UNIVERSITA' DEGLI STUDI DI PADOVA

Sede Amministrativa: **Università degli Studi di Padova**

Dipartimento Territorio e Sistemi Agro-Forestali (Facoltà di Agraria)

Dottorato di ricerca in: Meccanica e Meccanizzazione Agricola

Ciclo XVII

Assessing and Simulating Spatial Variability and Temporal Stability of Yield in a Maize – Soybean – Wheat Crop Rotation

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Con questo lavoro si conclude un altro
capitolo di un cammino personale
importante, ricco in esperienze
umane e momenti professionali,
reso possibile anche grazie
alla presenza costante di chi
ha sempre appoggiato
le mie scelte

Alla mia famiglia

Indice analitico

Riassunto

Il presente elaborato si propone di riportare gli aspetti più importanti dello studio condotto in collaborazione tra il Dipartimento Territorio e Sistemi Agro-Forestali – Università di Padova – ed il Dipartimento di Produzioni Vegetali – Università della Basilicata – nell'ambito dell'attività triennale (2002-2004) del dottorato di ricerca, ed avente come principale obiettivo l'analisi della variabilità spaziale e della stabilità temporale della resa monitorata nell'ambito di una rotazione colturale di mais (*Zea mays*, L.), soia (*Glycine max*, L.) e frumento (*Triticum aestivum*, L.). A tale scopo il lavoro si compone di una introduzione generale alle principali problematiche considerate, seguita da cinque sezioni indipendenti, in ognuna delle quali, corrispondenti alle singole fasi del lavoro svolto, vengono riportati alcuni degli obiettivi più importanti perseguiti ed i relativi risultati conseguiti.

L'attività di ricerca si è basata sull'elaborazione di dati grezzi, sull'esecuzione di prove sperimentali e rilievi in campo e sulla simulazione di lungo periodo di alcune delle variabili esaminate mediante l'utilizzo di apposito modelli di simulazione, in un appezzamento di 8,09 ha, avente terreno argilloso e situato presso un'azienda agricola privata in Ariano nel Polesine, Rovigo (44° 4' 12" N, 11° 47' 22" E, 6 m s.l.m.), Italia.

In particolare, il lavoro si è articolato in più fasi, ed ha inizialmente interessato la raccolta dei dati relativi alla variabilità spaziale (variabilità annuale) ed alla varianza temporale (variabilità pluriennale) esistenti a carico della resa monitorata nel corso di una rotazione quinquennale a base di mais, soia e frumento, finalizzata alla comprensione delle cause limitanti la resa, con particolare riferimento alle proprietà statiche del suolo (contenuto di argilla, sabbia, limo e sostanza organica) misurate lungo il profilo del suolo (0÷45 cm), ed alla individuazione delle aree omogenee in cui poter eseguire interventi agronomici ad intensità variabile, in accordo con la stabilità temporale della variabilità spaziale della resa. Sulla base dei risultati conseguiti e delle due zone stabili individuate all'interno dell'appezzamento il contenuto di argilla e di sostanza organica sono risultate le proprietà maggiormente correlate con la resa conseguita all'interno dell'appezzamento (valore medio del coefficiente di Pearson variabile da 0.33 a 0.51 per il contenuto di sostanza organica e da -0.38 a -0.39 per il contenuto di argilla), come evidenziato dall'analisi della corrispondenza tra le zone più o meno produttive e le aree aventi proprietà del suolo confrontabili, anche se tali fattori non sono risultati in grado di spiegare completamente la variabilità riscontrata a carico della resa. Sulla base delle zone omogenee identificate all'interno dell'appezzamento il

campo è risultato suddiviso in due aree stabili, caratterizzate da resa elevata e bassa, per le quali sono state riscontrate delle significative relazioni tra i dati di resa e le proprietà del suolo (es. R^2 = 0.62 nel caso della regressione tra resa e contenuto di argilla), tuttavia non sufficienti a spiegare completamente la variabilità a carico della resa.

L'identificazione di zone omogenee è quindi stata eseguita in *ArcView 3.2* per ciascuna coltura esaminata sulla base dei dati di resa simulati nel lungo periodo (1989-2002) mediante l'ausilio dei rispettivi modelli di simulazione (*CERES, CROPAGRO*) facenti capo al sistema decisionale *DSSAT 3.5*. Le aree stabili così definite sono risultate essere posizionate all'interno dell'appezzamento in corrispondenza delle medesime zone, mentre la superficie relativa di ognuna di esse è risultata variabile, a dimostrazione dell'esistenza di una componente colturale della variabilità pluriennale della resa. Dalla sovrapposizione delle mappe singole è stato quindi possibile individuare all'interno dell'appezzamento le zone effettivamente stabili nel lungo periodo, con la zona stabile ad alta resa avente una superficie complessiva pari a 1.27 ha..

Sulla base delle zone stabili identificate all'interno dell'appezzamento, nel caso del mais si sono valutati gli effetti di lungo periodo sulla resa, le proprietà del suolo (contenuto d'acqua del terreno e densità volumica) e le perdite di azoto per lisciviazione dovute all'adozione rispettivamente di tre differenti tecniche di lavorazione conservativa del terreno e della variazione della dose di fertilizzante azotato impiegata.

In particolare, nel caso delle lavorazioni del terreno sono state confrontate la minima lavorazione (*MT* – Minimum Tillage, consistente in discatura del terreno e preparazione del letto di semina con erpice rotante) e la semina su sodo (*NT* – No-Tillage, consistente nell'adozione della semina su sodo) rispetto al sistema di lavorazione conservativo tradizionalmente adottato in azienda (*CT* – Conventional Tillage, consistente nell'esecuzione di un intervento di ripuntatura, seguito dalla discatura, e nella preparazione del letto di semina con erpice rotante), mentre gli effetti di tali interventi sulle proprietà del suolo e sulla resa sono stati simulati nel corso della stagione colturale e del lungo periodo rispettivamente con il modello *CERES*¸ facente parte del sistema decisionale *SALUS.* Sulla base dei risultati conseguiti, i sistemi *CT* ed *MT* sono risultati in grado di assicurare i migliori risultati di resa all'interno delle due zone stabili *HS* e *LS*. Tale risultato è stato confermato anche dall'analisi economica della convenienza all'adozione del sistema gestionale delle lavorazioni del terreno, per il quale è stato quantificato un costo aggiuntivo unitario di 16 € ha^{-1}, avente un'incidenza variabile sul costo complessivo dei singoli interventi colturali e tanto più significativo al diminuire del costo totale del sistema considerato. In particolare, a seguito dell'andamento sfavorevole registrato a carico delle condizioni climatiche nel 2003 il reddito lordo

aziendale è risultato superiore in *HS* ed *LS* con il sistema *NT*, a causa della scarsa incidenza dei costi della lavorazione, mentre nel lungo periodo sono risultate in grado di assicurare un reddito maggiore i sistemi *CT* e *MT* nelle aree stabili *HS* e *LS* rispettivamente, a seguito della maggiore resa conseguibile rispetto al sistema *NT* maggiormente conveniente nelle annate poco favorevoli dal punto di vista delle condizioni climatiche.

Per quel che riguarda la concimazione azotata di copertura invece, la diversificazione della dose all'interno dell'appezzamento in base alle zone omogenee individuate è risultata una scelta giustificabile, sia in termini di superficie relativa delle aree stesse che di resa conseguibile con le differenti dosi esaminate. In particolare, è emerso come l'adozione di una dose di 180 kg ha^{-1} nell'area *HS* e di una dose di 120 kg ha^{-1} nell'area *LS* sia in grado di consentire una resa soddisfacente, statisticamente non significativa rispetto al risultato produttivo conseguibile con le dosi più elevate, garantendo nello stesso tempo una riduzione delle perdite di azoto per lisciviazione.

In conclusione, la combinazione di uno strumento GIS e di un modello di simulazione è risultata in grado di consentire l'individuazione all'interno dell'appezzamento delle zone omogenee stabili, nelle quali poter eseguire degli interventi a dosaggio variabile, per i quali la metodica messa a punto è risultata avere un'incidenza economica confrontabile con il beneficio ritraibile dall'applicazione o comunque non particolarmente incisivo sul costo unitario delle singole operazioni, oltre che essere giustificata in termini di resa ritraibile all'interno delle singole zone esaminate.

Abstract

This work presents the more important aspects relating to the research carried out during 2002-2004 period at the Territorio e Sistemi Agro-Forestali Department of the Padova University, in collaboration with the Produzioni Vegetali Department of the Basilicata University. The study considered the analysis of the spatial variability and the temporal stability of yield in a crop rotation of maize (*Zea mays*, L.), soybean (*Glycine max*, L.) and wheat (*Triticum aestivum*, L.). This work is composed of a general introduction and five independent sections, each relating to the single step analysed and the relative objectives considered, reporting the results obtained.

The study was based on row data elaboration, field trias and sampling and long-term simulation scenarios, and regarded a 8,09 ha field, having a clay soil and being situated at a private farm in Ariano nel Polesine, Rovigo (44° 4' 12" N, 11° 47' 22" E, 6 m s.l.m.), Italia.

In particular, the effects of soil static physical properties – *i.e.*, soil texture and organic matter content – measured along soil profile (0÷45 cm) on spatial variability and temporal stability of yield were analysed in a maize-soybean-wheat rotation, taking into account the intra-year and the inter-years variability of yield. The inter-years variability on yield was due to the variability of the climatic conditions and the differences regarding agronomic practices adopted. After visually considering the spatial correspondence between soil properties pattern and area within field having different yield level, correlation matrix and multiple regression model were performed to investigate the within-field intra-year spatial variability. According to the analysis of correspondence, the organic matter and clay contents resulted generally positively and negatively correlated with the yield level (average values of Pearson coefficients were r = 0.33 ÷ 0.51 and r = -0.38 ÷ -0.39, respectively), even if this result varied by considering different crops and growing seasons. The analysis of homogeneous management area performed according to the stability criteria showed the presence of two area oriented according to the principal axle of the field, being stable but having different level of yield (*HS* area – stable area with high yield; *LS* area – stable area with low yield). For these area soil static physical properties resulted significantly influencing yield variability, as shown by greater values of coefficient of determination (e.g., R^2 = 0.62 for clay content), but relationships between soil properties pattern and yield spatial variability were not sufficient to completely explain yield variability measured within field, probably because of the interrelationships among limiting factors, not accounted by classical analysis.

Based on these results, the long-term temporal stability of spatial variability of yield was simulated for single crop – maize (*Zea mays*, L.), soybean (*Glycine max*, L.) and wheat (*Triticum aestivum*, L.) – with the *CERES* and *CROPAGRO* modules of *DSSAT 3.5*, to take into account the influence of environmental conditions on yield variability. By overlying the long-term spatial variability and the temporal variance maps of maize, wheat and soybean, with *ArcView 3.2* the field resulted divided into two stable area, having different yield level and displaced according to the principle axle of the field, but having different surface by varying the considered crop. This confirmed the presence of a component of variability due to the crop cultivated. By overlying single maps, field resulted divided into two stable area, that with high yield – *i.e.*, *HS* area – having a surface area of 1,27 ha.

Based on the identified homogeneous *HS* and *LS* area, the effects on bulk density and soil water content variability of different tillage system adopted within homogeneous area were considered in maize. In particular, two different conservative tillage systems (*MT* – Minimum Tillage; *NT* – No-Tillage) were evaluated in comparison with the conventionally conservative tillage system – named *CT* – adopted by farm. The annual pattern of soil properties and yield under different soil tillage systems were simulated by using *SALUS* simulation model: as regards soil water content, the effect of tillage along soil profile was almost neglible, whilst the different interactions between soil properties (e.g., soil organic carbon and clay content) and water resulted more significant, being differences between stable area more appreciable. Contrarily, tillage effect resulted statistically significant on influencing bulk density values along soil profile, with a greater effect in *CT* plot, decreasing bulk density values more appreciably and with a more durable effect respect to *MT* treatment. As regard the effects on yield, during trials results were influenced by climatic conditions, with lower differences among treatments, whilst simulation data revealed that in *HS* area *CT* system could allow a greater yield than *MT* or *NT* plots, whilst in *LS* area *MT* system resulted better than control and no-tillage, at the same level of probability (P = 50%).

This result was confirmed also by the economic analysis. In fact, in 2003 yield resulted influenced by climatic conditions and resulted not appreciably statistically significant for different area of the field, NT system assuring a greater farm gross margin due to the more evident influence of cost of production than the economic value of yield. In particular, the cost due to the implementation of the precision farming system resulted quite low, being of 16 € ha^{-1}. As regards the long-term analysis yield was more appreciably different between stable area identified within field than for the complete field, and consequently *HS* and *LS* area were separately considered: the effects due to the tillage system resulted statistically significant on yield within each stable area, and consequently the

farm gross margin appreciably varied for different tillage systems. In particular, *CT* resulted the best system for *HS* area, assuring the greatest farm gross margin, whilst in *LS* area the greater value was assured by *MT* system, at the same level of probability (*P* = 50%).

Within the long-term stable area yield and N-losses pattern and variability were considered for four different rates (60, 120, 180 and 240 kg ha^{-1}) by using *DSSAT 3.5* – module *CERES-Maize*. The predicted long-term yield and N-losses seemed influenced by climatic conditions, whilst 180 kg ha^{-1} and 120 kg ha^{-1} resulted the optimal rates in the long-term predicted *HS* and *LS* area, assuring in both case a reduction of N-losses respect to rate and a higher yield than the greatest and the lowest rates investigated respectively at the same level of probability (*P* = 75%). This result signified, for the initial conditions of the experimental field a total reduction of almost 281.2 N kg, economically corresponding to a reduction of cost of 168.72 €.

In conclusion, the combination of GIS tool and simulation model resulted helpful for analysing variability of yield and for identifying homogenous stable area within field, according to the temporal stability of spatial variability of yield. The adoption of agronomic practices at variable intensity resulted justified in maize for the experimental initial conditions, both in terms of long-term predicted yield and economical return for farm, the same practices exerting a variable effects on soil properties. Furthermore, simulated scenarios revealed that the adoption of variable rate technologies resulted beneficial, preserving yield level and reducing N-losses.

1.- Introduzione

Nel corso degli ultimi anni, al sistema primario sono state rivolte richieste sempre più consistenti per un cambiamento della tendenza seguita fino al decennio scorso ed improntata quasi esclusivamente alla massimizzazione della resa, al fine di poter affiancare alla produzione di derrate sicure e di qualità, la tutela e la gestione del territorio e delle risorse naturali, così da raggiungere un maggior livello di sostenibilità. Nello stesso tempo, a seguito del sensibile costante aumento dei prezzi dei fattori produttivi e della riduzione del regime dei sostegni mediante la revisione della Politica Agricola Comunitaria, la riduzione dei costi di produzione è divenuta una necessità non più prorogabile per l'azienda agricola, a scapito del mantenimento della propria posizione sul mercato, a sua volta divenuto sempre più globale e competitivo. Dalla necessità di implementare dei sistemi gestionali mirati al raggiungimento di singoli obiettivi si quindi è passati gradualmente all'esigenza di sistemi gestionali globali in grado di integrare le numerose richieste avanzate al mondo agricolo e mirati alla qualità non solo di prodotto, ma anche di processo, ed improntati alla messa a punto di pratiche colturali fondate sul rispetto delle risorse naturali (es. riduzione della lisciviazione dei nitrati, miglioramento della fertilità del suolo, etc.) e la sicurezza degli operatori.

