getting average yield in line with those found in the literature.

From the energetic point of view, treatments that reached highest crop yields got the greatest amount of gross energy, while energy consumption differences are less evident (Fig. 5.2.).

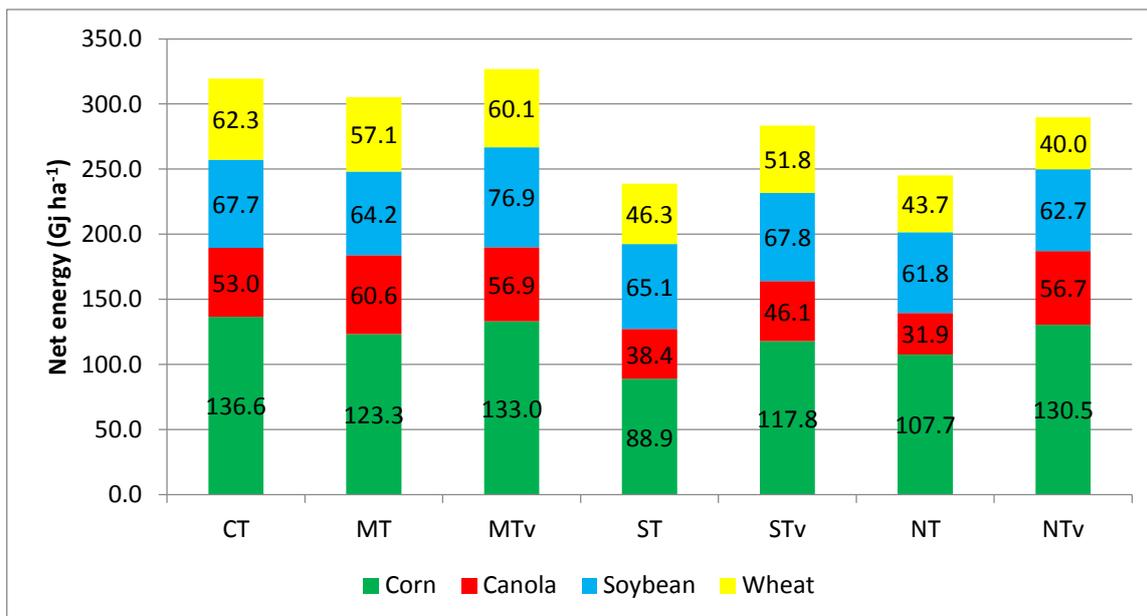


Figure 5.2: Average Net energy achieved by the considered crops under different tillage systems and inputs rate application.

In fact, no significant difference among both MT and MTv treatments and CT was found, but ST and NT got a reduction in net energy higher than 20% compared to CT. Besides, the contribution of precision agriculture allowed to mitigate the gap, with an increase in net energy of almost 20% for both the tillage systems compared to the same technique managed with fixed rate application of inputs.

Regarding energetic inputs, different trends were observed among the items composing the total inputs under the studied tillage systems. In fact, energetic input related to mechanization decreased adopting conservation tillage techniques, especially in reduced one. MT got a reduction of 33% compared to CT as well as ST (Fig. 5.3.).

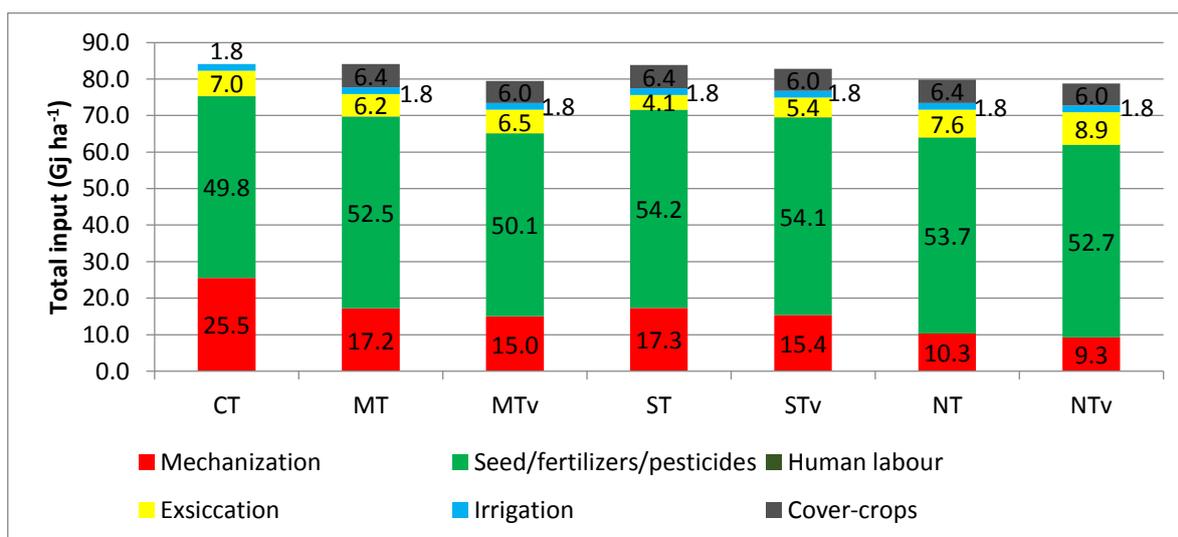


Figure 5.3: Total energetic input (Gj ha<sup>-1</sup>) of the considered crop rotation related to the different items.

Besides, NT reached the highest level of mechanization energy saving, with a reduction of 60% compared to CT. On the other hand, conservation tillage systems were affected by an increased

energy consumption related to seeds, fertilizers and pesticides. This item is negatively influenced by specific requirements of reduced tillage systems. Indeed, the additional 10% of seed rate applied in canola and wheat, and the glyphosate application for weeds control enhanced the energy consumption ranging from 5% in MT and 8% in ST and NT. However, PA technologies allowed to decrease total energetic inputs in CA techniques. A reduction of 10% was observed in mechanization for every CA system compared to the same technique managed without PA, while an increase in efficiency of seeds, fertilizers and pesticides was observed. It led to a reduction of total energetic inputs related to PA contribution of about 5% of the conservation tillage systems compared to CT. Finally, the adoption of cover-crops, meant as mechanization and seeds, affects the total energetic inputs in conservation tillage systems of 8%.

The energy efficiency was estimated as the ratio between the crops energetic content and the total input needed to their growth. Figure 5. shows the average energy efficiency gain achievable by each treatment considering the previously described crop rotation and spatial variability characterizing the study area.

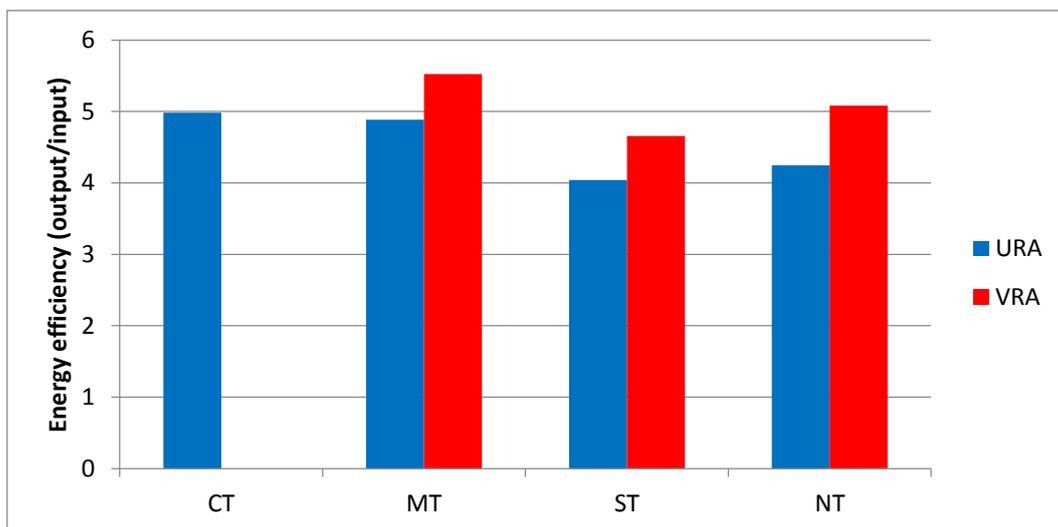


Figure 5.4: Energy efficiency for different soil tillage techniques managed with inputs uniform rate application (URA) and variable rate application (VRA).