La necessità di rispondere a queste esigenze si è spesso accompagnata alla domanda da parte delle aziende agricole di adeguati strumenti e soluzioni tecniche, la quale ha interessato anche il settore della meccanizzazione e della meccanica. Negli ultimi decenni infatti, l'evoluzione del settore delle tecnologie ed in particolare dell'applicazione dell'elettronica, l'informatica e la sensoristica alla meccanica, hanno interessato in maniera consistente anche il settore primario, mediante l'introduzione di soluzioni tecniche e pacchetti informatici (sensori, software, componenti hardware, etc.) che hanno comportato una integrale revisione del sistema produttivo: un significativo esempio in proposito è dato dalle soluzioni tecniche oggi presenti sulle trattrici e sulle macchine operatrici, che fanno di queste non più solamente delle centrali mobili di potenza accoppiate a delle attrezzature per l'esecuzione degli interventi colturali, ma dei mezzi ad elevato contenuto tecnologico, sempre più destinati al reperimento di informazioni sulla coltura o sull'appezzamento per una conseguente migliore gestione delle pratiche agronomiche.
La necessità di razionalizzare le singole fasi del processo di produzione si è infatti tradotta nella necessità di reperire informazioni sullo stesso, al fine di individuarne i punti critici ed adottare le conseguenti misure correttive, ma ciò ha gradualmente comportato una revisione di principi su cui

si basava il modo stesso di fare agricoltura. Per lungo tempo la resa media conseguita ha rappresentato il principale parametro su cui basare l'esecuzione degli interventi agronomici dell'annata successiva, i quali venivano poi attuati in maniera uniforme all'interno dell'appezzamento, con una penalizzazione dell'efficienza sia in termini agronomici che economici ed ambientali (Stafford, 1993; Stafford et al., 1996), in quanto non si teneva conto delle effettive potenzialità produttive dell'appezzamento stesso e delle condizioni ambientali in cui tali potenzialità si potevano esprimere.

In tale contesto, l'applicazione ragionata ed economicamente giustificata delle soluzioni ad oggi disponibili al sistema di produzione aziendale rappresenta un elemento da più parti interpretato come un'interessante opportunità per la pianificazione nel lungo periodo delle strategie colturali da mettere in atto, oltre che come una effettiva prospettiva per l'integrazione delle pratiche conservative e delle soluzioni ad elevato contenuto tecnologico, finalizzato ad un generale incremento di sostenibilità, ambientale ed economica.

1.1.- L'Agricoltura di Precisione

L'Agricoltura di Precisione è un'espressione di cui spesso si sente parlare che deriva dall'inglese Precision Agricolture o Precision Farming o Site Specific Farming Management, la quale, favorita e sostenuta proprio dalle potenzialità derivanti dalla diffusa applicazione delle nuove soluzioni tecniche al settore primario, nell'accezione originaria, consiste nell'applicazione di tecnologie, principi e strategie per una gestione spaziale e temporale della variabilità associata agli aspetti della produzione agricola (Pierce e Nowak, 1999), in relazione alle reali necessità dell'appezzamento ed alla loro variabilità spaziale e temporale (Nielsen et al., 1999; Stafford, 1999). Essa può quindi essere intesa come una forma di agricoltura progredita, volta all'impiego di tecniche e tecnologie mirate all'applicazione variabile degli input colturali all'interno degli appezzamenti, sulla base dell'effettiva esigenza della coltura e delle proprietà chimico-fisiche e biologiche del suolo, al fine di perseguire dei vantaggi di ordine agronomico, mediante l'accrescimento della performance della coltura, economico, attraverso la razionalizzazione degli input (Bakhish et al., 2000) e la riduzione dei costi colturali (Godwin, 2003), ed ambientale (Wang et al., 2003).

1.1.1.- Cenni storici

Un metodo di fare agricoltura basato sull'esecuzione di interventi accurati e differenti all'interno dell'appezzamento, ma soprattutto determinato dalla profonda conoscenza delle caratteristiche dell'appezzamento stesso, era ben noto nel passato, a dimostrazione di come le soluzioni proposte dall'Agricoltura di Precisione siano una risposta in chiave moderna a delle problematiche antiche, come dimostrano numerose testimonianze storiche tra le quali quelle riportata di seguito costituiscono un chiaro e significativo esempio:

"... chi vuole praticare l'agricoltura correttamente deve conoscere innanzitutto la natura del terreno. Chi infatti non sa ciò che il terreno può produrre, non può sapere né quello che deve seminare, né quello che deve piantare"
(Senofonte, 400 a.C., tratto dalla traduzione di Roscalla F. dell'opera "*Economico*")

"*Uno iugero di terreno, che vada concimato più abbondantemente, richiede ventiquattro carrettate di letame; se va concimato meno, ne bastano diciotto"…*

…"*uno iugero di terreno ricco richiede generalmente quattro moggi di frumento; se il terreno è mediocre, ce ne vogliono cinque….. Io stesso non seguo sempre la misura che ho dato, perché si tratta di una cosa che varia con le condizioni del terreno e del clima e con l'epoca di semina".*

(Lucio Giunio Moderato Columella, I secolo d.C.. Tratto dalla traduzione di Calzecchi Onesti R. dell'opera "*De re rustica*").

Sulla base di quanto esposto, emerge come la differenza immediatamente percepibile che caratterizza l'"Agricoltura di Precisione" rispetto a quanto accadeva in passato è data dall'impiego di *sistemi e tecnologie*, in grado di agevolare, ed in alcuni casi affiancare l'operatore nell'esecuzione delle pratiche colturali. Se gli interventi differenziati all'interno dell'appezzamento costituiscono la normale pratica agricola presso società in cui l'impiego di manodopera non rappresenta un fattore di costo, come avviene ad esempio in alcune regioni del continente africano od asiatico, o incide in maniera irrilevante sul costo di produzione complessivo, come accade per alcune zone realtà rurali dell'Europa orientale, nel caso di sistemi economici come quello occidentale l'impiego di manodopera rappresenta una voce di spesa non trascurabile, per la quale la meccanizzazione degli interventi colturali rappresenta una scelta obbligata. Allo stesso tempo, tale esigenza ha comportato negli ultimi decenni ad un'inevitabile grossolana semplificazione della gestione degli appezzamenti, trattati oggi in maniera pressoché uniforme, indipendentemente dalla dimensione e dalle loro caratteristiche podologiche. La possibilità di impiegare a tecnologie in grado di riconsiderare a costi accessibili il modo di fare agricoltura venutosi a creare negli ultimi anni ha perciò consentito la messa a punto di un metodo di fare agricoltura in grado di sfruttare quanto si faceva in passato ma rivisitandolo in maniera moderna. In quest'ottica, il modo di fare agricoltura definito "Agricoltura di Precisione", spesso utilizzato per raggruppare tutte le soluzioni disponibili o proposte nel settore agricolo ed aventi un elevato contenuto tecnologico, è stato messo a punto alla fine degli anni '80 negli Stati Uniti e si è diffusa inizialmente negli Stati centrali della confederazione, dove oggi, pur con le difficoltà di valutazione che ne derivano dato che è difficile stimare quante aziende siano effettivamente in grado di mettere in pratica tutti i precetti dell'Agricoltura di Precisione, si valuta che essa interessi soprattutto le colture estensive, con particolare riferimento per le aziende agricole ad indirizzo cerealicolo (30%), mentre nel caso della soia e del frumento le superfici interessate risultano inferiori, pari rispettivamente al 10% ed al 25% della superficie totale desinata a tali colture (Fountas et al., 2003). Agli inizi degli anni '90, essa ha iniziato a svilupparsi anche nelle regioni del Canada, della Nuova Zelanda e dell'Australia, mentre

qualche anno dopo hanno fatto la loro comparsa sul mercato europeo le prime mietitrebbiatrici equipaggiate di sensori per la mappature delle rese. Dopo un primo momento di rapido sviluppo ed una conseguente battuta d'arresto dovuta alle difficoltà incontrate, oggi l'Agricoltura di Precisione sta sviluppandosi anche nei paesi dell'America Latina, mentre in Europa i paesi che maggiormente possono essere interessati da un suo sviluppo nell'immediato futuro sono la Danimarca (Pedersen et al., 2003), il Regno Unito, i Paesi Bassi e la Germania: soprattutto in quest'ultimo caso sembra che la diffusione delle nuove metodologie su cui si fonda l'Agricoltura di Precisione stia indirizzandosi anche ad aziende di media dimensione, garantendone una più rapida diffusione (Gumpertsberger e Jürgens, 2003).

1.2.- I sistemi di posizionamento e navigazione satellitare

Uno degli aspetti che hanno influenzato in maniera determinante lo sviluppo e la diffusione dell'Agricoltura di Precisione è stato la possibilità di impiegare in agricoltura i ricevitori satellitari per la navigazione ed il posizionamento all'interno dell'appezzamento, così da poter riferire i dati raccolti e gli interventi da eseguire a delle posizioni univoche ed individuabili all'interno di questo stesso.

1.2.a.- Il sistema NAVSTAR-GPS

Il sistema di posizionamento maggiormente conosciuto ed utilizzato ai fini dell'Agricoltura di Precisione è dato dal sistema di navigazione e posizionamento globale americano *NAVSTAR-GPS* (*Navigation System Time and Ranging Global Positioning System*), meglio conosciuto come *GPS* (Figura 1). Esso è stato creato e reso operativo a partire dalla fine degli anni '70, con il lancio nello spazio del primo satellite nel 1978 da parte del Dipartimento della Difesa degli Stati Uniti, al quale ne compete il controllo, anche se l'utilizzo civile di tale sistema è stato consentito solamente a partire dal 27 aprile 1995. Tale sistema consiste in un insieme di 24 satelliti che orbitano a 20.180 km attorno alla superficie terrestre e compiono un giro completo attorno ad essa circa ogni 12 ore (11 ore e 58 minuti). Essi sono suddivisi in 6 percorsi orbitali (4 satelliti per ciascun percorso), inclinati di 55° sull'equatore, matematicamente definiti e conosciuti, così da garantire che almeno 4 satelliti siano potenzialmente ricevibili per 24 ore da un ricevitore posizionato in un qualsiasi punto della superficie terrestre (figura). Ciascun satellite, identificato dal numero di veicolo spaziale

(SVN), è equipaggiato di orologi atomici, dispositivi alimentati ad energia solare ed in grado di misurare il tempo con elevatissima precisione, sulla base delle oscillazioni periodiche naturali dell'atomo presente all'interno del meccanismo. In ogni satellite sono presenti 2 orologi al cesio e 2 al rubidio, per assicurare che almeno uno di essi sia sempre funzionante. Gli orologi misurano il tempo sulla base della scala temporale universale messa a punto per gli orologi atomici dal Bureau International de l'Heure de Paris, esprimendolo nel sistema in adozione all'Osservatorio Navale degli Stati Uniti.

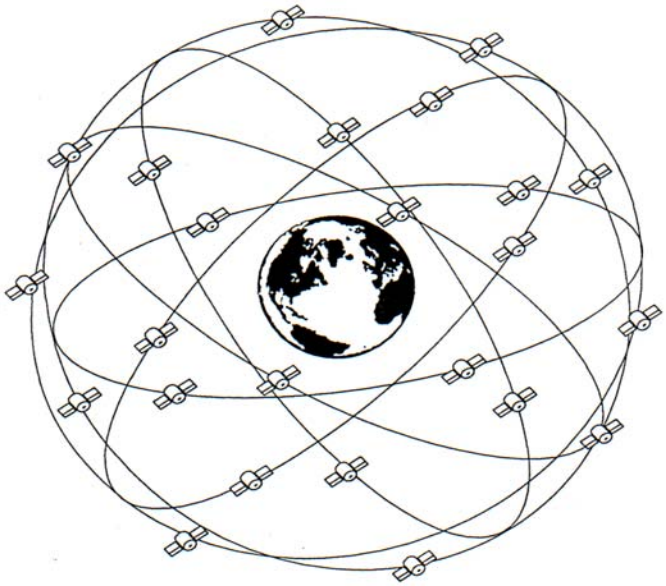

Figura 1.- Rappresentazione schematica del sistema di posizionamento e navigazione satellitare NAVSTAR-GPS, riportante le differenti orbite dei 24 satelliti in rotazione attorno alla superficie terrestre.

Il funzionamento e la precisione degli orologi infatti rappresenta un elemento critico del sistema, in quanto sta alla base dell'utilizzo dei satelliti per la determinazione della posizione e la navigazione.
All'interno di ogni satellite inoltre è presente un emettitore di onde radio, le quali vengono trasmesse di continuo ad una frequenza variabile da 1200 a 1500 MHz (milioni di cicli per secondo) e viaggiano attraverso l'atmosfera terrestre ad una velocità di poco inferiore a quella della luce nel vuoto (300000 km/s). Tale dispositivo di emissione è in grado anche di funzionare da ricevitore, così da captare i segnali provenienti dalle stazioni di controllo a terra.
Anche se l'orbita di ciascun satellite è definita da un modello matematico, la loro traiettoria può subire delle variazioni a seguito di molteplici fattori (asimmetrie del campo gravitazionale terrestre, pressione della radiazione solare, etc.). Di conseguenza esiste una rete di stazioni di monitoraggio a

terra da cui vengono misurati gli scostamenti (altezza, posizione e velocità) dell'orbita reale da quella teorica ad ogni passaggio (2 volte al giorno) sopra le stazioni: tali informazioni vengono quindi inviate al satellite in questione che le ritrasmette a ciascun ricevitore mediante il proprio segnale emesso, il quale contiene quindi un'informazione relativa alla misura del tempo, utilizzata per il calcolo della distanza, ed una serie di dati sulla dislocazione relativa di ciascun satellite. Questi ultimi vengono perciò utilizzati per il mantenimento di un'elevata accuratezza nella determinazione della posizione.
L'utilizzo di un ricevitore GPS consente perciò all'utente di captare il segnale emesso dai satelliti visibili sull'orizzonte del ricevitore stesso e di conoscere la propria posizione, la quale viene espressa come coordinate (X, Y, Z) di un sistema cartesiano tridimensionale di riferimento, avente l'origine corrispondente al centro della terra (sistema geocentrico) e conosciuto come WGS84, acronimo di World Geodetic System '84. A tale sistema di riferimento è associato un ellissoide (ellissoide GRS80), avente la stessa origine del sistema cartesiano: le coordinate cartesiane X ed Y fornite dal sistema GPS possono perciò essere convertite i coordinate geografiche (latitudine e longitudine) riferite a tale ellissoide.

Dal punto di vista dell'Agricoltura di Precisione, la possibilità di poter esprimere la posizione di un punto qualsiasi dell'appezzamento come coppia di coordinate geografiche e di associare ad esso una o più informazioni relative all'appezzamento (es. caratteristica del terreno) o alla coltura (es. dato di resa) ha costituito un radicale cambiamento per la gestione delle pratiche agricole, in quanto ha consentito di registrare la variabilità presente all'interno dell'appezzamento (es. livello di resa), codificandola ed esprimendola in un formato geografico all'interno di un sistema di riferimento: in questo modo è stato cioè possibile individuare la viariabilità spaziale esistente a carico di un determinato parametro ed individuarne la manifestazione all'interno delle singole parti dell'appezzamento, con una accuratezza differente a seconda dello strumento utilizzato e delle operazioni interessate, comunque in linea generale variabile da qualche decina di metri (es. campionamento del terreno) a qualche centimetro (es. navigazione semi-automatica dei mezzi agricoli). Mentre nel primo caso il dato utilizzato è quello direttamente fornito dal ricevitore satellitare, la possibilità di disporre di dati di posizionamento aventi una accuratezza compresa tra 50 cm e 2 cm siaccompagna alla necessità di disporre della correzione differenziale del dato grezzo, per la quale è possibile ricevere il dato da apposite compagnie (es. OMNISTAR, LANDSTAR, etc.) in grado di fornire tali servizi in cambio del pagamento di una canone annuo, oppure di utilizzare una stazione base (base station) in loco con cui incrementare l'accuratezza del dato fornito dal ricevitore satellitare. Un importante cambiamento relativo a tale aspetto si avrà a partire dal 2006-

2007, a seguito della possibilità di sfruttare gratuitamente il segnale fornito dal sistema di posizionamento e navigazione satellitare europeo, realizzato nell'ambito del progetto Galileo e meglio conosciuto come EGNOS.