In particular, PA contributes to increase energy efficiency in MT and NT with an increase with respect to CT of 10% and 2% respectively. Finally, ST supported by PA technologies shows an increase in energy efficiency of 15% compared to ST managed with a fixed rate of inputs.

In the same way, differences among the treatments in term of CO<sub>2</sub> emissions due to farming operations were observed. Because of the technical problems affecting ST during the first year of experimentation, which led to low crop yield, the analysis regarding carbon emissions was performed only considering CT, MT and NT. It represents the second component being part of the total carbon emissions in the atmosphere. However, this component is less affecting than soil emissions, ranging from 25% to 50%, but at the same time is possible to significantly decrease CO<sub>2</sub> emissions adopting specific strategies. It is split into different items, which are converted in kgCO<sub>2</sub> kg<sup>-1</sup> of product using conversion coefficients including production, packaging, transportation and

application. Besides, different managing strategies influence the weight that each item has compared to the total farming operations emissions.

However, the adoption of conservation tillage practices and precision agriculture technologies allowed to drastically decrease carbon emissions related to this items. In fact, both MT and NT thanks to the reduction of the intensive soil working passages reduced CO<sub>2</sub> emissions compared to CT of 24% and 53% respectively. Besides, the adoption of precision agriculture technologies, in this case, the automatic steering system, led to additional emissions saving of approximately 10% in MT and NT compared to the same treatments without PA implements. Besides, the sensitivity of conservation tillage systems to herbicides applications, especially NT, led to an increase in CO<sub>2</sub> emissions of this item of 42% in MT and almost three times in NT compared to CT. However, MT and NT were able to decrease carbon emission related to farming operations of 20% and 33% compared to CT, while precision agriculture contribution allowed to enhance the inputs efficiency without occurring in carbon emissions increments.

On the other hand, SALUS model was used both to define the best inputs rate to apply to each treatment and simulate the supplied biomass and its evolution in the soil in different management scenarios. In this regard, SALUS model shown a high level of reliability in simulating the parameters considered in this study.

SALUS model simulation was useful to study the evolution of SOC in the 0-0.4m soil layer in homogeneous zones characterized by different physical-chemical features under different tillage systems. Considering the different initial soil features, especially SOC, all the homogeneous zones followed the same trend. Changing in SOC led to a different trend in annual CO<sub>2</sub> emissions among the studied treatments. CT is always characterized by carbon losses in the atmosphere. However, a significant reduction in SOC losses was observed in MT and NT compared to CT, 17% and 63% respectively.

Therefore, the adoption of conservation tillage techniques allowed to decrease SOC losses and carbon emissions related to the farming operations, while PA technologies led to an optimization of the exhaustible sources such as fossil fuels and fertilizers. Finally, this work demonstrated that the synergy between conservation tillage systems, especially NT, and PA strategies represents a useful tool in term of carbon emissions mitigation, under current climatic condition and the studied field variability, reaching the highest level in NTv with a reduction of 56% of total CO<sub>2</sub> emitted by CT. In conclusion, the evolution of agricultural systems requires the definition of crops suitability of arable land and define the best managing strategies. Further studies are necessary to verify these results, including more sites and simulation under future climatic conditions.

The synergy between conservation agriculture and precision agriculture could lead to additional benefits. In fact, adding information layers it is possible to modulate soil tillage intensity and soil tillage working depth. It can be achieved using specific indices or algorithms able to define the degree of crop residue over the field through remote sensing. Besides, controlled traffic farming reaches higher crop yield and better quality parameters compared to random traffic farming (Annex 1). However, remote sensing could be a useful tool to monitor crops cycle and define

physiological parameters enable to assess stress factors. Therefore, implementing remote sensing with crop modeling provide the possibility to assess the best inputs rate and managing strategies in order to increase their efficiency. It could be get studying the evolution of soil biochemistry under different conditions and its influence on nutrients dynamics and availability. In this regards, predictive models such as SALUS can simulate the nitrogen leaching and soil nitrogen exchange with the atmosphere, parameters useful to assess the environmental impact. Finally, different field management strategies can be also adopted during harvesting time. Indeed, information provide for near infrared spectroscopy sensors (NIRs) give the possibility to perform a differential harvesting on the basis of crop qualitative parameters such as protein content in durum wheat (Annex 2).

## 6 Annex1: Traffic effects on soil compaction and sugarbeet (*Beta vulgaris* L.) taproot quality parameters

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Soil compaction is a critical issue in agriculture having a significant influence on crop growth. Sugar beet (*Beta vulgaris* L.) is accounted as a crop susceptible to compaction. Reduction of leaf area, final yield, and root quality parameters are reported in compacted soils.

The most obvious visual indicator of topsoil compaction is root depth affected by agricultural tractor and machinery traffic up on the soil. Such indicators are mainly correlated to initial soil condition, tyre features, and number of passages. For this reason, controlled traffic farming can be a successful approach. Monitoring and controlling frequency and position of machine traffic across the field, in such a way that passages are completed on specific, well-defined tracks, can assist with minimization of compaction effects on soil.

The objective of the present work was to analyze the subsoil compaction during the growing period of sugar beet with different farming approaches including controlled traffic passages and random traffic. To this end, tests were carried out following each agro technical operation using penetrometer readings in order to monitor the state of cone-index (CI) after each step. In addition, at the harvesting time, root quality parameters were analyzed with particular attention to length and regularity of the taproot, total length, circumference, mass, and above-ground biomass.

Such parameters were usefully implemented in order to evaluate the effects of controlled traffic passages compared to the random traffic in a cultivation of sugar beet. Results highlight how an increase in crop yield, derived from samples monitored, higher than 10% can be expected with implementation of a careful traffic management.

### 6.1 Introduction

Currently, agricultural systems are considered (analyzed and studied) from different points of view compared to the past. One is the protection of the environment in terms of carbon emission and soil characteristics (López-Garrido et al., 2009; Pezzuolo et al., 2014, Basso et al., 2016). Soil characteristics are negatively modified by soil compaction, a side effect of modern agriculture experienced on soils in different parts of the world. Soil compaction is defined as “the process by which the soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby increasing the bulk density” (Kroulík et al., 2011). Soil compaction leads to negative consequences such as the reduction of soil porosity, decrease of aeration (McHugh et al., 2009), reduction of saturated hydraulic conductivity and an increase in soil resistance to roots exploration (Balbuena et al., 2003; Valdes-Abellan et al., 2015). Some different approaches have been recently proposed in the last year for fast characterisation of soil condition, mainly consisting of sensors mounted on tines or discs allowing on the go data collection (Chukuw and Bowers, 2005; Hemmat et al., 2008; Hemmat et al., 2009). A more traditional approach is the measurement of soil mechanical resistance is, assessed taking advantage of a penetrometer with a conical tip. Mechanical resistance, expressed as cone index (CI), is calculated dividing the insertion force by the base area of the cone. Such stop and-go method results a not practical approach in

large-scale fields, even when automated, since it is high time consuming and provides only single location variability (Hall and Raper, 2005). Additionally, the method is influenced by soil moisture, which has in general to be considered whenever quantitative analyses are carried out (Ayers and Bowen, 1987; Botta et al., 2002; Hummel et al., 2004). Despite these limitations, the cone index method is relatively simple and intuitive and widely recognised, also by the American Society of Agricultural and Biological Engineers (ASABE, 2006). For this reason, such method was implemented for the present study.

Machines traversing fields are the main source responsible for soil compaction (Chen & Yang, 2015), and their most influencing factors are tire dimension, wheel loads, and inflation pressure.

Several mechanical, agronomical, and management solutions are available to mitigate soil compaction. Implementation of low ground pressure tires can allow a reduction of soil compaction on topsoil for about one third of the pressure in comparison with conventional practices (50-80 kPa) (Chamen *et al.*, 1990), and in equipping machines with rubber tracks, a reduction in soil compaction on subsoil is observed (Ansorge & Godwin 2007, 2008). It is possible to use lighter machines and reduce passages in the fields adopting minimum tillage or no-tillage techniques. Subsoiling allows to enhance soil porosity and water drainage. In addition, compaction is reduced adding organic carbon on soil, depending on soil texture (Kumar *et al.*, 2009; Martín-Lammerding *et al.*, 2013).

Generally, soil compaction leads to negative growth conditions for crops due to high mechanical impedance for roots, decrease in soil aeration, and decrease in water storage (Da Silva & Kay, 1996). There are crops more susceptible to soil compaction than others, as suggested by Koch et al., (2008). Sugar beet (*Beta vulgaris* L.) is accounted as a susceptible crop to compaction (Tijink & Maerlaender, 1998). Reduced emergence, initial growth, final yields, and root quality parameters are reported in compacted soils (Chancellor, 1976; Gemtos & Lellis, 1997; Tolon-Becerra *et al.*, 2011). Compaction can reduce leaf area, dry matter accumulation, and plant population in sugar beet. Furthermore, the total length and distribution of roots in the soil profile can be reduced by topsoil compaction up to 50% (Brereton *et al.*, 1986). Adopting the previous described solutions, such as using rubber track machines, do not lead to a mitigation of problems due to soil compaction in sugar beet (Mosimann *et al.*, 2007).

Controlled traffic farming (CTF) is one of the most interesting and often efficient ways to mitigate soil compaction. In CTF, all or most of operations are performed on well -defined traffic lanes. Machines are equipped with satellite guidance systems which permit crossing repeatedly the same lanes; additionally, machine widths are closely matched with standardized track widths >3m and narrow tires are implemented (Holpp *et al.*, 2011).

Machines never exit defined traffic lanes, therefore, topsoil is only marginally affected by compaction (Hamza & Anderson, 2005; Chamen, 2006). CTF has demonstrated an increase in crop yield related to random traffic farming. Advantages can be significant in root and bulb crop systems for instance potatoes, onions and sugar beet (Gasso *et al.*, 2013; McPhee *et al.*, 2015). The present work is focused on sugar beet, with the aim of analyzing the subsoil compaction during the growing period of sugar beet with different farming approaches: controlled traffic passages and random traffic.

## 6.2 Materials and methods

### 6.2.1 Experimental site

The present study was performed in a private farm in north-eastern Italy in a typical Po Valley field (45.280989 N, 12.006930 E). The soil can be defined, according to the USDA, as silty-loam containing 28.45% sand, 49% silt, and 22.55% clay, 1.9% organic matter, 22.5% total  $\text{CaCO}_3$ , 1.31  $\text{g kg}^{-1}$  total nitrogen, C/N ratio=8.4 and pH ( $\text{H}_2\text{O}$ )=8.0. Before beginning of experiments, the area had winter wheat (*Triticum aestivum* L.) as preceding crop, harvested in June, with chopping and spreading of straws.

### 6.2.2 Description of the experiment

The test field was divided into two equal sub-fields, namely RT (*Random Traffic* area) and CT (*Controlled Traffic* area), as depicted in Figure 6.1. The area was seeded with a total of 84 sugarbeet rows, identifying 83 inter-row spaces.

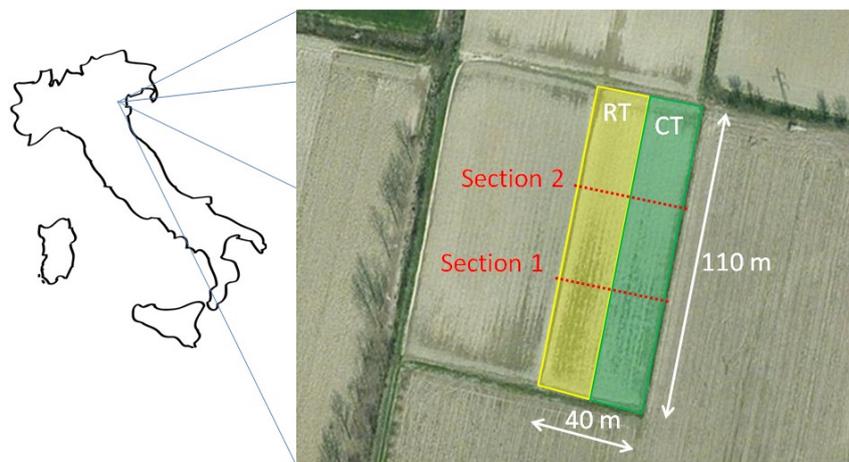


Figure 6.1: Identification of the experimental field.

In the RT sub-field, agricultural operations were carried out with a homogeneous/random distribution of tractor lanes over the area. Conversely, in the CT sub-field, agricultural operations were performed adopting Controlled Traffic basics. To this end, standardized machines work widths ( $ww$ ) were preliminarily assessed and implemented allowing the tractor to run on defined lanes. Specifically, for the present research, a reference width of 2.70 m was considered for the following operations: seedbed preparation, sowing, and hoeing operations. Additionally, other agricultural operations characterized by high working widths such as fertilization, weeding, and pesticide applications were carried out using machines with a working width multiple of the reference one. A  $ww = 13.5$  m was then implemented, i.e. 5 times greater than the reference width. Reference data, together with working depth are reported in Table 6.1.

In both RT and CT cases, all of the operations with the exception of harvesting were carried out using a 77 kW 4WD tractor. The weight of the machine excluded implements is 5500 kg, and is supported by 540/65R24 front tyres and 600/65R38 rear tyres, with an inflation pressure of 162 kPa and 182 kPa respectively. A satellite guidance system allowed proper positioning and steering of the tractor, allowing crossing of the same lanes in the field during the entirety of the scheduled agricultural operations. To this end, the authors had at their disposal a Trimble Fm-1000 integrated monitor with RTK GNSS (Real Time Kinematic Global Navigation Satellite System) rover

and base station, allowing positioning with an accuracy better than  $\pm 4$  cm (Sartori et al, 2014). Other details on implements are given in Table 6.1.

Table 6.1: Working width of the monitored agricultural operations.

Monitored agricultural operations	Date	Working width [m]	Empty weight [kg]	Working depth [cm]	Soil moisture* [%]
Seedbed preparation	1st week March	2.7	2430	15	23.0
Sowing operation	1st week March	2.7	1560	4	23.4
Weeding	2nd week March	13.5	800	0	22.5
Fertilization	3rd week April	13.5	800	0	23.9
1st pesticide application	4th week April	13.5	800	0	21.1
Hoeing operation	2nd week May	2.7	560	10	21.7
2nd pesticide application	1 st week June	13.5	800	0	21.5
Harvesting	1st week August	2.7	22000		

\* Average soil moisture measured 3-5 days after agricultural operation, during penetrometer measurements, on four different positions at 10-25 cm depth

Finally, the field was not irrigated in order to allow observation of the effects of the different traffic managing strategies on crop yield based only on rainfall water. The area was monitored by means of a wireless weather station (*Davis Vantage Pro2 Plus*) equipped with a rain collector, temperature, humidity and radiation sensors. Main precipitations for the period of interest are reported in Figure 6.2.