1.2.b.- Il sistema di posizionamento e navigazione satellitare europeo (EGNOS)

EGNOS, acronimo di *European Geostationary Navigation Overlay Service*, è la versione europea dei sistemi americano *WAAS*[1], utilizzabile negli USA per l'Agricoltura di Precisione (Sullivan et al., 2001), e mediorientale (*MSAS*), sviluppata dall'Agenzia Spaziale Europea, la quale integra i sistemi di navigazione americano (*GPS*) e russo (*GLONASS*) già esistenti. Il sistema, nella sua soluzione definitiva, si basa sull'integrazione di tre elementi:

- una rete di tre satelliti geo-stazionari, tra i quali un satellite (AOR) per la copertura del continente europeo ed un satellite (IOR) per la copertura del continente asiatico;
- una rete terrestre di stazioni di elaborazione dei dati relativi ai ritardi del segnale emesso dai satelliti del sistema GPS a causa della ionizzazione dell'atmosfera, distribuite sul territorio europeo: ciascuna stazione elabora l'errore sulla base di procedure differenziali per la propria zona di competenza;
- una rete di stazioni centrali a terra che raccolgono i dati elaborati dalle precedenti.

I fattori di correzione così elaborati vengono inviati ai satelliti del sistema per essere ritrasmessi ad un qualsiasi ricevitore a terra utilizzando la frequenza di trasmissione L1 del sistema *GPS*.

Il ricevitore, appositamente predisposto, grazie ad uno speciale software in grado di elaborare i dati ricevuti, selezionando i fattori di correzione dei punti a terra ad esso più vicini ed utilizzandoli per la correzione dei segnali ricevuti, con una precisione nella determinazione della posizione che oggi risulta variabile nel range di 2÷3 metri.

Ad oggi il sistema è in fase di messa a punto con una parte dei satelliti già in orbita ed è sottoposto ai test di validazione, che terminerà nel 2008 con il sistema completo e pienamente operativo; di conseguenza esso non è attualmente in grado di garantire la stabilità del servizio, mentre negli intervalli di tempo in cui esso è attivo la copertura delle regioni europee è eseguita quasi

[1] WAAS è l'acronimo di Wide-Area Augmentation System, messo a punto dall'Amministrazione Federale dell'Aviazione statunitense per motivi di sicurezza, al fine di applicare i concetti della navigazione satellitare agli aerei in transito nei cieli degli USA. Esso consiste nell'integrazione del già esistente GPS, di cui viene fornita gratuitamente la correzione del
segnale, con una accuratezza nella determinazione della posizione confrontabile con quella ottenibile con il sistema di correzione differenziale già esistente, tanto da poter essere utilizzata in Agricoltura di Precisione.

esclusivamente (90% dei casi) dal satellite IOR, il quale si trova basso all'orizzonte di un ricevitore utilizzato nelle nostre zone, con una conseguente cattiva ricezione del segnale.
Nel momento in cui il sistema risulterà operativo a tutti gli effetti, esso conterà di 30 satelliti in orbita (27 operativi e 3 di riserva), stazionati su tre orbite terrestri ad un'altezza di 23.222 km e con un'inclinazione di 56° rispetto all'equatore, mentre il funzionamento del satellite destinato alla coperta delle regioni europee consentirà di aumentare la precisione del dato di posizione.
In questo modo, EGNOS si inserisce in maniera perfettamente complementare nei sistemi dedicati alla navigazione globale già esistenti, consentendo l'integrazione dei segnali ed il loro utilizzo senza necessità di correzione differenziale: nel caso della navigazione all'interno dell'appezzamento l'utilizzo del sistema EGNOS infatti porterebbe ad una differenza significativa tra la traiettoria attesa e quella reale (Stuevel, 2003 a), ma sarebbe comunque in grado di garantire una precisione superiore a quella del dato privo di correzione (Stuevel, 2003 b) e questo può rappresentare un importante fattore ai fini della diffuzione delle soluzioni tecnologiche previste dall'Agricoltura di Precisione e basate sull'utilizzo di un ricevitore satellitare.

1.3.- La variabilità

Il presupposto fondamentale che giustifica, dal punto di vista tecnico ed economico, il ricorso ai principi, i sistemi e le tecnologie proprie all'Agricoltura di Precisione è la presenza di variabilità all'interno dell'appezzamento, la quale deve necessariamente risultare gestibile in maniera differenziata. Analizzando tale aspetto con una maggiore precisione, è necessario che la variabilità riconstrabile all'interno dell'appezzamento sia dotata di una propria struttura spaziale e si manifesti ad intensità gestibile dal punto di vista tecnico, così da trovare una giustificazione dal punto di vista economico: nel caso dei parametri del suolo ad esempio, la resitenza alla penetrazione del terreno si caratterizza per una variabilità spaziale molto accentuata, addirittura inferiore a pochi centimetri (Clark, 1996), e ciò rende molto difficoltosa l'individuazione di zone in cui essa risulti variabile in un range di valori contenuto così da poter eseguire un intervento ad intensità differente rispetto alle regioni adiacenti, mentre per quanto riguarda l'intensità della variabilità è intuibile come la convenienza all'adozione di strategie ad intensità variabile nella gestione delle tecniche colturali sia tanto maggiore quanto più apprezzabili e marcate sono le differenze a carico di un dato parametro all'interno dell'appezzamento (Pringle et al., 2003).

Per quanto riguarda la variabilità misurata all'interno dell'appezzamento inoltre, come nel caso specifico della resa, essa è la risultante di una componente spaziale (Nielsen et al., 1999) e di una componente temporale (Stafford, 1999), dal momento che gli stessi fattori che costituiscono dei limiti all'espressione della massima produttività da parte della coltura assumono un'entità variabile nel tempo (Machado et al., 2000; Machado et al., 2002), oltre ad una componente colturale dovuta alla differente risposta produttiva manifestata da colture diverse all'interno dello stesso appezzamento (Bjarne J. and H. Steffen, 2003).

1.3.a.- La variabilità spaziale

Per variabilità spaziale di un determinato parametro si intende la sua attitudine a manifestarsi con intensità differente nello spazio, discostandosi in maniera più o meno accentuata dal valore medio misurabile all'interno dell'appezzamento. L'aspetto principale che distingue i differenti parametri e che consente di caratterizzarne la modalità con la quale si manifestano nelle diverse aree del campo è quindi la dipendenza spaziale dei valori da essi assunti, come accade ad esempio con le proprietà del suolo, i cui valori possono risultare più o meno intensamente dipendenti dal punto di vista spaziale, con la conseguenza che non solo risulta variabile anche la stessa influenza che essi possono esercitare a carico della resa, in quanto fattori limitanti l'espressione della massima produttività della coltura, ma la stessa capacità di interpretare e rappresentare tale variabilità varia in funzione della dipendenza spaziale di quest'ultima e quindi della struttura spaziale che caratterizza il parametro in questione (Gupta et al., 1997).

1.3.b.- La variabilità temporale

La variabilità temporale rilevata a carico di un determinato parametro (es. resa della coltura) si riferisce all'attitudine dello stesso ad assumere un'intensità differente nel tempo in corrispondenza dello stesso punto all'interno dell'appezzamento. In particolare, si possono individuare due componenti a carico della variabilità temporale di un dato parametro:

- ***variabilità temporale a carico del medesimo punto del campo riscontrabile nel corso della stessa annata***: in questo caso il parametro in esame tende a manifestare un'intensità differente nel corso del tempo, sulla base delle condizioni ambientali e delle interazioni con gli altri fattori presenti, come può accadere ad esempio per il contenuto di acqua disponibile per la

coltura nel corso del ciclo colturale, parametro che risulta variabile all'interno dell'appezzamento a seconda dell'andamento stagionale (Timlin, 1998; Cassel et al., 2000);

- ***variabilità temporale riscontrabile nel corso di annate differenti*** (intesa come varianza temporale): in questo caso il parametro in questione manifesta la tendenza a variare nel tempo in corrispondenza dello stesso punto, indipendentemente dall'eventuale variazione subita nel corso della singola stagione colturale, come nel caso della resa ad esempio, la quale può assumere valori differenti in corrispondenza di una stessa zona del campo nel corso degli anni, pur manifestando per tale zona una produttività maggiore rispetto a quelle adiacenti (Blackmore et al., 2003).

1.3.c.- La stabilità temporale della variabilità spaziale

Sulla base di quanto esposto quindi, l'obiettivo principale dello studio della variabilità presente all'interno dell'appezzamento è quello di caratterizzarne non solo la struttura spaziale e l'intensità con la quale si manifesta, ma anche di individuarne la stabilità temporale nel corso degli anni, al fine di poter individuare delle zone omogenee in grado di assumere le stesse caratteristiche nel corso del tempo, dal momento che la possibilità di fruttare al meglio la potenziale variabilità presente all'interno dell'appezzamento in sede di applicazioni a dosaggio variabile si realizza soprattutto per le zone del campo in cui sia riscontrabile un'elevata stabilità temporale a carico della variabilità spaziale (Pierce and Novak, 1999).

1.4.- Le principali fasi costituenti l'Agricoltura di Precisione

Una volta raccolti e georeferenziati i dati all'interno del campo, da essi è quindi possibile ricavare ed elaborare le informazioni necessarie alla comprensioni delle cause che hanno limitato la coltura nell'esprimere la massima produttività potenziale nel corso del ciclo colturale, fino ad arrivare alla pianificazione degli interventi mirati ed eseguiti ad intensità variabile. A tal proposito quindi il reperimento dei dati, intesi come semplice osservazione oggettiva do un fenomeno da cui estrapolare poi le informazioni, ossia i rapporti relazionali di causa-effetto, svolge un ruolo chiave ai fini dell'elaborazione delle informazioni necessarie alla messa a punto delle strategie

agronomiche successive, con la possibilità di strutturare l'Agricoltura di Precisione complessivamente in tre fasi, come riportato schematicamente in seguito (Figura 2).

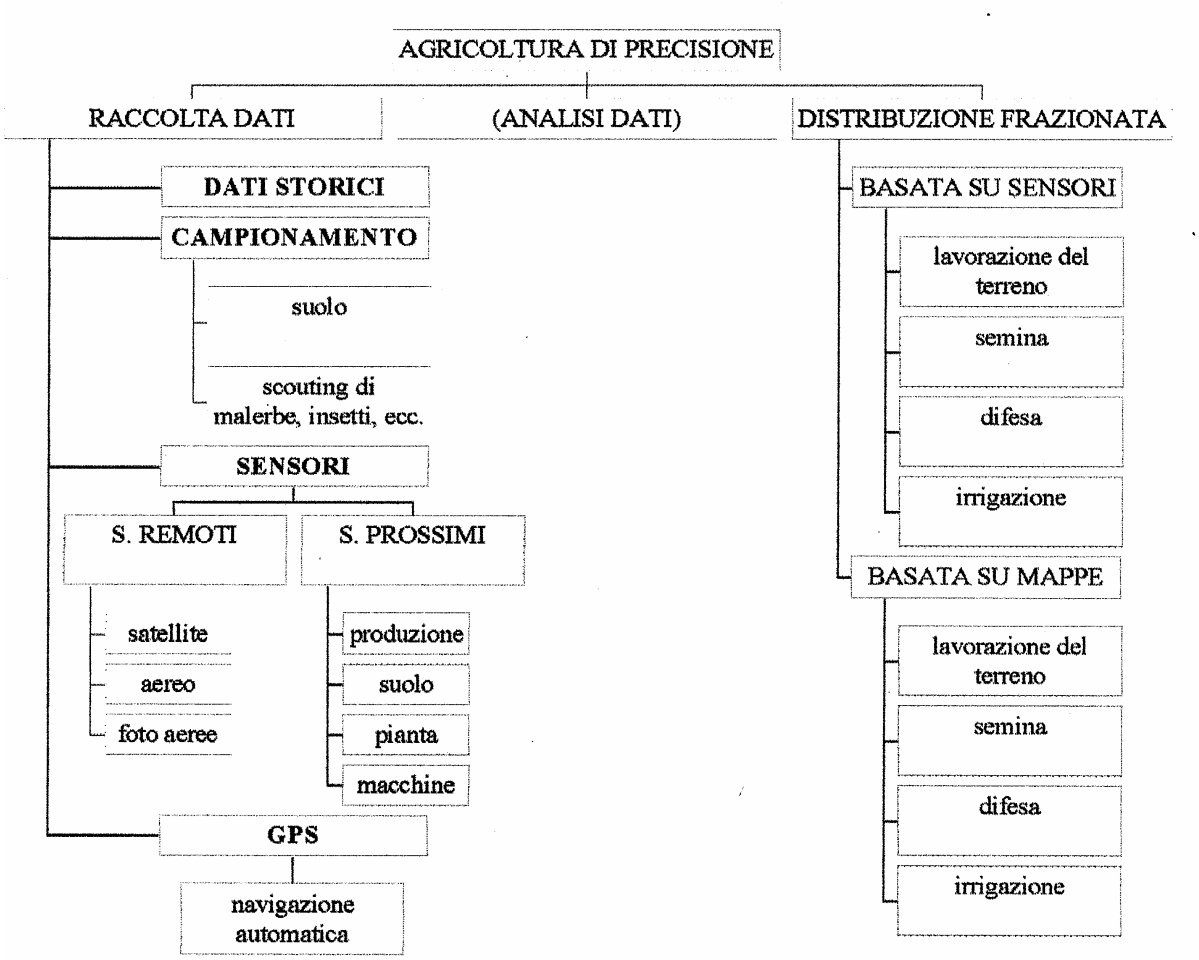

Figura 2.- Rappresentazione schematica delle principali fasi costituenti l'Agricoltura di Precisione e delle soluzioni percorribili all'interno di ognuna di esse (tratto da: Sartori e Rizzo, 1999).

1.4.1.- Raccolta dati

Il reperimento dei dati relativi alla variabilità dei parametri riscontrabili all'interno dell'appezzamento rappresenta una fase generalmente molto onerosa dell'intero processo, ma costituisce un aspetto fondamentale in quanto consente di caratterizzare con certezza l'azienda, definendone i fattori sui quali concentrare le risorse nella successiva fase decisionale. Tra le tecniche maggiormente impiegate per l'acquisizione di dati sulla variabilità in campo la mappatura delle produzioni rappresenta di sicuro quella più diffusa per il reperimento di informazioni relative

alla resa, sostenuta dall'elevato livello tecnologico delle moderne macchine operatrici impiegate nella raccolta, accanto alla possibilità di utilizzare le foto aree o le immagini da satellite, le quali vengono utilizzate più facilmente nel caso delle colture da reddito come gli arborei. Nel caso specifico delle proprietà del terreno invece, le tecniche che sono state messe a punto di recente sono molto numerose e rivolte in linea generale all'acquisizione in real-time di un numero limitato di dati da cui poter ricavare informazioni relative alle molteplici caratteristiche del suolo (es. rilevazione della capacità dielettrica da cui risalire indirettamente anche alla tessitura, al pH ed all'umidità del terreno) (Godwin and Miller, 2003; Adamchuk et al., 2004).