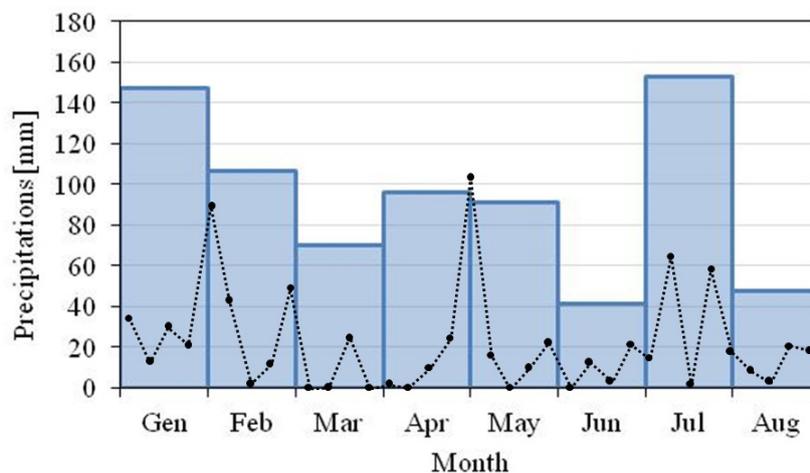


Figure 6.2: Month precipitations (histogram bars) and week values (dotted line) in the proximity of the experimental field.

### 6.2.3 Data analysis

The experimental field can be considered as homogeneous. However, in order to take rid of or detect some possible variability, and to increase the experimental basis, measurements were doubled and taken on two different field portions (namely *Section 1* and *Section 2* in Figure 1). The two sections crossed rows and inter-rows, characterized by different conditions in terms of number of machines passages for both CT and RT scenarios:

- CT0, soil portion not affected by machines compaction (i.e. no tractor wheels passes during the whole agricultural cycle)
- CT3, lanes undergoing three machines passes
- CT8, lanes undergoing eight machines passes
- RT, lanes undergoing a number of passes randomly varying between 0 and 8, and with an average of 1.4 passes.

With regard to the controlled traffic area, 33% of the soil can be classified as CT0, 53% as CT3, and 13% as CT8. For each section, 20 rows and 19 inter-rows were monitored, collecting data related to the four conditions summarized above.

### 6.2.4 Penetrometer analysis

Penetrometric analyses were carried out after each agricultural operation, in order to investigate the possible evolution in soil compaction correlated to machines passages and its role in final yield. Specifically, seven sets of tests were considered: after seedbed preparation, sowing operation, fertilization, weeding, two pesticide applications and after hoeing before harvesting. For the scope, a penetrometer *Eijkelkamp Penetrologger (mod. 06.15.SA)* was implemented, allowing georeferentiation of collected data. Measurements has been carried out, with instrument descent speed set in the range 3-4 cm/s and with a maximum depth of 0.80 m, as recommended by ASAE standard (ASAE, 2001). A total of 38 inter-rows was monitored: 19 located adjacently in the CT area and 19 located adjacently in the RT area; each inter-row was sampled in two different positions, lying in correspondence of the two sections. Collected data were not corrected for moisture content due to its relatively low variability during the experimental tests. Data were averaged based on relative depth: to this end the zero starting point was defined based on the position of the peak of the second derivative of the measured force. All CT and RT curves were averaged into two mean datasets; additionally, CT curves were averaged based on the number of passages in three corresponding mean dataset.

### 6.2.5 Sugar beet plants analysis

At the harvesting time, a total representative sample of over 150 sugar beet plants was singularly harvested. Specifically, four plants per row where picked in the test field, in order to have a comprehensive description of the four traffic conditions (CT0, CT3, CT8, RT). In the case of rows sided by different traffic conditions, the plant was ascribed to the most stressed conditions. By way of example: in the case of a plant picked within a row standing between a CT3 and a CT8 line, it was associated to the CT8 group.

Samples were specifically analyzed in terms of some of the most important qualitative parameters for sugar beet: length, total length, circumference, mass, and regularity of the taproot and aboveground biomass as already done by other authors (Gemtos et al., 2000; Kiyamaz and Ertek,

2015; Kenter et al., 2006). Consequently, samples were analyzed to correlate sugar beet parameters to soil compaction due to machines passages between RT and CT.

### 6.3 Results

Main results are proposed and summarised in the present paragraph. With regard to penetrometer analyses, average values from different inter-rows are reported after each agricultural operation for the 4 conditions (CT0, CT3, CT8 and RT) in Figure 6.3.

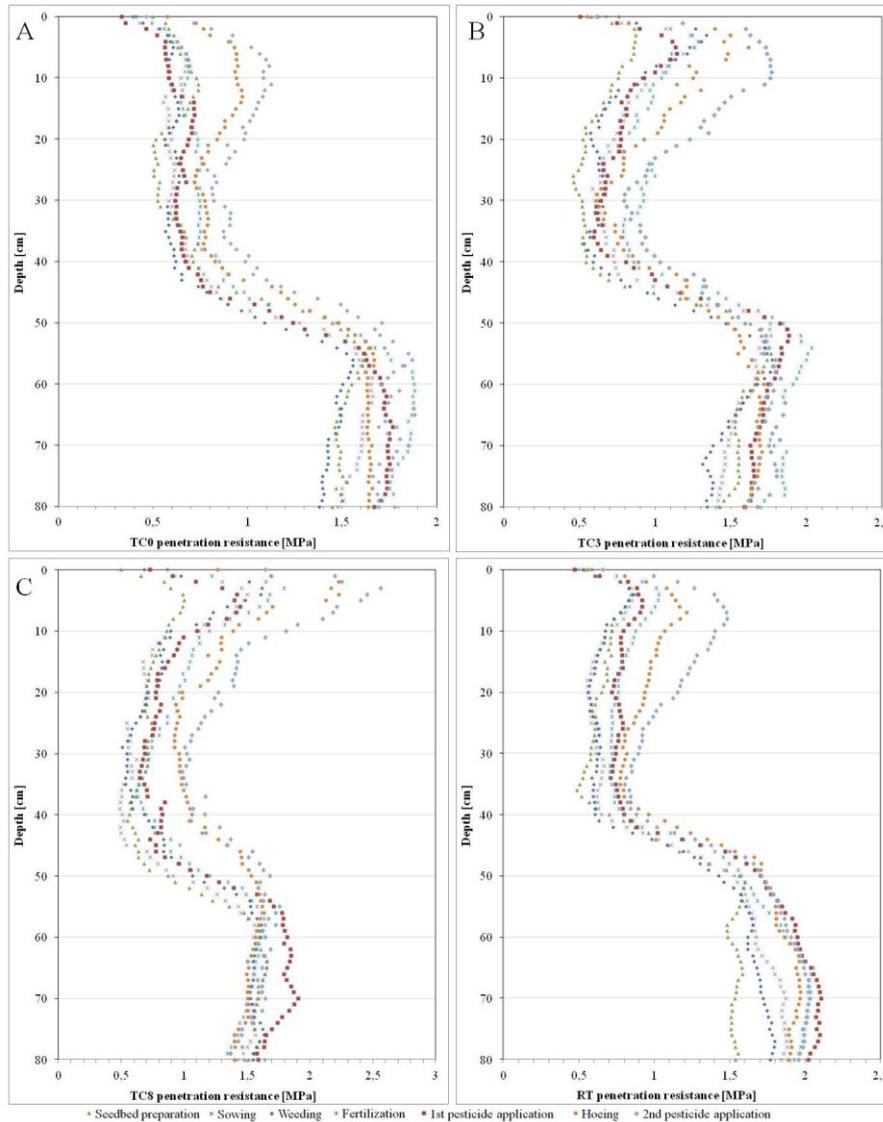


Figure 6.3: . Penetrometer resistance after each operation (seedbed preparation, sowing, weeding, fertilization, hoeing and pesticide applications), in the four scenarios CT0 (A), CT3 (B), CT8 (C) and RT (D).