1.4.1.a.- Mappatura delle produzioni

La mappatura delle produzioni consiste nell'impiego di appositi sensori (sensori di flusso, umidità, densità, velocità, posizionamento, etc.) in dotazione alle mietitrebbiatrici per la determinazione del livello di resa ottenuto per i singoli punti dell'appezzamento (Figura 3), con un margine di errore relativo ridotto (4-5%), il quale può essere mantenuto su livelli accettabili anche grazie all'adozione di procedure per la corretta acquisizione e gestione dei dati grezzi in campo (Bertocco et al., 2004) ed all'impiego di apposito tecniche per la loro conseguente fase di filtraggio e correzione (Han et al., 1997; Beck et al., 2001; Han at al., 2004), essendo i dati stessi affetti da errori ed imprecisioni intrinseci al sistema di mappatura (Blackmore and Marshall, 1996; Whelan and McBratney, 1997). Tra le motivazioni che hanno portato ad una sua relativa rapida diffusione hanno rivestito un ruolo di notevole rilievo sia l'importanza rivestita dalla resa per l'azienda, in quanto indicatore finale del processo di produzione messo in atto, sia il livello tecnologico delle macchine operatrici impiegate nella raccolta, in alcuni casi ormai equipaggiate di serie dei sistemi per la mappatura delle produzioni.

Figura 3.- Esempio di mietitrebbiatrice equipaggiata con un sistema per la mappatura delle produzioni.

1.4.1.b.- Campionamento del terreno

L'indagine condotta mediante il campionamento del terreno consente di ottenere informazioni sulle proprietà fisiche, chimiche e biologiche dello stesso, al fine di esaminarne l'eventuale variabilità spaziale riscontrabile all'interno dell'appezzamento. A tal proposito, l'accuratezza con la quale viene rappresentata la variabilità all'interno dell'appezzamento risulta in parte essere direttamente proporzionale al numero di prelievi eseguiti, anche se ciò comporta la necessità di ponderare la risoluzione spaziale del dettaglio esaminato con la richiesta di risorse per l'esecuzione dei prelievi, sia in termini di tempo dedicato che di costo per l'analisi delle singole proprietà indagate: se è vero infatti che il costo del campionamento deve in qualche modo essere ottimizzato, è anche vero che l'indagine basata sull'esecuzione di pochissimi prelievi per ettaro è utile per evidenziare le differenze macroscopiche (Domsch et al., 2002) ma non consente l'analisi della variabilità effettiva esistente a carico del suolo. Sulla base di tali considerazioni, la metodologia seguita per l'esecuzione del campionamento delle proprietà del suolo, soprattutto per quanto riguarda il numero di campioni necessari ad una rappresentazione attendibile della variabilità spaziale e la loro dislocazione all'interno dell'appezzamento, ha subito profonde revisioni nel corso degli anni, a seguito anche dell'incremento di conoscenze specifiche sulle caratteristiche delle singole proprietà del suolo (McBratney and Pringle, 1999). In particolare, gli aspetti principali che devono essere tenuti in debita considerazione riguardano la dislocazione dei singoli punti in cui eseguire il prelievo del terreno e lo schema da seguire all'interno dell'appezzamento. Dallo schema classico a maglia o griglia regolare, che prevede il prelievo del terreno in corrispondenza di punti a distanza

definita e costante, si è infatti passati ad uno schema più irregolare, spesso definito casuale, in quanto il numero di prelievi che lo schema classico comporta risulta oneroso in termini economici (Mohamed et al., 1996) ma soprattutto può non essere estremamente necessario in presenza di proprietà con una buona struttura spaziale. Nel caso dello schema causale però, tale metodica, consistente inizialmente nel posizionare a caso mediante l'aiuto di appositi algoritmi il numero di campioni all'interno dell'appezzamento, si può correre il rischio che questi di concentrino in aree dell'appezzamento che poi risultano essere meno interessanti di altre, magari parzialmente scoperte dalla maglia di punti così definita (Castrignanò, 1997). La casualità con cui si decidono i punti in cui eseguire il campionamento va perciò intesa in senso ragionato, in opposizione allo schema classico, ma basata sulla preliminare caratterizzazione dell'appezzamento, al fine di individuare eventuali zone in cui eventuale concentrare le indagini. Sulla base delle relazioni dimostrate tra la struttura spaziale della resa e la variabilità spaziale del suolo (Kaspar et al., 2003; Jiang and Thelen, 2004; Bing and Farrell, 2004), pur non essendo queste in grado di spiegare in maniera sempre esaustiva la variabilità riscontrabile a carico del livello produttivo (Sudduth et al., 1996; Mallarino et al., 1999), l'indicatore che più facilmente può essere utilizzato per indirizzare il campionamento risulta essere la produzione ottenuta nelle annate precedenti (van Alphen e Stoorvogel, 1998), così da poter mirare l'indagine alla conoscenza di quelli possono aver costituito dei fattori limitanti per la produttività della coltura. A tal proposito, la possibilità di poter georeferenziare i siti in cui è stato prelevato il campione rappresenta uno strumento di fondamentale importanza in quanto sulla base dell'identificazione di ciascun punto all'interno dell'appezzamento mediante una coppia di coordinate geografiche cui associare l'osservazione della variabile esaminata è poi possibile risalire all'entità della stessa variabile tra punti vicini non campionati, mentre un aspetto di cruciale rilevanza in proposito è rappresentata dalla distanza tra i siti campionati. Poiché la possibilità di stimare mediante apposite tecniche (es. interpolazione, etc.) i valori non campionati consente di risalire alla struttura spaziale della variabile è infatti importante che i punti campionati si trovino a distanza variabili, così che le stesse informazioni rilevate siano in grado di assecondare la struttura spaziale della proprietà esaminata, ed a tale scopo la soluzione più semplice è che i differenti siti di campionamento si trovino dislocati a distanza progressiva su vettori immaginari orientati in ogni direzione, così da evitare che i dati siano influenzati dall'orientamento con cui si procede al prelievo dei campioni stessi.

Infine, l'ultimo aspetto che riguarda il campionamento del terreno eseguito allo scopo dell'analisi della variabilità è l'intensità con cui eseguire i prelievi, sia in termini di numerosità di campioni in corrispondenza di ciascun vettore, che di frequenza temporale. A tal proposito la problematica

risulta essere notevolmente complessa, e comunque variabile a seconda della proprietà del suolo investigata. Per quanto riguarda infatti l'intensità di prelievi, questa infatti è funzione della variabilità del parametro, in quanto a fronte di proprietà del suolo aventi una forte struttura spaziale, quali l'argilla, per le quali i valori rilevati in un punto risentono dell'influenza dei punti vicini su distanze medio grandi, altre variabili, quali ad esempio il contenuto di composti azotati (Cahn et al., 1994) o la resistenza del terreno alla penetrazione (Clark, 1996) risultano dotate di una grande variabilità all'interno dell'appezzamento, probabilmente a seguito della loro mobilità come nel caso dei nutrienti o della variabilità delle cause che concorrono alla determinazione del valore assunto in determinato punto dell'appezzamento.

Il campionamento del terreno, sulla base di quanto detto, rappresenta perciò uno strumento di fondamentale importanza per la conoscenza e la gestione della variabilità presente all'interno dell'appezzamento, il cui utilizzo però va ponderato sulla base della possibile integrazione con altri strumenti di diversa natura ed efficacia (es. immagini da satellite, metodi indiretti o di analisi multiple, etc.) e dell'investimento di risorse richiesto, mentre all'interno del sistema "agricoltura di precisione" dovrebbe necessariamente collocarsi di seguito alla mappatura delle rese, al fine di poterne massimizzare l'efficacia d'esecuzione.

1.4.2.- Elaborazione dei dati raccolti

Se la possibilità di ottenere i dati grezzi dall'appezzamento (es. resa, proprietà del terreno, etc.) oggi dal punto di vista della fattibilità non rappresenta più una seria problematica per l'azienda, molto più complicata risulta invece la loro interpretazione e la conseguente estrapolazione delle informazioni, a seguito dell'interazione a carico dei valori monitorati tra la varianza temporale e la variabilità spaziale. L'elaborazione dei dati deve essere principalmente mirata all'individuazione della variabilità eventualmente presente in campo e nella conseguente interpretazione della struttura spaziale delle variabili investigate all'interno dell'appezzamento, così da poter non solo individuare le cause che hanno maggiormente limitato o favorito l'estrinsecarsi della potenziale produttività della coltura, ma soprattutto definire le zone omogenee al cui interno poter adottare interventi colturali ad intensità variabile. In tale fase rivestono un ruolo di fondamentale importanza alcuni strumenti molto utili nell'interpretazione della variabilità a partire dai dati raccolti in campo, quali la geostatistica, i sistemi informativi geografici ed i modelli di simulazione.

1.4.2.a.- Geostatistica

La geostatistica è la disciplina che prende in considerazione la variabilità esistente a carico delle caratteristiche del suolo, e si basa sul principio in base al quale osservazioni vicine all'interno dell'appezzamento hanno una maggiore probabilità di essere simili rispetto a quanto non accada con osservazioni lontane tra loro (Castrignanò, 1997), con la possibilità di costruire una mappa raffigurante la variabilità spaziale del parametro esaminato.

In particolare, la geostatistica prende in considerazione le osservazioni eseguite all'interno dell'appezzamento ed espresse come coppia di coordinate geografiche (X,Y) cui è associata la variabile in esame, ed utilizza il fatto che i punti siano georefenziati per la costruzione dei semi-variogrammi, ossia la rappresentazione grafica della varianza media dei punti campionati separati dalla stessa distanza nello spazio, in accordo con la seguente relazione:

$$\mathbf{y(h) = 1/N(h) \times \Sigma(z_j - z_{j+h})^2}$$

in cui:

y(h) = semivarianza per classi di intervallo h;

h = intervallo di distanza tra le classi;

$\mathbf{z_j}$ = valore campionato nel punto di coordinate $(\text{est; nord})_j$;

$\mathbf{z_{j+h}}$ = valore campionato nel punto di coordinate $(\text{est; nord})_{j+h}$;

N(h) = coppie di valori complessivi per intervallo di ampiezza h,

con la quale, data una popolazione qualsiasi di punti georeferenziati e separati da distanze variabili gli uni dagli altri, è possibile suddividerli in classi di distanza, confrontando la distanza assoluta tra due punti oggetto d'esame – $\mathbf{D_i}$ – e l'ampiezza dell'intervallo di classe – **h** – fornito all'inizio dell'analisi, in base alla relazione ***classe*** **=** $\mathbf{[D_i/h + 1]}$), ed all'interno di ciascuna classe di punti calcolare la varianza. L'espressione della varianza così calcolata in funzione della ampiezza progressiva delle classi di distanza consente perciò di ottenere il semi-variogramma, il quale può assumere andamenti anche molto differenti tra loro (Figura 4), pur rimanendo valido il principio in base al quale i parametri che caratterizzano il semi-variogramma possono essere utilizzati per la comprensione della struttura spaziale della variabile, come di seguito riportato per i casi generali:

- il ***nugget*** **(C_o):** graficamente rappresenta l'intercetta della curva con l'asse Y, ossia l'entità del rumore di fondo (noise) avutosi in fase di campionamento e legato sia alle condizioni operative che all'accuratezza del campionamento; esso rappresenta la quota di varianza che non può essere spiegata;

- il ***sill*** **(C_o+C)**: graficamente rappresenta l'intercetta dell'asintoto della curva con l'asse Y, ossia il valore massimo di varianza ottenuto per la classe di distanza in esame e rappresenta la quota di varianza che può avere una motivazione spaziale;
- il ***range*** **(A_o):** graficamente rappresenta l'ascissa in prossimità della quale la curva assume un andamento asintotico, ossia la distanza all'interno della quale le singole osservazioni risultano influenzate dal valore assunto dalle osservazioni vicine, mentre per i valori che si trovano oltre il valore del range non è possibile fornire alcuna spiegazione sulla struttura spaziale dei dati.

In particolare, mentre ad esempio un andamento di tipo sferico si riferisce ad un modello con il quale è possibile dare una spiegazione della struttura spaziale dei dati all'interno del range, nel caso del modello lineare ciò non è possibile, in quanto all'aumentare della distanza tra i punti aumentano anche i valori delle osservazioni, e questo ha un'importanza fondamentale in quanto mentre nel primo caso, conosciuto il range si può adeguare il campionamento in modo tale che due punti campionati distino tra loro al massimo di un valore pari al range stesso, in questo caso non è possibile adeguare il campionamento per conoscere la struttura spaziale tra le osservazioni.

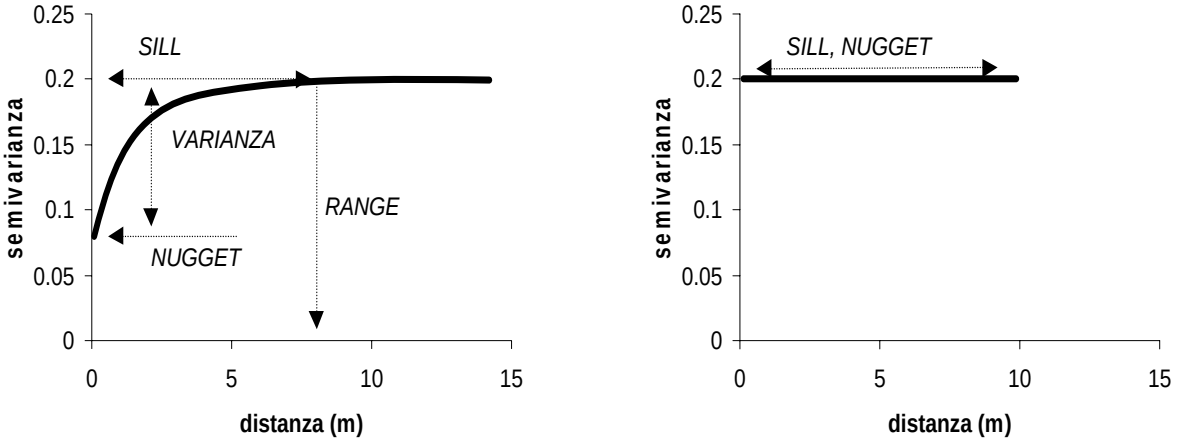

Figura 4.- Esempio di semivariogramma, per il quale il modello in grado di spiegarne l'andamento in funzione della distanza è rispettivamente di tipo sferico (a sinistra) e lineare (a destra).

La spiegazione della variabilità spaziale attraverso la semi-varianza è un passaggio fondamentale perché consente l'utilizzo di differenti tecniche di interpolazione (es. kriging, inverse weighted distance, etc.) con le quali è possibile utilizzare i valori assunti da osservazioni vicine per la stima

dei valori assunti dal parametro nello spazio tra esse comprese, rappresentando poi il tutto graficamente mediante delle mappe in cui a colori differenti corrispondono zone in cui la variabile varia all'interno di uno stesso intervallo predefinito.

1.4.2.b.- Sistemi Informativi Geografici (GIS, Geographic Informative Systems)

L'impiego di sistemi GIS in Agricoltura di Precisione è molto importante in quanto consente di stoccarne e gestirne una mole di dati anche molto consistente, al fine di eseguire le elaborazioni rinecessarie e visualizzare poi i risultati in formato grafico in maniera georeferenziata, ossia nello spazio, cosa che non è possibile con gli strumenti classisi di analisi data la difficoltà di gestire un numero di dati così elevato e di integrare dati diversi nello spazio e differiti nel tempo (Earl et al., 2000; Neményi et al., 2003). La potenzialità dei sistemi di questo tipo infatti è proprio quella di gestire i dati abbinando alle osservazioni le coordinate di riferimento, in modo da poterle sempre riferire alla posizione occupata nello spazio e quindi, nel caso specifico, alle differenti aree dell'appezzamento. Tali strumenti si strutturano come un sistema integrato e complesso, il cui elemento fondamentale è dato da un database, o base di dati, di tipo relazionale, a cui si associano poi le varie funzioni di analisi ed elaborazione e la possibilità di visualizzare graficamente i dati. Nel caso della gestione variabile di un appezzamento, tali modelli consentono di sovrapporre informazioni differenti riferite alla stessa area, facilitando la comprensione delle relazioni esistenti a loro carico nella parte di appezzamento in esame (Basso et al., 2004).

1.4.2.c.- Modelli di simulazione

Un modello di simulazione è uno strumento in grado di simulare le singole fasi costituenti un fenomeno, quale la crescita e lo sviluppo di una singola pianta, sulla base di una serie di informazioni che nel caso degli strumenti impiegati nell'Agricoltura di Precisione si possono suddividere in informazioni relative al suolo (es. limiti idraulici, tessitura, densità volumica, etc.), alla coltura (es., coefficienti genetici relativi alle varie fasi sviluppo della pianta), alle condizioni climatiche (es., piovosità, temperatura, etc.) ed alle pratiche colturali messe in atto nel corso del ciclo colturale. In questo modo è perciò possibile tenere in considerazione ed analizzare le molteplici relazioni spaziali e temporali esistenti a carico delle variabili che all'interno del campo limitano l'estrinsecarsi della potenzialità produttiva ottimale della coltura. In tale ottica, i modelli di simulazione della crescita e dello sviluppo delle colture rappresentano un valido strumento conoscitivo ed interpretativo dei processi dinamici legati al movimento dell'acqua e delle risorse

nutritive del suolo e della pianta. Tali modelli, integrando funzionalmente le caratteristiche genetiche , le informazioni variabili legate al suolo e i dati climatici storici possono effettivamente simulare i processi d sviluppo e crescita della pianta coltivata. La possibilità di simulare, analizzare e confrontare scenari differenti ha quindi assunto una valenza scientifica indiscutibile nella ricerca, in quanto in questo modo è possibile estendere i risultati ad areali con caratteristiche anche molto differenti rispetto a quelli di riferimento, indipendentemente dalle condizioni iniziali, dalle condizioni climatiche e dalle tecniche colturali adottate, superando i limiti degli studi classici, i cui risultati per quanto importanti rimangono inevitabilmente confinati all'area sperimentale e consentendo di formulare non solo previsioni sui risultati ma anche di pianificare gli interventi agronomici da mettere in atto. I risultati conseguibili con i modelli di simulazione, sia in termini agronomici che ambientali, sono infatti in grado di fornire informazioni utili per individuare strategie di gestione per il conseguimento di un maggior livello di sostenibilità del processo di produzione (Cora et al., 1999; Basso et al., 2001).

1.4.3.- Definizione di aree omogenee

La fase di elaborazione dei dati raccolti deve essere finalizzata alla comprensione della variabilità e quindi all'individuazione di zone omogenee all'interno dell'appezzamento, dove per ***"zona omogenea"*** si intende ***"una parte dell'appezzamento in cui i fattori limitanti la resa, dotati di una struttura spaziale, esercitino la loro azione in maniera uniforme e l'intensità della variabilità spaziale sia tale da giustificarne, in termini tecnici ed economici, una gestione differente rispetto alle zone contigue"***. La natura di tale obiettivo viene spesso trascurato in quanto le aziende che si apprestano ad adottare le soluzioni proposte dall'Agricoltura di Precisione hanno delle oggettive difficoltà nel seguire una metodica semplice e nello stesso tempo affidabile per l'individuazione delle aree in cui poter eseguire gli interventi agronomici ad intensità variabile, a partire dall'interpretazione delle stesse mappe di produzione e della variabilità in esse riportata. A tal proposito, sono state proposte alcune soluzioni per l'identificazione delle zone omogenee all'interno dell'appezzamento (Boydell and McBratney, 2002; Zhang and Han, 2002; Blackmore, 2003), le quali si propongono di caratterizzare le singole aree dell'appezzamento non solo in termini di variabilità spaziale ma anche di varianza temporale, al fine di poter definire delle zone omogenee in cui l'espressione dei fattori limitanti la resa abbia una varianza temporale molto bassa. Ciò si accompagna inevitabilmente alla necessità di considerare la variabilità monitorata in differenti annate, soprattutto se si opera con colture differenti, al fine di incrementare l'affidabilità dei dati

ottenuti (Joernsgaard and Halmoe, 2003), ed a tal proposito la combinazione di strumenti GIS e modelli di simulazione può risultare un valido aiuto per l'identificazione delle aree da gestire in maniera variabile.

1.4.4.- Adozione di interventi ad intensità variabile

Il presupposto per un intervento ad intensità variabile è l'esistenza di una variabilità spaziale e temporale gestibile all'interno dell'appezzamento con soluzioni accessibili dal punto di vista tecnico ed economicamente convenienti, sulla base della distinzione secondo la quale la variabilità a carico di un parametro può essere caratterizzata da (Pringle et al., 2003).

L'adozione di interventi ad intensità variabile consiste nell'attuazione delle diverse pratiche agronomiche ad intensità differente a seconda delle effettive condizioni ed esigenze riscontrate in campo: in particolare si fa riferimento all'applicazione a dosaggio variabile, o VRA (VRA – Variable Rate Application) nel momento in cui si prendono in considerazione un sistema ed una metodologia in grado di consentire l'applicazione di una fattore colturale, mentre si fa riferimento a VRT (VRT – Variable Rate Technology) quando ci si riferisce più in particolare alle tecnologie disponibili con cui poter realizzare l'applicazione a dosaggio variabile.

Dal punto di vista operativo, le soluzioni che si possono adottare per l'esecuzione di interventi ad intensità variabile sono fondamentalmente di due tipi, sostanzialmente differenti tra loro anche se le strumentazioni, i principi ed i sistemi utilizzati sono spesso comuni:

1. **VRA basata su mappe**: in questo caso l'entità di prodotto da distribuire viene decisa e variata in fase dei applicazione sulla base delle informazioni relative alle caratteristiche dell'appezzamento contenute nelle mappe di prescrizione. Questo metodo presuppone che esista un sistema di localizzazione della macchina all'interno dell'appezzamento e che per ciascun punto del campo, la cui posizione geografica viene espressa come coppia di coordinate (X, Y), sia disponibile il dato relativo alla quantità di prodotto da distribuire (Figura 5).
2. **VRA basata su sensori**: in questo caso vengono utilizzati dei sensori, installati sulla trattrice o direttamente sull'operatrice, che misurano in tempo reale uno specifico parametro, quale ad esempio lo stato nutrizionale della coltura, rilevando in questo modo i dati che poi vengono processati per regolare l'intensità con la quale eseguire l'intervento colturale (es. distribuzione di principi attivi o fertilizzanti).

Figura 5.a.- Esempio di distribuzione azotata a dose variabile in copertura su fumento mediante trattrice equipaggiata con ricevitore di posizione e unità di controllo, abbinata a spandiconcime centrifugo dotato di attuatore elettrico-idraulico.

Figura 5.b.- Esempio di distribuzione azotata a dose variabile in copertura si mais mediante trattrice equipaggiata con ricevitore di posizione e unità di controllo, abbinata a spandiconcime pneumatico dotato di attuatore idraulico.

Tale metodo non richiede necessariamente l'impiego di un ricevitore satellitare per il posizionamento dell'operatrice all'interno dell'appezzamento, ma i dati di posizione possono

essere comunque registrati e, opportunamente georeferenziati, servire per la costruzione di mappe per altre utilizzazioni.

1.4.5.- Esempi di interventi a dosaggio variabile

L'aumento delle conoscenze relative allo studio ed all'interpretazione della variabilità presente all'interno dell'appezzamento e lo sviluppo verificatosi nel settore delle tecnologie applicate al settore agricolo (informatica, meccatronica, sensoristica, etc.) consentono oggi di poter eseguire con alcuni interventi agronomici ad intensità variabile, con maggiore affidabilità ed accuratezza di quanto potesse avvenire in passato, ipotizzando nello stesso tempo un'estensione di tali sistemi per il controllo e la regolazione dell'intensità con cui si opera in campo anche ad operazioni colturali fino ad oggi meno interessate a tali sviluppi, quali ad esempio la variazione della dose di semina all'interno dell'appezzamento.

L'operazione colturale fino ad oggi più studiata è la concimazione minerale, in quanto da subito la possibilità di variare la dose dei fertilizzanti minerali all'interno dell'appezzamento ha evidenziato la possibilità di contenere i costi di esercizio ma soprattutto di ridurre la pressione esercitata a carico delle risorse naturali, con particolare riferimento nel caso specifico ai rilasci di azoto in falda, imputabili alla lisciviazione dei composti azotati lungo il profilo del terreno. Ciò ha comportato l'approfondimento ormai decennale di tali tematiche e la recente messa a punto di sistemi in grado di consentire l'esecuzione di una concimazione a dosaggio variabile, pur restando ancora da definire con maggior precisione alcune problematiche di carattere operativo, quali le dosi tecnicamente ottimali ed economicamente convenienti da utilizzare, la risoluzione spaziale (es. larghezza di lavoro della macchina v.s. dimensione della zona da trattare in maniera differenziata) e la capacità dei sistemi di rispondere in tempo reale alla variabilità riscontrata in campo (es. ritardo nell'assecondare le informazioni contenute nella mappa di prescrizione).

Se nel caso della concimazione minerale i risultati ottenuti sono incoraggianti, la punto da poter prospettare una prossima diffusione dei sistemi messi a punto, nel caso delle lavorazioni del terreno invece la possibilità di intervenire con tecniche di lavorazione ad intensità variabile è ancora relegata ad una fase sperimentale, anche se è evidente la loro importanza nell'ambito dell'attività agricola per la riduzione dei costi di produzione (es. riduzione del consumo di carburante, aumento della capacità operativa, etc.) e dell'impatto esercitato dalle tecniche di coltivazione sulla fertilità del terreno (es. mineralizzazione della sostanza organica, etc.) e sulle risorse naturali (es. erosione eolica, ruscellamento superficiale, etc.).

1.4.5.a.- Concimazione a dosaggio variabile basata su sensori

Nel caso dei sensori utilizzati per la distribuzione di fertilizzanti minerali a dosaggio variabile, i più importanti prototipi messi a punto risultano essere basati, direttamente o indirettamente, sulla rilevazione di un parametro relativo allo status della coltura in campo, di cui in seguito sono riportati alcuni esempi significativi (Figura 6).

Sensore di riflessione della luce

Il sistema (figura 4.2) è costituito dall'insieme di sensori e software che operano in movimento: la quantità ottimale di azoto da distribuire alla coltura viene valutata sulla base dell'analisi del fattore di riflessione della luce della coltura stessa. Il sistema regolerà automaticamente l'attrezzatura per la distribuzione in base alle reali necessità della pianta. L'apparato di rilevamento è posizionato sulla parte superiore della cabina del trattore, in modo tale da permettere una perfetta visuale sulla coltura: i sensori misurano la riflessione della luce effettuata dalla coltura stessa da quattro differenti angolazioni andando a coprire così una superficie di circa 50 m^2 (Margotti, 2000). La quantità di luce riflessa dipende sia dal contenuto di clorofilla delle foglie, che dal LAI: entrambi i parametri sono direttamente influenzati dalla dotazione azotata delle piante (Heege, 2002). E' inoltre presente un altro sensore per la misurazione dell'intensità della luce, al fine di tenere in considerazione il grado di copertura e la radiazione incidente in pieno campo.
I dati raccolti vengono inviati all'unità centrale di elaborazione (all'interno della cabina del trattore) che li traduce in quantità ottimale di azoto da distribuire. A questo punto un apposito dispositivo regola l'effettiva distribuzione di fertilizzante (Margotti, 2000), con la possibilità di distribuire un quantitativo di azoto per ettaro tale da soddisfare le effettive richieste dalla coltura (Balsari, 2000).

Sensore di fluorescenza

Si basa sulla registrazione della luce fluorescente emessa dalle piante, la quale è normalmente un indicatore dell'efficienza energetica associata con i processi fotosintetici: quanto più il processo fotosintetico è inefficiente tanto maggiore è la quota di luce fluorescente e su questo principio si basa il funzionamento del sensore, dal momento che un apporto di azoto incrementa la quantità di clorofilla alla foglia e quindi riduce la frazione di luce emessa. Il livello dei picchi di emissione, rientranti nello spettro dell'infrarosso, viene quindi utilizzato per la valutazione della

concentrazione di clorofilla e quindi del livello di azoto nelle foglie, con la conseguente regolazione della dose di azoto da distribuire per colmare la deficienza nutrizioale (Heege e Thiessen, 2002).

Figura 6.- Sistema per la distribuzione a dosaggio variabile dell'azoto basato sulla presenza di un sensore di riflessione della luce da parte della coltura.

Sensore a pendolo

Questo sensore è di tipo "meccanico" ed è costituito da un sensore a pendolo posto anteriormente alla trattrice, in prossimità alla massa vegetale della coltura. Mano a mano che la trattrice procede all'interno dell'appezzamento, l'angolo che il pendolo forma con il piano verticale subisce delle modifiche a seconda della resistenza che incontra, la quale è proporzionale alla biomassa della coltura. Per via indiretta è quindi possibile risalire alla quantificazione di quest'ultima e regolare mediante curva di calibrazione la dose di fertilizzante da distribuire (Heege e Thiessen, 2002).

Problematiche legate all'impiego dei sensori

A fronte di indiscutibili vantaggi derivanti dall'impiego di dispositivi in grado di assecondare le esigenze della coltura in termini di concimazione azotata, quali la possibilità di essere utilizzati in assenza di mappe di produzione e di ricevitore satellitare, oltre che la possibilità di intervenire in campo con la regolazione della dose da distribuire sulla base di frequenti misurazioni del parametro di riferimento eseguite su una ampia superficie dell'appezzamento, l'impiego di sensori per la variazione della dose "on-the-go" all'interno dell'appezzamento si accompagna a delle problematiche non trascurabili rispetto alla possibilità di ricorrere alla distribuzione di fertilizzante

azotato basata su mappe. In particolare, iprimi due sistemi descritti (quello basato sulla riflessione della luce e quello basato sulla fluorescenza) non analizzano direttamente la richiesta di azoto ma sfruttano il contenuto di clorofilla come indicatore indiretto della disponibilità di azoto per la pianta. Tale informazione è però soggetta alla variabilità e soprattutto all'influenza anche di altri parametri, quale ad esempio il generale status nutrizionale della pianta (Heege e Thiessen, 2002), con conseguente penalizzazione dell'accuratezza del dato elaborato relativo alla dose da distribuire. Nel caso del sensore a pendolo le problematiche rimangono le medesime, in quanto la quantità di biomassa risente della disponibilità idrica della coltura, la quale può quindi risentire di eventuali situazioni di stress indipendentemente dalla dotazione di azoto del terreno (Ehlert et al., 2003).