It can be clearly noted that after the first operation, penetrometer resistances at increasing depths are still very similar, with only negligible differences on the first 5 cm layer. After eight passages (and about after 4 months), the soil has undergone relevant compaction effect, more evident in the case of the CT3 and CT8 condition lanes, but recognizable also in the RT condition. A slight difference can be noticed also in the case of the CT0 condition. This compaction variation is clearly not related to wheels passage but rather to the effect of atmospheric phenomena. The trend can be better appreciated looking at the average penetration resistance at a depth ranging between 5 and 25 cm, where the sugarbeet root typically grows (Figure 6.4.).

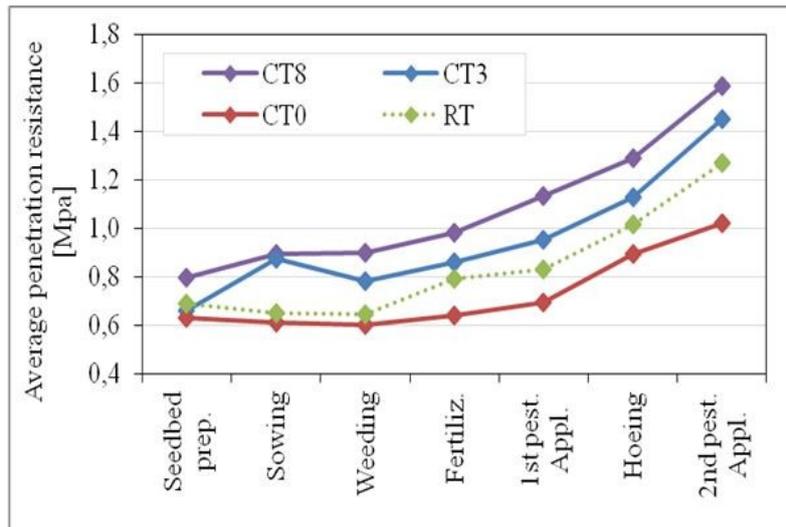


Figure 6.4: Penetrometer resistance averaged in a depth comprised between 5 and 25 cm, after each operation (seedbed preparation, sowing, weeding, fertilization, hoeing and pesticide applications), in the four scenarios CT0, CT3, CT8 and RT.

Specifically, it can be noticed how penetration resistance increases at a rate of about 0.06 MPa after each operation in the case of TC0, 0.10 MPa in the case of random traffic management, and 0.13 MPa in the case of lanes with 3 or 8 passages. In all of the cases, the increase is particular relevant after the first pesticide application. The reason for such behaviour, which is common to all of the scenarios, is ascribable both to the long time passed before the last operation (about two months) but also to the relevant precipitations in the same period. In order to verify if such soil management difference has a statistically evident effect of sugar beet plant conditions, different parameters were analyzed after harvesting and subjected to ANOVA and Tukey statistical studies. With regard to the regularity of the taproot, no statistical effect was highlighted with an occurrence of forking phenomena which was similar both for the random and for the controlled traffic conditions.

On the other hand, a significant effect was determined in the case of the taproot circumference. As reported in Figure 6.5A, the estimated circumference was higher in the case of un-trafficked lanes (35.4 cm) and lower in the case of trafficked lanes with a minimum in the CT8 condition (27.9 cm). Thus, a compacted soil tends to inhibit the growth of the taproot. Indeed, considering the taproot length (Fig. 6.5B.), average values close to 25 cm were detected only in the case of the CT0 condition, while values lower than 20 cm were in general monitored in trafficked and randomly trafficked lanes. The soil compaction ultimately plays a role in both underground and aboveground plants mass. Results relative to above-ground biomass are reported in Figure 6.5C with the same trend described above, and the best performance is always displayed by the un-trafficked lanes, with a biomass of about 0.6 kg: 27% higher than in the case of random traffic plants or at CT8 condition.

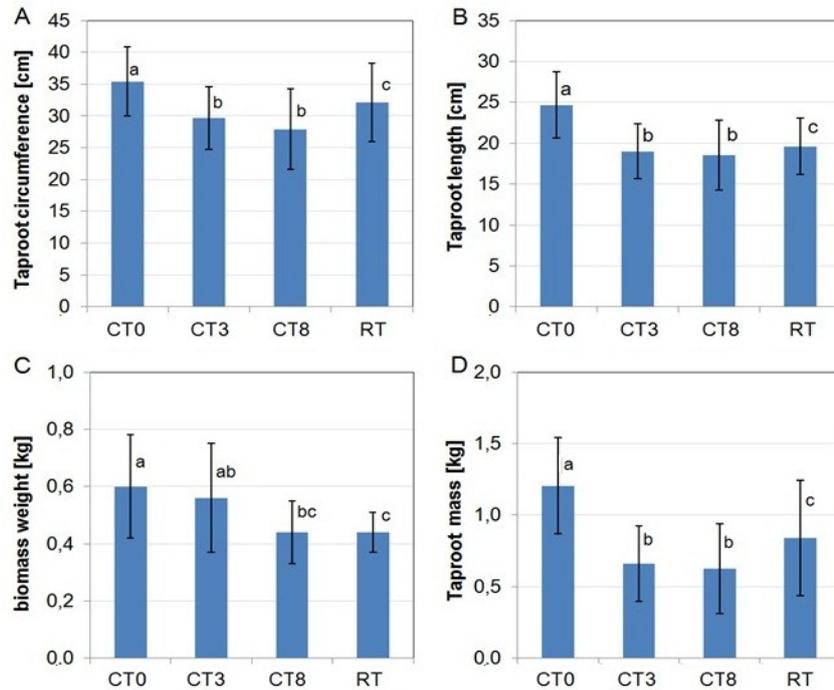


Figure 6.5: Comparison between taproot circumference (A), taproot length (B), taproot mass (D), and biomass weight (C).

Undisturbed soils and healthy above-ground vegetation allow proper growth of the taproot. This is eventually evident on the taproot mass with an average of 1.2 kg, and CT0 sugar beets were 30% heavier than RT ones and 46% heavier than CT3 and CT8.

## 6.4 Discussion

Soil compaction, in both random and in controlled traffic conditions, causes a general decline of sugar beet growth. Controlled traffic fields showed an improvement only in those rows not undergoing traffic stress. As already stated, such rows are only the 33% of the total area, however, they allow a general improvement of the yield in the whole CT area.

Considering the average sugarbeet weights in different scenarios and the relative distribution of rows with different passages (33% as CT0, 53% as CT3 and 13% as CT8), a theoretical total yield increase of 1.3% should be detected in the controlled traffic area compared to the random traffic area. On the other hand 89.5 and 81.1 t/ha actual yields were found respectively for the CT and RT areas. Such values bring the difference at a difference of about 10%, which is far higher than the theoretical one. Such difference was due not only to an increased production but also to a better condition of the plants in a particularly rainy season. Indeed, controlled traffic areas are less subject to losses due to water logging, in a percentage which can vary between 5% and 15% depending on the specific season, weather, and rainfall in particular. Such phenomena affecting more seriously random traffic areas result in a loss of product which amplifies the benefits produced by controlled traffic. Such results are in a good agreement with those reported in literature (Chamen et al., 1992) relative to European countries, where implementation of controlled traffic farming techniques in root and bulb crop systems (such as sugarbeet, onions, potatoes, etc.) bring and increased yields of about 4–14%, when compared with random traffic approaches.