1.4.5.b.- Lavorazione del terreno

Nel caso delle lavorazioni del terreno, l'esecuzione di interventi di lavorazione ad intensità variabile, intesa come risultato dell'interazione tra la profondità di lavoro adottata e della tecnica di lavorazione messa in atto all'interno dell'appezzamento, è stata interpretata in maniera differente dai diversi autori, con il risultato che dal punto di vista operativo si possono individuare schematicamente due differenti approcci alla problematica, basati rispettivamente su:

a) ***la variazione della profondità di lavoro***. In questo la variazione della profondità di lavoro in fase di lavorazione è stata realizzata mediante la costruzione o l'adattamento di singoli prototipi di macchine operatrici muniti di sensori per la misurazione di un parametro del suolo all'interno dello strato interessato dall'intervento agronomico. In particolare, il parametro che più è stato studiato in proposito è la resistenza del terreno alla penetrazione: un primo approccio in proposito è stato realizzato mediante la misurazione di tale parametro per la costruzione della relativa mappa indicante come varia la resistenza alla penetrazione del terreno per i vari strati del profilo all'interno dell'appezzamento. Sulla base di tali dati è poi possibile creare una vera e propria mappa di prescrizione contenente le informazioni necessarie per la regolazione della profondità di lavoro, che può essere ottenuta mediante un sistema di regolazione e comando delle ancore, nel caso di un coltivatore, costituito da dei martinetti idraulici che consentono il movimento degli organi lavoranti sul piano verticale (Sartori, 2000) (Figura 7). Tale soluzione si è accompagnata però ad una serie di inconvenienti di non trascurabile importanza che ne hanno impedito la diffusione, quali fra tutti la necessità di sostenere una dettagliata e dispendiosa fase di campionamento in campo

per misurare l'andamento della resistenza alla penetrazione, la quale a sua volta risulta legata a numerose variabili del terreno (es. umidità del suolo, dotazione di sostanza organica, tessitura, etc.), e quindi i valori misurati possono subire delle variazioni nel tempo al variare delle stesse condizioni del terreno (es. l'umidità del suolo ad una certa profondità risulta essere anche molto differente al momento dell'esecuzione delle lavorazioni rispetto ai valori assunti durante il ciclo colturale). Non solo, la stessa attrezzatura da utilizzare può necessitare dell'impiego di trattrici di elevata potenza, al fine di poter sostenere l'aumentata richiesta di forza di trazione all'aumento della profondità di lavoro durante l'esecuzione della stessa lavorazione.

Figura 7.- Esempio di coltivatore combinato equipaggiato per la variazione dell'intensità di lavorazione all'interno dell'appezzamento mediante attuatori di tipo idraulico.

Un'evoluzione in proposito si è ottenuta con l'impiego di un'attrezzatura combinata per la quale la profondità di lavoro è stata variata da un minimo di 10 cm ad un massimo di 25 cm, agendo sul sistema idraulico della trattrice in base a differenti caratteristiche del terreno (es. capacità di infiltrazione, tessitura, contenuto di sostanza organica) inserite in un'equazione complessa per la regolazione della profondità (Voβhenrich and Sommer, 2003). Anche in questo caso però si rende necessaria una dettagliata e costosa indagine sulle caratteristiche del terreno prima dell'esecuzione della stessa lavorazione del terreno, mentre la ridotta profondità di lavoro raggiungibile rappresenta comunque un limite per interventi più energici.

Date le evidenti difficoltà nella misurazione dei parametri del suolo da considerare per la regolazione della profondità di lavorazione, gli studi si sono indirizzati sulla messa a punto di prototipo di coltivatore dotato di alcune celle di carico, montate sulle ancore: sulla base della resistenza alla penetrazione opposta dal terreno, misurata in continuo, la centralina di comando confronta il valore misurato con quello pre-impostato e regola la profondità di lavoro delle ancore (Adamchuk et al., 2003). In questo caso, pur eliminando la fase di campionamento del terreno preliminare, le difficoltà rimangono legate alla scelta del valore di resistenza da utilizzare come limite soglia per decidere se approfondire o meno la lavorazione, soprattutto se si considera la variabilità temporale che tale parametro può manifestare col passare all'interno dell'appezzamento.

b) ***l'adozione di differenti sistemi di lavorazione***. L'obiettiva difficoltà incontrata nella variazione della profondità di lavoro mediante delle macchine operatrici opportunamente modificate si è accompagnata alla considerazione di agire non tanto su singole operazioni (lavorazione primaria) o singole attrezzature (es. coltivatore ad ancore), ma sul sistema di lavorazione complessivo adottato in azienda, in modo da localizzare le diverse tipologie di intervento sulla base delle caratteristiche del terreno rilevate all'interno dell'appezzamento. In sede di lavorazione primaria, un primo esempio potrebbe essere l'esecuzione di un intervento localizzato per la rottura della suola di lavorazione o l'aumento di porosità in presenza di eccessivo compattamento superficiale del suolo (es. ormaie, testate dell'appezzamento) solamente dove fossero riscontrate tali condizioni all'interno dell'appezzamento. A seguito di tale intervento colturale, potrebbe essere variata l'intensità della preparazione del letto di semina (es. variazione del numero di passate) in funzione del tipo di suolo, della presenza di infestanti o residui in superficie, fino all'adozione di tecniche di lavorazione differenti a seconda delle caratteristiche complessive dell'appezzamento (es. giacitura, andamento climatico stagionale, proprietà del suolo, tipo di coltura, etc.), quali possono essere la lavorazione ridotta in presenza di terreni difficili (es. terreni argillosi) fino al caso limite della semina su sodo per le zone dell'azienda ben drenate ed aventi terreno di medio impasto. In ogni caso, la scelta della tipologia di lavorazione da effettuare dovrebbe interessare solamente le zone dell'appezzamento in cui l'intervento sia ritenuto effettivamente necessario, mentre è in genere auspicata la scelta di pratiche agronomiche ispirate all'agricoltura conservativa, in maniera tale da conciliare gli aspetti economici (convenienza all'adozione della lavorazione) con quelli di natura agronomica ed ambientale

(mantenimento dei residui in superficie, riduzione dell'erosione, etc.). Un importante aspetto da considerare in proposito è la possibilità di poter impiegare le attrezzature presenti azienda o comunque facilmente reperibili sul mercato, così da contenere i costi dell'investimento iniziale ed aumentare il reddito ritraibile dal loro impiego (Ginting et al., 2003): mentre nel caso di macchine operatrici in grado di regolare la profondità di lavoro è inevitabilmente necessario il loro acquisto, l'adattamento della tecnica di lavorazione adottata consente di conciliare l'esecuzione dell'intervento ad intensità variabile con la possibilità di sfruttare il parco macchine aziendale, aspetto che spesso può giustificare tali cambiamenti dal punto di vista economico anche in annate difficili (es. siccità, scarsa resa, etc.).

1.5.- I benefici raggiungibili con l'adozione dell'Agricoltura di Precisione

L'applicazione delle strategie proprie all'Agricoltura di Precisione può essere considerata come un'opportunità a disposizione degli agricoltori per ottenere benefici economici dall'ottimizzazione degli input e per ridurre la pressione esercitata dai sistemi agricoli sull'ambiente (Vrindts et al., 2003; Ping et al., 2004), pur essendoci delle oggettive difficoltà che ne possono rallentare lo sviluppo e la diffusione. In particolare, rispetto alle forme manageriali improntate all'esecuzione di interventi colturali uniformi all'interno degli appezzamenti, la gestione delle pratiche colturali si può accompagnare a numerosi benefici, i quali possono essere schematizzati in vantaggi di natura economica, dovuta ad una razionalizzazione nell'utilizzo dei diversi fattori colturali, e vantaggi di natura ambientale, connessi con la riduzione dell'impatto negativo esercitato sulle risorse naturali dalle pratiche colturali costituenti il processo di produzione messo in atto dall'azienda agricola.

1.5.a.- Aspetti economici

In linea generale, i benefici di natura economica che si possono conseguire dall'attuazione delle strategie messe a punto nell'ambito dell'Agricoltura di Precisione derivano da una generale ottimizzazione degli interventi agronomici ed una razionalizzazione delle pratiche colturali, più che da una riduzione nell'impiego di un singolo fattore colturale, pur essendo questo un aspetto di non trascurabile entità per alcune specifiche pratiche colturali (Godwin et al., 2002 ; Harmel et al., 2004), o dal risparmio conseguito in una specifica pratica agronomica (Bullock and Bullock, 2000), e di conseguenza è difficile giungere ad una monetizzazione di tali risparmi. Sull'entità di

quest'ultimi esiste inoltre una certa discrepanza tra le sperimentazioni condotte, a causa sia delle differenze strutturali che si possono avere tra zone differenti (es. differenze in termini di prezzo di fattori produttivi, etc.) sia dell'eventuale mancanza di convenienza riscontrabile per un singolo fattore colturale per il quale si è adottato il dosaggio variabile rispetto ad altri per i quali invece tali strategie possono risultare convenienti (Lowenberg-DeBoer and Swinton, 1997). In generale si possono perciò riscontrare delle differenze in termini economici sia tra quanti ne non giustificano la convenienza all'introduzione in azienda, sia tra quanti sono invece arrivati a quantificare un reale beneficio monetario ritraibile nelle condizioni sperimentali di riferimento a seguito del reperimento dei dati sulla variabilità presente in campo e del loro utilizzo ai fini dell'esecuzione di interventi ad intensità variabile. A tal proposito rivestono comunque un ruolo fondamentale l'intensità con la quale la variabilità del fenomeno in questione si manifesta all'interno dell'appezzamento, essendo la stessa convenienza economica soggetta a variabilità spaziale e temporale (Watkins et al., 1998; Giau, 1999; Bongiovanni and Lowenberg-DeBoer, 2004), e la propensione al rischio dell'imprenditore agricolo (Marra et al., 2003), per il quale possono essere individuate una attitudine o una repulsione al rischio derivante dall'investimento di risorse richiesto per l'implementazione di un sistema gestionale basato sui principi dell'Agricoltura di Precisione, a sua volta legato oltre che da motivazioni soggettive anche dall'effettiva difficoltà che si può riscontrare nella determinazione accurata della convenienza economica, soprattutto nel breve periodo, in quanto questa richiede un'approfondita analisi dei benefici che si possono ritrarre e degli investimenti che si devono sostenere rispetto ad una gestione uniforme dell'appezzamento, i quali però risultano a loro volta variabili e di intensità differente nelle diverse aree omogenee definite, oltre che essere legati ad aspetti che generalmente non sono tenuti in considerazione in fase decisionale, come accade per le la gestione dei dati (Snyder et al., 1998), i quali richiedono non solo un costo di acquisizione ma anche di gestione ed utilizzo, al pari di un qualsiasi fattore produttivo (Mazzetto e Landonio, 1999; Werner, 2003).

Nel complesso i casi i cui si è dimostrata la convenienza per l'adozione delle metodiche proprie all'Agricoltura di Precisione riguardano soprattutto la concimazione a dosaggio variabile, in quanto la possibilità di contenere l'impiego di fertilizzante è da subito risultata di immediato interesse presso gli operatori del settore, sia a fini gestionali che ambientali, per il quale il beneficio economico è risultato variabile n funzione non solo della superficie aziendale ma anche della complessità e del livello tecnologico del sistema adottato (Schmerler e Basten, 1999), oltre che del livello di preparazione tecnica degli operatori, per la quale la formazione rappresenta un costo,

seppur non particolarmente incisivo, per l'azienda ma riveste un'importanza fondamentale ai fini dell'implementazione del sistema nel suo complesso.

1.5.b.- Aspetti ambientali

L'adozione di pratiche sostenibili per il processo di produzione attuato dall'azienda agricola è oggi uno dei più importanti e strategici aspetti per il miglioramento dell'efficienza in agricoltura e la soluzione di alcune problematiche ambientali (Bakhsh et al., 2000). A tal proposito l'adozione di sistemi in grado di consentire l'esecuzione degli interventi colturali ad intensità variabile può rappresentare un'opportunità interessante soprattutto per quelle operazioni per le quali è dimostrata l'esistenza di esternalità negative sulle risorse naturali, quali possono essere appunto le lavorazioni del terreno, la distribuzione di fitofarmaci nella difesa alla coltura e l'impiego di concimi minerali azotati di sintesi. Nel caso delle lavorazioni infatti è noto che l'eccessiva intensità con la quale vengono eseguiti gli interventi colturali può portare ad una mineralizzazione della sostanza organica del terreno e quindi ad una perdita della fertilità, mentre la stessa inversione degli strati, se eseguita in maniera uniforme all'interno dell'appezzamento, si accompagna ad una riduzione dei residui in superficie, con conseguente incremento del rischio che si verifichino fenomeni erosivi, sia di origine eolica, come spesso accade in fase di preparazione del letto di semina, che di natura idrica (Laflen et al., 1978; Dickey et al., 1985; Ginting et al., 1998a; Ginting et al., 1998b).

Nel caso della difesa alla coltura, numerose sono le soluzioni allo studio per poter consentire una riduzione non solo dei quantitativi di prodotto impiegato ma anche delle perdite di prodotto distribuito a causa del mancato raggiungimento del bersaglio da trattare (effetto deriva) (Balsari, 2004), anche se tali soluzioni si accompagnano a complicazioni di carattere costruttivo non trascurabile.

Per quel che riguarda invece l'impiego di fertilizzanti di sintesi, è ormai riconosciuta l'importanza delle perdite di nutrienti in falda, quali fosfati e nitrati, a seguito delle pratiche colturali messe in atto durante il ciclo colturale, con conseguente contaminazione delle acque di falda e superficiali, oltre a trattarsi di fenomeni particolarmente negativi dal punto di vista del bilancio economico dell'azienda agricola, trattandosi di un ingiustificato aggravio dei costi dovuto alla perdita di elementi nutritivi distribuiti in campo per soddisfare le esigenze nutrizionali della coltura (Godwin et al., 2003). La possibilità di modulare quindi gli interventi colturali sulla base delle esigenze effettivamente riscontrate in campo rappresenta una prospettiva interessante per l'azienda, soprattutto se interpretata come una opportunità per integrare le soluzioni tecnologiche offerte dal

mercato con le tecniche conservative ormai consolidate, e che nel caso specifico della lavorazione del terreno si propongono la non inversione degli strati, il mantenimento dei residui in superficie ed in generale si basano sulla necessità di arrecare al suolo il minore disturbo possibile, al fine di non danneggiarne la fertilità. Sulla base di quanto esposto, non mancano in bibliografia gli esempi a favore dell'adozione delle tecniche facenti capo all'agricoltura di precisione, che nel caso della distribuzione di concimi minerali evidenziano un miglioramento dell'efficacia dell'intervento agronomico a seguito della possibilità di ridurre le quantità di fertilizzante impiegate (Godwin et al., 2002; Harmel et al., 2004) e della diminuzione delle perdite di azoto (Larson et al., 1997; Ferguson et al., 1998; Rejesus e Hornbaker, 1999; Thrikawala et al., 1999). L'entità dei miglioramenti conseguibili è comunque variabile, a seconda delle condizioni iniziali, tra le quali rivestono un ruolo di notevole importanza sia il tipo di terreno che le modalità di distribuzione (Bouma, 1998; Wang et al., 2003), oltre all'interazione tra tali fattori e la capacità di assorbimento della coltura (Roberts et al., 2001). Tali benefici, sia nel caso delle lavorazioni del terreno che nel caso della distribuzione di fertilizzanti, sono inoltre difficilmente quantificabili con le tecniche d'analisi classica in quanto se risultano essere variabili le condizioni in campo alle quali si cerca di rispondere in maniera differenziata, è altrettanto dimostrato che gli effetti derivanti da interventi ad intensità variabile risultano differenti all'interno dell'appezzamento, sia intermini spaziali che temporali (Basso et al., 2003). Di conseguenza, il riscontro ambientale può essere tanto più positivo quanto maggiore è la capacità non solo di monitorare gli effetti di un trattamento ad intensità variabile, ma di approfondire la conoscenza sui molteplici legami relazionali che si instaurano trai numerosi fattori coinvolti, sia per quel che riguarda la coltura che per quanto concerne il terreno.

1.6.- L'Agricoltura di Precisione in Italia

La futura diffusione dell'Agricoltura di Precisione nel nostro Paese dipende quindi essenzialmente dall'andamento assunto dalle condizioni strutturali che caratterizzano il settore agricolo, ma soprattutto dal cambiamento di approccio che fino ad ora ha caratterizzato la maggior parte degli operatori, cosicché essa non venga recepita solamente come un'insieme di tecnologie, ma come un sistema completo ed integrato, la cui adozione richiede una generale revisione del sistema aziendale, al fine di poter adattare alle esigenze specifiche i principi che ne stanno alla base e che costituiscono i cardini delle strategie manageriali con cui gestire la specifica realtà aziendale. In quest'ottica la messa a punto di metodiche e procedure affidabili per l'implementazione di tale sistema rappresenta una fase cruciale per la diffusione delle soluzioni tecnologiche ormai

consolidate messe a punto nell'ambito dell'Agricoltura di Precisione, soprattutto se incentrate sull'importanza delle informazioni e della loro corretta gestione, intese elemento per la comprensione della variabilità presente in azienda e quindi come punto di partenza per l'ottimizzazione gestionale del processo di produzione. Non solo, la messa a punto di metodiche affidabili può rappresentare un contributo di notevole rilievo da parte del mondo della ricerca al tentativo di utilizzare soluzioni tecniche ad elevato contenuto tecnologico per dare non solo una risposta a quelle che sono le esigenze che l'azienda agricola interessata al mantenimento di una posizione competitiva sul mercato si trova a dover affrontare, ma anche per fornire al Legislatore degli elementi oggettivi con i quali valutare i risultati conseguiti a livello aziendale per quanto riguarda il miglioramento della prestazione ambientale dell'azienda agricola, al fine di una pianificazione di lungo periodo della politica economica indirizzata al settore agricolo.

2.- Obiettivi del lavoro di tesi

Il presente lavoro di tesi, di durata triennale (2002-2004), si è proposto di prendere in esame la struttura spaziale e la variabilità temporale esistenti a carico della produzione monitorata all'interno dell'appezzamento, al fine di mettere a punto una metodologia con la quale esaminare tale variabilità e tale da consentirne la gestione mediante l'individuazione di aree omogenee all'interno dell'appezzamento, nelle quali poter mettere in pratica degli interventi colturali ad intensità variabile. Sulla base delle considerazioni formulate in merito all'identificazione delle zone omogenee e dei successivi interventi agronomici ad intensità variabile sono stati poi presi in considerazione gli effetti di questi ultimi nel lungo periodo, sia dal punto di vista agronomico, e quindi del risultato produttivo ottenibile, ambientale, per il quale si sono prese in considerazione le perdite di azoto derivanti dalla concimazione con dosaggi di azoto differenti, che in termini economici, intesi come analisi dell'andamento nel lungo periodo del reddito lordo aziendale.
La fase di studio e le successive prove in campo sono stati condotti presso un azienda privata situata in Ariano nel Polesine, in provincia di Rovigo, Italia, con il coordinamento della fase sperimentale da parte del Dipartimento Territorio e Sistemi Agro-Forestali (Università di Padova) per la parte relativa alla meccanizzazione, e del Dipartimento di Produzioni Vegetali (Università della Basilicata), per la parte di agronomia e modellistica, al fine di poter integrare i vari aspetti relativi alle singole fasi dell'Agricoltura di Precisione e valutarne la effettiva applicabilità nelle condizioni sperimentali.
Sulla base di tali considerazioni, il presente elaborato è stato suddiviso in cinque distinte sezioni, ognuna relativa ad una fase del lavoro svolto e contenente alcuni dei principali obiettivi perseguiti nell'analisi condotta e riportante i risultati conseguiti, come schematizzato di seguito:

- ***Sezione 1***. L'analisi della variabilità spaziale presente all'interno dell'appezzamento in esame e riportata dalle mappe di produzione relative alla rotazione quinquennale eseguita dal 1998 al 2002 – *i.e.*, mais (*Zea mays,* L.), soia (*Glycine max,* L.) e frumento (*Triticum aestivum,* L.) – ha interessato la produzione e le principali proprietà statiche del suolo (contenuto percentuale di argilla, sabbia, limo e sostanza organica), al fine di ***(i)*** individuare la variabilità spaziale delle proprietà statiche del terreno all'interno dell'appezzamento, ***(ii)*** evidenziare l'eventuale influenza di queste ultime a carico della resa per ciascuna coltura,

(iii) identificare le zone omogenee da gestire in maniera uniforme all'interno dell'appezzamento sulla base della stabilità temporale della variabilità spaziale della resa.

- ***Sezione 2***. L'identificazione della stabilità temporale della variabilità spaziale è stata condotta nel lungo periodo (1989-2003) per ciascuna coltura facente parte della rotazione quinquennale esaminata – *i.e.*, mais (*Zea mays,* L.), soia (*Glycine max,* L.) e frumento (*Triticum aestivum,* L.) – mediante l'impiego di un apposito modello di simulazione, al fine di ***(i)*** verificare l'accuratezza del modello nel predire la resa per le singole colture, e ***(ii)*** individuare la variabilità spaziale e la varianza temporale esistenti a carico della resa all'interno dell'appezzamento, così da poter tener conto dell'influenza delle condizioni climatiche sulla stabilità del dato produttivo in fase di determinazione delle zone omogenee all'interno dell'appezzamento.

- ***Sezione 3***. Il confronto tra due tipologie di lavorazione conservativa del terreno, nello specifico la minima lavorazione (*MT* – Minimum Tillage, consistente in una lavorazione del terreno con erpice a dischi e nella successiva preparazione del letto di semina con erpice rotante) e la semina su sodo (*NT* – No-Tillage, consistente nella semina su sodo), rispetto alle pratiche conservative normalmente adottare in azienda (*CT* – Conventional Tillage), date dalla lavorazione primaria del terreno con ripuntatore ed erpice a dischi, seguita dalla preparazione del letto di semina con erpice rotante, è stato mirato in mais (*Zea mays,* L.) ***(i)*** all'analisi dell'influenza esercitata dai diversi sistemi di lavorazione del terreno a carico della densità e del contenuto d'acqua misurati lungo il profilo del suolo nella stagione colturale, ed ***(ii)*** alla valutazione del risultato produttivo ottenibile nel lungo periodo (1989-2002) mediante la differenziazione degli interventi di lavorazione all'interno delle aree omogenee, sulla base delle condizioni ambientali caratteristiche del campo sperimentale.

- ***Sezione 4***. Il confronto tra due tipologie di lavorazione conservativa del terreno, nello specifico la minima lavorazione (*MT* – Minimum Tillage, consistente in una lavorazione del terreno con erpice a dischi e nella successiva preparazione del letto di semina con erpice rotante) e la semina su sodo (*NT* – No-Tillage, consistente nella semina su sodo), rispetto alle pratiche conservative normalmente adottare in azienda (*CT* – Conventional Tillage), date dalla lavorazione primaria del terreno con ripuntatore ed erpice a dischi, seguita dalla

preparazione del letto di semina con erpice rotante, è stato mirato in mais (*Zea mays,* L.) ***(i)*** all'analisi delle principali voci di costo che l'azienda deve sostenere per poter adottare una strategia di lavorazione del terreno ad intensità variabile, e ***(ii)*** alla considerazione della convenienza economica all'adozione di una delle tecniche proposte sulla base dell'influenza delle condizioni climatiche sulla resa ottenibile nel lungo periodo (1989-2003) per ciascun sistema esaminato.

- ***Sezione 5.*** Il confronto tra quattro differenti dosi di fertilizzante azotato distribuito in copertura all'interno delle zone omogenee dell'appezzamento è stato eseguito mediante l'impiego di un modello di simulazione ed è stato finalizzato in mais (*Zea mays,* L.) ***(i)*** all'analisi degli effetti di lungo periodo dovuti alla distribuzione di dosi differenti sull'andamento della resa e le perdite di azoto lungo il profilo del terreno, sulla base delle condizioni sperimentali e dell'influenza delle condizioni climatiche, e ***(ii)*** all'individuazione della dose di azoto in grado di garantire una resa soddisfacente ed una riduzione delle perdite di azoto per lisciviazione.

– Sezione 1 –

Influenza della tessitura e del contenuto di sostanza organica del suolo sulla stabilità temporale della variabilità spaziale della resa in una rotazione di mais, soia e frumento

Riassunto

L'Agricoltura di Precisione rappresenta un'interessante prospettiva per l'azienda agricola in quanto in grado di consentire il conseguimento di benefici di natura economica ed ambientale attraverso l'ottimizzazione dell'efficienza degli interventi colturali eseguiti ad intensità variabile all'interno dell'appezzamento. A tale scopo, la comprensione e l'interpretazione della variabilità esistente all'interno dello stesso appezzamento, mirate all'individuazione della struttura spaziale e la variabilità temporale dei fattori limitanti la resa, rappresentano un aspetto di fondamentale importanza. L'obiettivo del lavoro presentato in questo capitolo è quello di indagare l'esistenza di variabilità spaziale a carico delle proprietà statiche del terreno, con particolare riferimento alla tessitura ed al contenuto di sostanza organica, in modo da evidenziare come queste influiscano sulla variabilità spaziale della resa, riportata nelle mappe di produzione collezionate nel corso di una rotazione quinquennale (1998-2002) di mais (*Zea mays*, L.), soia (*Glycine max*, L.) e frumento (*Triticum aestivum*, L.), presso un'azienda privata situata in provincia di Rovigo. Lo studio è stato mirato all'analisi dell'influenza esercitata sulla resa da parte delle proprietà statiche del suolo sia nel corso delle singole annate che nell'ambito dell'intera rotazione, analizzando la stabilità temporale della variabilità spaziale per le singole colture. In particolare, sono state studiate le relazioni (correlazione e regressione multipla) esistenti tra le singole proprietà statiche e la resa conseguita all'interno dell'appezzamento nelle diverse annate, con coefficienti di determinazione differenti a seconda della proprietà del suolo e della profondità investigate, ed un ruolo maggiore da parte del contenuto di sostanza organica e della percentuale di argilla misurate lungo l'intero profilo del suolo (0÷45 cm). Tale dato è risultato essere concorde con quanto evidenziato dall'analisi della corrispondenza tra le zone omogenee riportate nelle mappe di resa e le mappe del suolo, da cui si poteva ricavare come le aree aventi, in termini relativi, una resa più elevata nel corso degli anni avessero un tenore di argilla confrontabile ed un maggiore contenuto di sostanza organica.

Sulla base della variabilità spaziale e della varianza temporale manifestate dalla resa nel corso della rotazione, è stata calcolata la stabilità temporale quest'ultima all'interno dell'appezzamento, corrispondente all'esistenza di due zone stabili ad alta (*HS* area – aree aventi resa stabile ed elevata) ed a bassa (*LS* area – aree aventi resa stabile e bassa) resa, marcatamente distinte ed orientate secondo l'asse principale dell'appezzamento, accanto ad una zona perimetrale instabile (*U* area – area caratterizzata da un livello di resa variabile nel tempo), in genere coincidente con le aree vicine alle testate dell'appezzamento.

Le matrici di correlazione ed i modelli di regressione multipla hanno evidenziato come per tali aree i fattori maggiormente influenti sulla variabilità della resa fossero il contenuto di argilla e di sostanza organica misurati lungo il profilo del suolo, con una maggiore significatività statistica rispetto ai risultati ottenuti per l'intero appezzamento: a tal proposito però, tali fattori sono risultati particolarmente significativi in alcune aree e non in altre, con differenze apprezzabili per le diverse colture e le differenti annate colturali, a dimostrazione di come le proprietà statiche del suolo possano esercitare un'influenza non trascurabile, anche se non tale da spiegare completamente la variabilità della resa, dipendendo quest'ultima dalla presenza di altri fattori limitanti, ma soprattutto dalle loro molteplici interazioni. A tal proposito, l'impiego di modelli di simulazione può rappresentare un valido strumento nella comprensione della variabilità esistente all'interno dell'appezzamento.

***Parole chiave*:** proprietà statiche del suolo; resa; sostanza organica; stabilità temporale; tessitura; variabilità spaziale; zone omogenee.

Abbreviazioni: *HS* – area con resa alta e stabile nel tempo; *LS* – area con resa bassa e stabile nel tempo; *U* – area con resa alta o bassa ed instabile nel tempo.

– Section 1 –

Effects of soil texture and organic matter content on temporal stability of spatial pattern of yield in a maize-soybean-wheat rotation

Abstract

The effects of soil physical static properties – *i.e.*, soil texture and organic matter content – on spatial variability and temporal stability of yield were analysed in a maize-soybean-wheat rotation, taking into account the intra-year and the inter-years variability of yield. The inter-years variability on yield was due to the variability of the climatic conditions and the differences regarding agronomic practices adopted. After visually considering the spatial correspondence between soil properties pattern and area within field having different yield level, correlation matrix and multiple regression model were performed to investigate the within-field intra-year spatial variability. According to the analysis of correspondence, the organic matter and clay contents measured along soil profile (0÷45 cm) resulted generally positively and negatively correlated with the yield level (average values of Pearson coefficients were r = 0.33 ÷ 0.51 and r = -0.38 ÷ -0.39, respectively), even if this result varied by considering different crops and growing seasons. The analysis of homogeneous management area performed according to the stability criteria showed the presence of two area oriented according to the principal axle of the field, being stable but having different level of yield. For these area soil static physical properties resulted significantly influencing yield variability, as shown by greater values of coefficient of determination (e.g., R^2 = 0.62 for clay content), but only partly explained the variability of yield. In fact, a relationships between soil properties pattern and yield spatial variability was found but it was not sufficient to completely explain yield variability measured within field, probably because of the interrelationships among limiting factors, not accounted by classical analysis.

Keywords: management zones; soil static properties variability; yield spatial variability; yield temporal stability.

Abbreviations: *DUL* – drained upper limit; *HS* – area with high and stable yield over years; *LL* – lower limit; *LS* – area with low and stable yield over years; *OM* – organic matter; *S* – area with high and low stable yield; *U* – area with high or low yield over years**.**

1.1.- Introduction

Since the last 15 years, the adoption of strategies to manage field based on localized requirements or deficiencies within field is considered one of the most important and strategic factors to improve agricultural production sustainability while minimizing environmental impacts. In fact, a field has been traditionally considered as a homogeneous productive unit, despite to the spatial variability, and in general agronomic practices were uniformly adopted and usually based on the average yield level obtained with the precedents crops (Stafford et al., 1996), but the uniform applications of inputs is resulted inefficient for both the environmental impacts and the productive costs (Stafford, 1993).

In this framework, the technological advances of the last few years in agriculture, generally grouped on solutions proposed by Precision Agriculture, will play a crucial role in achieving these objectives and increasing the effectiveness of their applications (Earl et al., 2000; Sidney, 2002; Adamchuk et al., 2004). Precision Farming strategies in fact can be considered an opportunity for farmers to optimise crop production, but their potential economic (Schmerler and Basten**,** 1999; Godwin et al., 2003) and environmental (Thrikawala et al., 1999; Wang et al., 2003; Hamel et al., 2004) benefits are highly dependent on both the intensity and the magnitude of spatial variability of limiting factor affecting yield and on the accuracy of the understanding of its spatial structure within field (Pierce and Novak, 1999). Furthermore, the variability detected within field is composed by both a spatial pattern (Nielsen et al., 1999) and its stability over years (Stafford, 1999; Blackmore et al., 2003), with field having lower temporal variance which are characterised by the highest potential for measuring variability and the consequent adoption of variable rate management.

In particular, yield at any point in a field is a result of genetics, plant population, management and weather (Dobermann et al., 2003; Kravchenko et al., 2003), that set the yield potential for the particular season, and temporal integration of stresses that reduce yield from the potential during the season (Kravchenko and Bullock, 2000; Batchelor et al., 2002), the same limiting factors being characterised by different spatial and temporal pattern (Machado et al., 2000; Machado et al., 2002).