Furthermore, yield difference can be increased by implementing larger machine widths which allow an enhancement of the CT0 incidence on the total area. It is expected that proper application of controlled traffic management can potentially reduce yield losses up to 30%.

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## **7 Annex2: DIFFERENTIAL harvesting strategy: Technical and economic feasibility.**

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Differential Harvesting (DH) is performed to differentiate the product according to a precise quality standard in order to gain an economic advantage from temporal and spatial field variability. In agriculture this technique has been extensively applied in grape harvesting. There are fewer examples for extensive crops, since DH is mostly used for products with a value at harvest that differs depending on their quality characteristics. DH can be achieved through the use of sensors applied on the combine or through qualitative yield maps.

The aim of this paper is to compare the technical and economic feasibility of five DH methods identified in the literature and a new technique proposed by the authors. The analysis was conducted using yield and protein maps obtained in two years of experimentation growing durum wheat. Results highlight how management zone harvesting allows an increase of about 28 % of high-protein wheat, with a subsequent growth in gross revenue.

### **7.1 Introduction**

Differential Harvesting (DH) is a harvesting approach performed to differentiate products according to predefined quality standards and allowing exploitation of economic advantages from the temporal and spatial field variability (Bramley *et al.*, 2005).

The first applications of DH were in the fishery and forestry sectors. In the fishery sector it is applied to improve the quality of the product by reducing the unintentional catching of undersized fish. In forestry it is used to limit damages caused to the forest and preserve the wood quality (Zilberman *et al.*, 1997). In agriculture this technique has been applied extensively in grape harvesting, where DH is achieved by simultaneously conveying the harvested grape into two or more hoppers with specific harvesting machines or through fractional grape harvesting. In the latter, the different zones are harvested at different times after analysis of vegetation indices performed with multispectral images derived from satellites or other platforms.

Implementing scalar harvesting enables to obtain different grape quality classes, resulting in the delivery of a product with homogeneous features. There are fewer DH examples for extensive crops as their value mostly different depending on their quality parameters at harvest-time (Meyer-Aurich *et al.*, 2008). On the other hand, extensive crops as cereals take up an important role to satisfy the food demand and the food quality (Pezzuolo *et al.*, 2014; Basso *et al.*, 2016). By way of example, Durum wheat (*Triticum durum* Desf.) is the main cereal crop in several countries of the Mediterranean basin mainly used for pasta, bread, and couscous production. Durum wheat market constantly demands a grain protein content of 13.5 % or higher (Clarke, 2001), since this trait represents the most important factor affecting pasta-making properties. However, for the farmer point of view, produce wheat with high protein levels allow a high income thanks to major market value and the premium price established by food companies.

This led to the idea of segregating wheat in different quality classes, achieved through the use of sensors mounted on combines (Taylor *et al.*, 2005; Long *et al.*, 2013; Marinello *et al.*, 2015) or qualitative yield maps (Tozer *et al.*, 2007).

The aim of this paper is to define the technical and economic feasibility of the application of DH based methods. Different DH methods found in the literature are compared with the one proposed here (on-combine differential harvesting). The methods are tested using yield and protein maps obtained in two years of experimentation on durum wheat.

## 7.2 Materials and methods

### 7.2.1 Experimental site and climatic data

The grain yield and protein maps used in the present analysis were collected during the 2010/2011 and 2011/2012 wheat crops in a farm in the Venice Lagoon Watershed – Veneto – Italy (45°23'N; 12°09'E).

The experimental field measured 13.46 ha (520 m long and 260 m wide), with a soil defined as sandy according to the USDA classification. In terms of climate, most of the annual average rain falls in the months of April (90.6 mm), July (86.2 mm), October (119.4 mm) and November (82.8 mm). Temperatures peak in the summer months and daily average values are lower in the winter months (January and February), with mean values of 13 °C over the entire season.

Durum wheat, cultivar Biensur (RAGT Semences – France), was managed with traditional agro-technical practices and the fertilization practice was applied using variable rate distribution techniques.

### 7.2.2 Homogeneous zone management

The three homogeneous zones were characterized by a different soil fertility (high, medium and low), on which different nitrogen fertilization levels were distributed (Fig.7.1.). In addition, each zone was split into two parts at flowering stage: one considered as control and the other treated with UAN (urea-ammonium-nitrate) solution (Tab. 7.11).

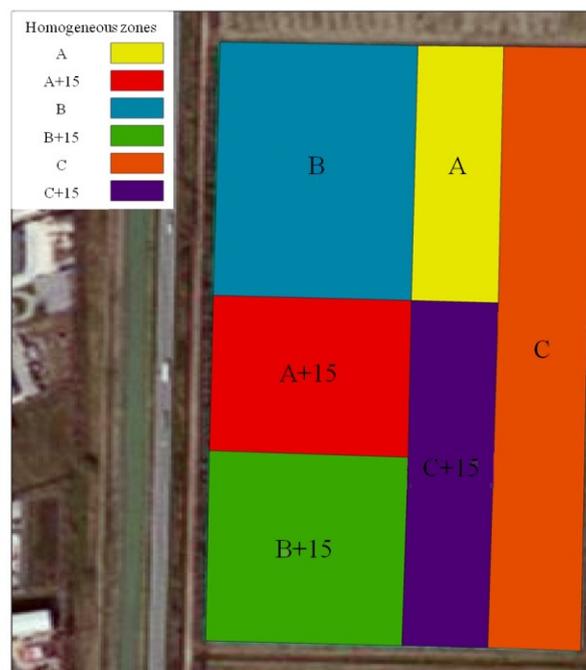


Figure 7.1: Homogeneous zones of the field trial during the wheat cropping seasons 2010/2011 and 2011/2012. The homogeneous zones were identified according to soil fertility parameters.

Table 7.1: Nitrogen fertilizer supply for each homogeneous zone.

Fertilization practices (kg N·ha <sup>-1</sup> )	Homogeneous zone						Date		Fertilizer
	A	A+15	B	B+15	C	C+15	2010/2011	2011/2012	
	High	high	medium	medium	low	low			
Tillering fertilization	52	53	54	55	56	57	24/02/2011	02/03/2012	Ammonium nitrate (26%)
Stem extension fertilization	78	78	108	108	100	100	07/04/2011	06/04/2012	Urea (46%)
Stem extension fertilization					48	48	19/04/2011	27/04/2012	
Flowering stage fertilization		15		15		15	09/05/2011 17/05/2011	14/05/2012 24/05/2012	UAN
<b>TOTAL</b>	<b>130</b>	<b>145</b>	<b>160</b>	<b>175</b>	<b>200</b>	<b>215</b>			

### 7.2.3 Yield and protein mapping

Grain yield was recorded by a yield mapping system (Agrocom CL021) mounted on a combine harvester (Claas mbH *mod.* Lexion 460).

Consequently, protein content was measured with a Near Infrared Spectroscopy sensor (GraiNIT – RxGrains, Italy) associated to the mapping system GPS. As suggested by Morari *et al.* (2013), NIRS accuracy was tested in 32 points of the field comparing the protein content measured by a NIRS used in laboratory and traditional Kjeldhal-method. Data were collected with a relatively high frequency (0.15-0.20 Hz), allowing high field resolution. Raw maps were post-processed in order to filter out points collected in correspondence of turn operations or in stationary combine conditions. Finally, data derived from maps were uploaded in a GIS software and interpolated using the Kriging-function (Fig. 7.2.).

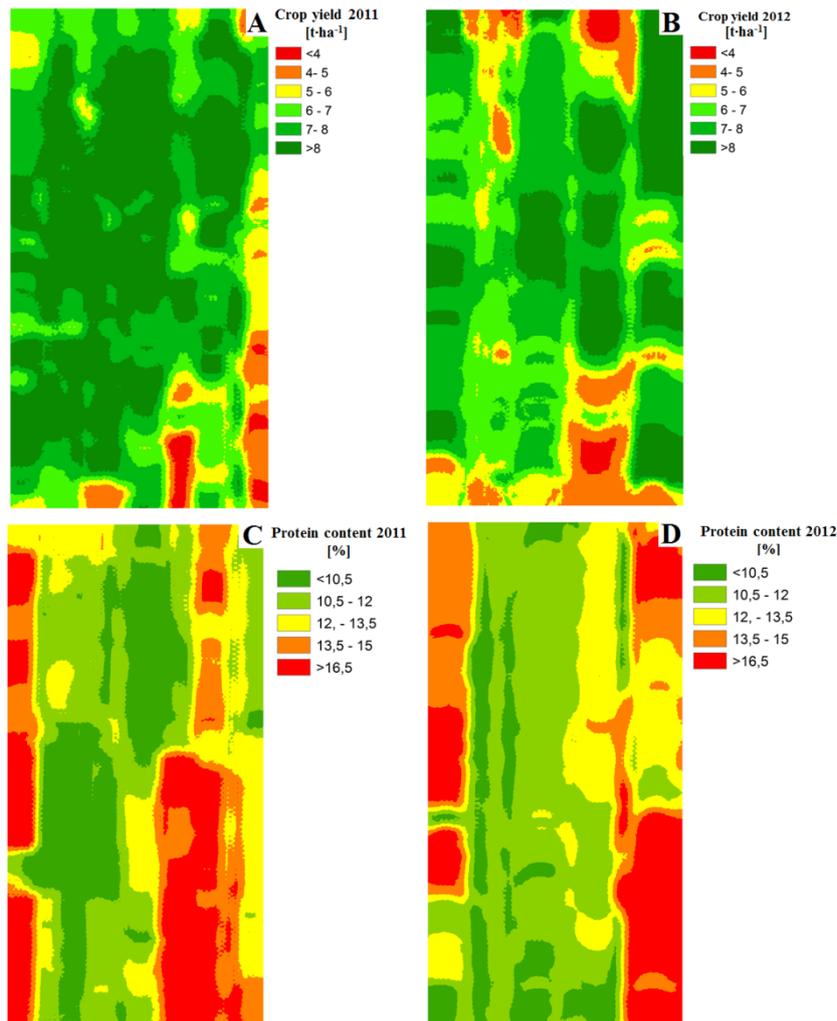


Figure 7.2: Grain yield and protein content maps of the field trial during the 2010/2011 (A; C) and 2011/2012 (B; D) wheat seasons.

#### 7.2.4 Differential harvesting strategy

Collected data were used in order to evaluate 4 different DH techniques (including a new method proposed by the authors) and compare with the uniform harvesting technique.

**Uniform harvesting (UH):** uniform harvesting of the field and undifferentiated unloading of wheat into the truck using a conventional combine without the possibility of segregating high-protein wheat.

**Management zone harvesting (MZ):** each homogeneous zone is harvested separately. Homogeneous areas within the field must be identified using GNSS (Global Navigation Satellite System) and the use of NIRS sensor is not necessary. Wheat yield is selected and unloaded on the basis of the protein content of the whole area.

**On-truck differential harvesting (TD):** the product is unloaded into two different trucks according to the average protein content found during the harvest. This strategy requires a NIRS sensor installed on the combine and information about the protein distribution in the field derived from the previous year protein maps.

**On-combine differential harvesting (CD):** the combine has two hoppers and the yield is differentiated on the basis of the indications of the NIRS sensor. Wheat with lower and higher

protein concentrations falls into two different hoppers. This technique does not provide information about field protein, but it is important to check the right cut-off value. It is possible to assess the optimal cut-off value harvesting through a representative run of the field which allows to know the protein level present in the field. The basic requirement for successful application is a normal field distribution of protein. In this study a cut-off value of 13.5 % was considered.

Optimized on-combine differential harvesting (OCD): the hopper combine is divided into 8 equal parts of approximately 1 m<sup>3</sup> capacity. Each part is equipped with electrically controlled damper opening systems at the top and bottom. All the bottom openings convey into a pre-compartment where a screw allows the unloading operation. During the harvest operation wheat passes through the elevator and is conveyed into the different bins on the basis of protein content read by NIRS. In this way it is possible to know the protein level of each bin. In the unloading phase different bins are opened in order to mix the wheat and obtain a product with a protein content above the threshold. The control software is not limited to managing the protein content of the bin, but calculates the protein content of the truck at each unloading and determines the maximum quantity of low-protein wheat that can be mixed without falling below the threshold level.

### 7.2.5 Technical and economic analysis

Four parameters were calculated to evaluate the technical and economic feasibility of all the previously described DH strategies.

Combine working times: including turning and unloading times. It considers the working width and the average working speed. Turning and unloading time were monitored during harvesting time.

Machine operating costs: a model was built encompassing all the operating costs that were added to the combine working time in order to obtain the operating cost of different techniques.

Grain Protein Concentration: evaluates the amount of collected product with a protein level higher than 13.5 % and the relative gross saleable production thanks to the protein maps of previous years obtained with NIRS sensor. Using the first three parameters the operating income was calculated, considering all other farming operations as constant. The different nitrogen rates applied to the different homogeneous zones were considered during the farming operation costs calculation.

Payback period: period needed for each DH technique considering the different technologies applied in each method.

Operating costs of the harvest for each DH strategy have been calculated using the ASABE standards (ASABE, 2011a; 2011b). Costs related to buying seeds, insecticides, fungicides and their application are the same for all the scenarios. On the other hand, it is assumed that the harvesting machines suitable for each DH method are available on the market and are not intended as experimental prototypes.

Gross revenues were determined for each year using price schedules of durum wheat on the AGER corn exchange of Bologna - Italy during the first week of July for both experimental years. The bonus payment for high-protein wheat was 15 EUR·t<sup>-1</sup>, the threshold that distinguishes the product quality was 13.5 % for both the years (Tab. 7.2.). The results of the various DH methods were compared with those of traditional harvesting.

Table 7.2: Wheat price at different protein content.

Protein content (%)	Durum wheat market price (EUR·t <sup>-1</sup> )	
	2010/2011	2011/2012
< 13,5	297,5	256,5
≥ 13,5	312,5	271,5

## 7.3 Results and discussion

### 7.3.1 Harvesting costs

UH presents lower harvesting costs due to no need for additional investment, and greater field capacity of the combine (tab. 7.3.).

All DH methods have a low field capacity due to more turns or extra unloading times and the difference in price compared to a machine used for the UH ranges between EUR 10.000 (for the GNSS components required for MZ or for the installation of NIRS used by TD) and EUR 20.000 (required to install the additional bins necessary for CD and OCD).

Separating the combine bins leads to a reduction in the autonomy of the combine and an increase in the unloading time. All these factors affect the field capacity of the harvesting machine: field capacity for UH was estimated to be 2.06 ha·h<sup>-1</sup>, whereas there were reductions of 7 and 13 % respectively for MZ and OCD.

Harvesting costs were estimated to range from 141 EUR·ha<sup>-1</sup> in the case of UH, to 188 EUR·ha<sup>-1</sup> in the case of CD and automatic harvesting determines cost increases of 31.1 % compared to UH. Despite the higher initial investment, OCD does not determine significant cost increases (19.4 %) compared to UH.

Table 7.3: Harvesting costs for the differential harvesting strategy.

Economics parameters	UH		MZ		TD		CD		OCD	
Initial investment (EUR)	272.000		282.000		282.000		292.000		292.000	
Operating or turning time (h·ha <sup>-1</sup> )	0.03		0.07		0.03		0.03		0.03	
Unloading time (h·ha <sup>-1</sup> )	0.058		0.055		0.058		0.192		0.128	
Actual field capacity (ha·h <sup>-1</sup> )	2.06		1.92		1.84		1.61		1.80	
Harvesting cost (EUR·ha <sup>-1</sup> )	141		155		161		188		168	
Experimental year	<b>2011</b>	<b>2012</b>								
Cultivation cost (EUR·ha <sup>-1</sup> )	667	673	667	673	666	673	666	673	666	673
Total cost (EUR·ha <sup>-1</sup> )	808	814	821	828	828	834	854	861	835	841

### 7.3.2 High-protein wheat segregation capacity

The amount of segregated high-quality wheat is related to different characteristics of the methods. Total wheat production was 90.2 tons in 2011 and 86.9 tons in 2012 year. The UH has supplied a product with an average protein content of 12.3 % in the first year and 12.4 % in the second, therefore below the threshold of 13.5 %.

All DH methods have allowed a high-protein product differentiation but at different levels. Because of the quantity and distribution of protein in the field, each scenario has segregated different quantities of wheat with high protein content (Tab. 7.4.). OCD is the best technique in segregating wheat with a high protein content (47.2 % and 43.6 % in the two experimental years).

As reported by Long et al. (2013), all other harvesting methods succeed in segregating approximately 30 % of high-protein product. Gross revenues have been calculated on the base of the high-protein wheat collected by each DH method.

Table 7.4: Percentage of high-protein wheat segregated by each differential harvesting strategy.

DH Strategy	2010/2011		2011/2012	
	Average yield (t·ha <sup>-1</sup> )	Segregated fraction (%)	Average yield (t·ha <sup>-1</sup> )	Segregated fraction (%)
UH	6.7	0	6.4	0
MZ	6.7	32.8	6.4	23.8
TD	6.7	30.2	6.4	35.7
CD	6.7	31.3	6.4	28.7
OCD	6.7	47.2	6.4	43.6

### 7.3.3 Gross revenues

Wheat with a protein content higher than 13.5 % obtains the bonus payment of 15 EUR·t<sup>-1</sup>.

Gross revenues are therefore higher in the DH method that can collect a larger quantity of high-protein wheat. DH techniques allow to increase gross revenue of 28 EUR·ha<sup>-1</sup> (+ 1.5 %) and 45 EUR·ha<sup>-1</sup> (+ 2.5 %) respectively for MZ and OCD compared to UH.

Gross revenues obtained from different DH scenarios do not appear to be consistent. This is probably due to the “low bonus” awarded to the product with high protein content.

### 7.3.4 Income

As shown in Table 7.5, MZ allows higher operating profit compared to UH due to higher gross revenues. Despite this type of harvesting method requires a preliminary preparation of the field for each homogeneous zone, harvesting costs are slightly higher than UH one. The automatic DH methods using separate bins have high gross revenues, demonstrating how this is a viable technique to differentiate large quantities of wheat with high protein content. On the other hand, the operating income of this scenario is lower than that of the UH due to high harvesting costs that undermine higher revenues.

High harvesting costs come from the lower capacity of the bin, due to its division into two sections. Consequently, a decrease of bins operative efficiency is observed with a consequent decrease in field capacity of the combine. OCD can partially lessen problems that characterize DH methods using separated bins. Indeed, OCD optimizes the segregation of high-protein wheat. The high flexibility of the hopper capacity, high gross revenues and moderate harvesting costs allow economic feasibility of this method.

Table 7.5: Analysis of operating income deriving from DH scenarios examined.

DH Strategy	Incomes (EUR·ha <sup>-1</sup> )			Operating income (EUR·ha <sup>-1</sup> )			Operating income gap (compared UH)		
	2011	2012	mean	2011	2012	mean	2011	2012	mean
UH	1994	1658	1826	1186	843	1015	-	-	-
MZ	2027	1681	1854	1205	853	1029	19.05	9.13	14.09
TD	2025	1693	1858	1197	858	1027	10.29	14.55	12.42
CD	2026	1686	1856	1171	824	998	-15.23	-18.92	-17.08
OCD	2042	1700	1871	1207	858	1032	20.31	14.96	17.63

### 7.3.5 Payback period

Considering a durum wheat harvesting season of 20 days and the field capacity of the different DH methods, the maximum harvestable area does not exceed 300 ha·year<sup>-1</sup>. In this situation the payback period is less than 2 years for MZ and TD and 3 and 4 for OCD and CD respectively.

If a payback period of 5 years is considered, the minimum annual areas to harvest are approximately 100 ha for TD MZ, 125 ha for OCD and 200 ha for CD (Fig. 7.3.).

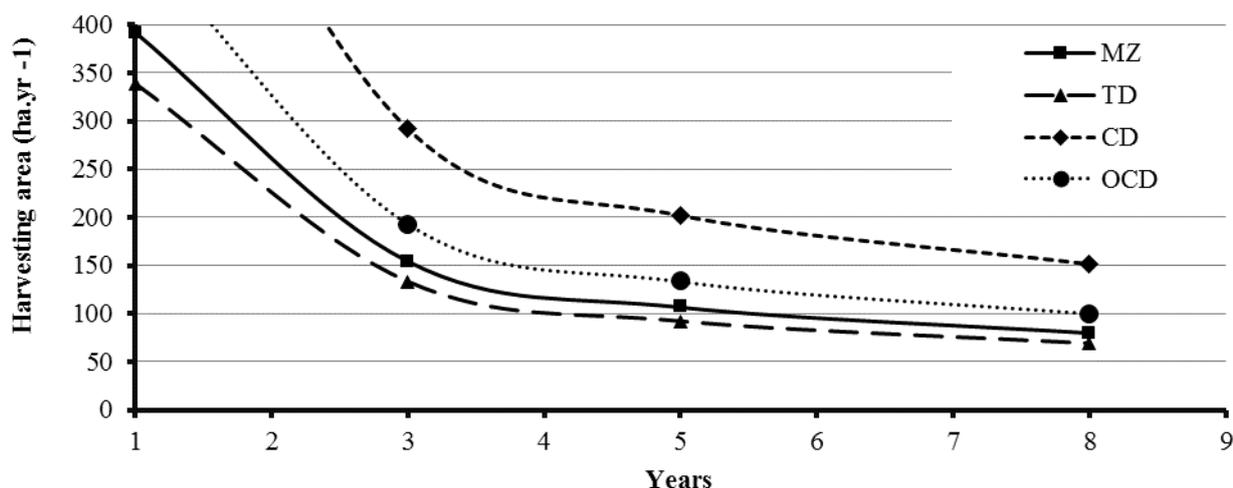


Figure 7.3: Minimum area harvested to pay off the technology applied to machines for the different DH strategy.

## 7.4 Conclusion

The aim of this paper is to evaluate the technical and economic feasibility of DH methods found in the literature and the technique proposed by the authors for durum wheat harvesting, on the basis of protein content.

In this specific study case characterized by small field size, small homogeneous zones and a moderate bonus payment (15 EUR·t<sup>-1</sup>), a different behaviour distinguishing the different DH strategies was observed. MZ, as discussed also by Tozer *et al.* (2007), seems to be advantageous due to the regularity and size of the six zones found in the field. However, to obtain an economic advantage from this technique it is essential to have big differences in terms of potential protein between homogeneous zones. DH on-truck methods using NIRS can generate more profits if the distribution of the protein in the field and the field measures are adequate.

The high harvesting costs related to on-combine DH methods are moderated by OCD. The hopper divided into 8 sections can be more effective than the one divided into 2. This allows to enhance the bin operative efficiency, and consequently an increase in the combine field capacity.

Moreover, the software able to optimize the truck protein content at each unloading can segregate large amounts of high-protein wheat obtaining higher income.

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