An appreciable influence on yield level within field is exerted by soil parameters in terms of both spatial and temporal variability. Soil properties can explain yield variability in some parts of the field but not in the remnants (Mallarino et al., 1999). Soil parameters are in fact characterised by a different spatial pattern, and can be classified – according to the semivariance values relieved after sampling (Cambardella et al., 1994) – as soil properties strongly spatially dependent (e.g. pH), moderately spatially dependent (e.g. phosphorus amount), and weakly spatially dependent or non-spatially correlated (e.g. soil strength) (Clark, 1996), depending on the spatial relationship existing between different measured values separated by a variable distance and taking into account also the relationship between values monitored at different depths along soil profile (López-Granados et al., 2002). As regards temporal stability of spatial variability of soil parameters, soil parameters can be divided on static properties, relating to physical properties which are affected by spatial variability but stable over time, as soil texture or pH, the latter resulting for example quite permanent between sampling dates, respect to the pattern of nutrients (Earl et al., 2003), and dynamic properties, being characterised by a temporal variability of spatial pattern both throughout and between different growing seasons (e.g. NO_3^-) (Cahn et al., 1994).
Furthermore, correlations relationship among soil properties within field have an important role on direct and indirect determination of yield level, but the pattern of soil properties may be different over time (Fleming et al., 2000), with a consequent different accuracy in their interpretation (Gupta et al., 1997). The effective water storage capacity and the amount of water available for plants (Cassel et al., 2000) for example are important soil parameters have to be considered in order to understand the spatial variability of yield, it being influenced by soil properties (e.g. texture, organic matter, etc.) (Kravchenko and Bullock, 2002), attributes (e.g. slope, erosion, etc.) (Jiang and Thelen, 2004; Bing and Farrell, 2004), and characteristics (e.g. soil compaction, etc.) (Kaspar et al., 2003), with an appreciable role of the interactions on soil parameters exerted by rainfall trend (Timlin et al., 1998) and tillage practices adopted in different growing seasons (da Silva et al., 2001). Because of the different characteristics of soil properties, the detailed analysis of their both spatial and temporal variability increases the understanding of these relationships (Ping et al., 2004), in order to differently manage the within-field variability, according to the general concept for which the variable management of the field increases while the spatial dependence and temporal stability increase.

The understanding of spatial structure of soil parameters is the first step required to identify factors limiting yield and define homogeneous manageable zones, intended as a sub-region of field that

expresses a homogeneous combination of yield limiting factors for which the effectively manageable different rate application of a specific crop input is appropriate, in order to achieve the benefits being attractive for farmers. The benefits effectiveness of implementing site-specific management in fact partially depends on the cost of identifying the magnitude of variability and the area that will be managed differently. At this regard, yield monitoring is widely used to recorder yield data, but the interpretation of the information contained in the yield map and the identification of the area characterised by a different yield level in comparison with the mean is not always so clear for farmers, especially by considering that different crops may have variable yield pattern within the same field and that temporal variance may override the spatial variability (Eghball and Varvel, 1997). Since the last ten years many different methods were developed to measure (McBratney and Pringle, 1999) and analyse the spatial variability of soil and the relationship with yield (Lark, 2001; Zhang and Han, 2002) and to increase the comprehension of the temporal stability of yield pattern (Blackmore, 2000; Blackmore et al., 2003), with the consequence that the analysis of a multiple-year yield map may reduce the variability over years (Joernsgaard and Halmoe, 2003), whilst 5-year (±2 years) satellite imagines were found sufficient to estimate stable yield zones with the same crop (Boydell and McBratney, 2002). The utilization of informative geographical system for interpreting variability by overlying the different yield map and soil properties layers amplified the potential understanding of the presence of yield limiting factors and the within-field spatial variability and its temporal stability (Bakhsh et al., 2000; Earl et al., 2000).
But the yield static limiting factors are stable through and between different growing seasons? and the identified management zones are really stable or we would expect some differences over years?

The main objectives of this study are (***i***) to investigate the spatial variability of soil static physical properties, (***ii***) to examine the intra-year and inter-years influence of spatial variability of soil static physical properties on yield pattern, and (***iii***) to identify stable and unstable management zones within field in a 5-year crop rotation (*Zea mays,* L., *Glycine max,* L., *Triticum aestivum,* L.).

1.2.- Material and methods

1.2.1.- Site description and climatic data

The data for this research were obtained from a 8-ha flat field, situated near Rovigo (44° 4’ 12” N, 11° 47’ 22” E, 6 m a.s.l.), NE Italy, during a 5-year rotation (1998-2002). Soil was clay, according to the USDA particles-size distribution limits. The climate of the area (data relating to the 1989-2002 period) is characterised by an annual average rainfall of 700 mm, distributed mostly in Autumn and Spring. The annual average temperature is 13.3 °C, with a monthly maximum of 23.5 °C in July and a minimum of 3.2 °C in January (Figure 1).

1.2.2.- Agronomic management

The crop rotation adopted consisted on maize (*Zea mays*, L.) in 1998 and 2000, soybean (*Glycine max*, L.) in 1999 and in 2002, and wheat (*Triticum aestivum*, L.) in 2001. The farming system adopted during the crop rotation generally consisted on reducing tillage intensity according to soil characteristics and crop species and on adopting integrated strategies in the weed control. The specific agronomic practices adopted during the crop rotation are reported below for each crop.

Maize

In 1998 soil was tilled in August with a subsoiler and a rear mounted hitch disk harrow at a depth of 35 cm and 15 cm respectively, in order to incorporate the organic fertilizer (having a total of 112 N kg ha^{-1}, 37 P kg ha^{-1} and 150 kg ha^{-1}), applied with a manure spreader, whilst in 2000 tillage practices consisted of subsoiling and disk harrowing in October. Seedbed preparation was performed in both year by using a S-tines harrow in January and in March, whilst only in 2000 rotary harrowing was performed in March. The *Pregia* (in 1998) and *PR34F02* (in 2000) cultivars were sown with a planter (0.75 cm rows) in March 23 and in March 17, respectively. The seeding rate consisted of 28.4 kg ha^{-1} and 37.3 kg ha^{-1} of seeds (8.1 plants m^{-2}) in 1998 and 2000, respectively.

In 1998 mineral fertilisers (57 P kg ha^{-1} and 63 K kg ha^{-1}) were distributed before seedbed preparation with a double spinner disk, and after sowing 185 N kg ha^{-1} was applied in May with a pneumatic distributor. In 2000 44 P kg ha^{-1} was distributed before tillage with a double spinner

disk, whilst 159 N kg ha^{-1} was applied in April 21 (85 N kg ha^{-1}) and in May 11 (74 N kg ha^{-1}), with a pneumatic distributor. In both years weed control was performed through the combination of herbicide application, distributed with a field sprayer in April and in May, and row crop cultivation by using a weeder in May. Harvest was carried out in September 18 and in August 23 in 1998 and 2000 respectively.

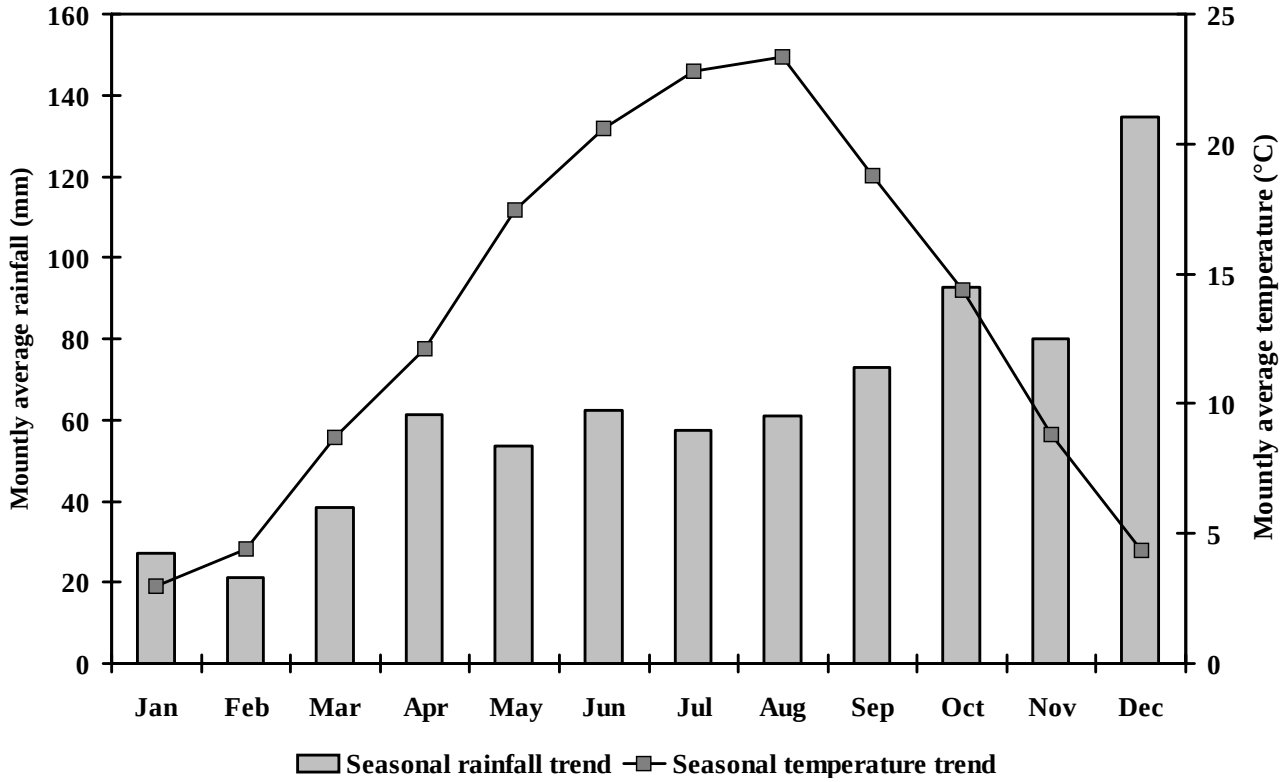

Figure 1.- Monthly total rainfall (mm) and average temperature (T °C) long-term trend (1989-2002) in the area where the study was carried out.

Soybean

In 1999 soil tillage was performed with a subsoiler in September 19 and with a rear mounted hitch disk harrow in November 24, at a depth of 35 cm and 15 cm respectively, whilst in 2002 subsoiling and disk harrowing were performed in July 2 and September 21, respectively. Only in 2002 S-tines harrow was used in November 17. In both years seedbed preparation was performed in March with rotary hoe to obtained weeds emergence. Their suppression was then achieved with herbicide in April in 1999, whilst in 2002 the same purpose was attained with a twice use of rotary hoe in April and May. The *Loria* (in 1999) and *Bio-Nikir* (in 2002) cultivars were sown with a planter (0.75 cm

rows) in April 26 and in May 30, in 1999 and 2002 respectively. The seeding rate consisted of 59 kg ha^{-1} (1999) and 49.5 kg ha^{-1} (2002) of seeds (30-35 plants m^{-2}). Only in 1999, 50 P kg ha^{-1} and 50 K kg ha^{-1} were applied in November with a double spinner disk. Weed control was performed in 1999 through the combination of herbicide application (in April 28, in May 25 and in June 18) and row crop cultivation, by using a weeder for two times in May, whilst in 2002 it was achieved by using a tined weeder and a weeder in June and July. Harvest was carried out in September 27 and in October 10 in 1999 and 2002 respectively.

W*heat*

Seedbed was directly prepared on September 2000 with a rear mounted disk harrow at a depth of 15 cm. The *Amarok* cultivar was sown with a grain drill on October 23, with a 204 kg ha^{-1} seeding rate (approximately 450 seeds m^{-2}). The field was fertilised before sowing with 50 P kg ha^{-1}, whilst N fertilisers was applied after sowing (45 kg ha^{-1} in February 17, 45 kg ha^{-1} in March 12, and 136 kg ha^{-1} in April at the beginning) with a double spinner disk. Weed control was achieved by herbicide application in Marc 19 with a field sprayer. Harvest was carried out in June 25.

For each crop cultivars sown were chosen according to the best genetic characteristic for the environmental conditions of the experimental area.

1.2.3.- Yield monitoring

Yield monitor data were recorded by using a *New Holland TX 64* combine equipped with a yield monitor system (grain mass flow and moisture sensors) and the site coordinates for each yield measurement were determined with a differentially-corrected (*OMNISTAR* signal) *Trimble 132* receiver. The *SMS software version 3.0*^{TM} (*AgLeader Tecnology, Inc*.) was used to read the row yield data (expressed at 14% dried matter).

1.2.4.- Field measurements

The soil properties – *i.e.*, soil texture and organic matter (*OM*) – were measured by collecting soil samples at 36 locations randomly displaced within field (Figure 2). An undisturbed soil core sampler (*Eijkelkamp*, Glesbeek, NL) was used to collect samples for determining texture and organic matter of soil. The hydrometer method was used to determine the textural characteristics of the soil. The organic matter content was calculated by using the Walkley-Black method (Walkley and Black, 1934). Soil water limits (DUL – drained upper limit and LL – lower limit) were calculated using the procedure suggested by Ritchie et al. (1999).

All the measurements were made at three soil depth layers (0-15 cm, 15-30 cm, 30-45 cm), and a portable *Trimble 132* receiver was used to localise each point within field.

1.2.5.- Spatial analysis of yield data and soil properties

For yield data and for soil properties semivariograms were created by using *GS+* software *version 3.1*^{TM} (*Gamma Design Software*, 1999), and the best fit model was selected based on model fitness to the data. Yield maps were then visually evaluated , in order to investigate the correspondence of yield and soil properties spatial pattern within field.

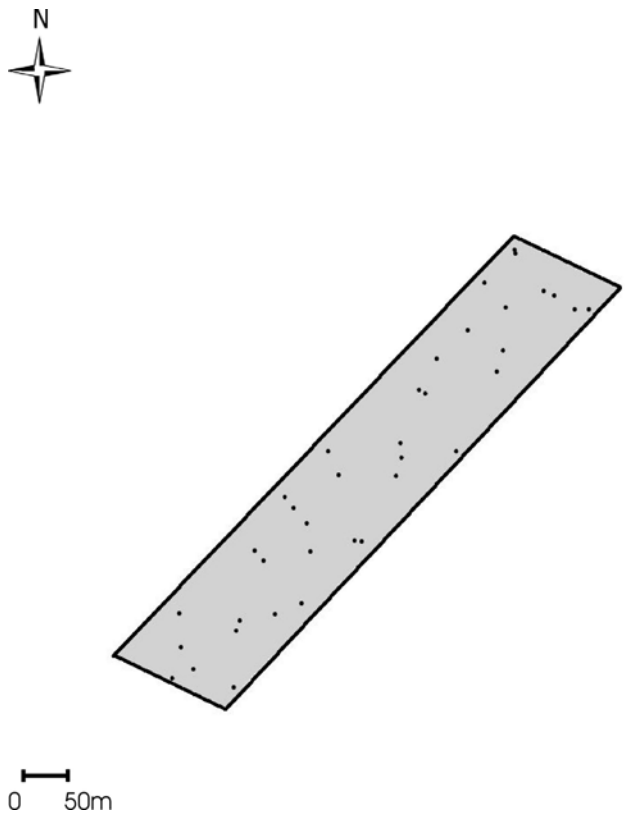

Figure 2.- Sampling scheme adopted for the measurement conducted within field.

1.2.6.- Criteria for identification of management zones

The identification of homogeneous management zones was carried out by considering the level of yield obtained within field and the degree of stability characterising its variability over years, according to the suggestions of Blackmore (2000). In particular, the spatial variability of yield was analysed in *ArcView version 3.2*^{TM} (*ESRI*, 1999), by calculating for each year the relative percentage difference of yield crop from the average yield level obtained within field at each point mapped, according to the following equation (eq.1):

$$\bar{y}_i = \left[1/n * \sum_{k=1}^{n} y_{i_k}\right] \qquad \text{(eq.1)}$$

where:

$\bar{y}_i$ = mean of the y_i values;

y_i = interpolated yield value (t ha^{-1}) at location *i*;

n = number of years.

The final map reporting the area with different yield was elaborated by overlying the single map reporting the relative percentage difference of yield. Different zones were then classified in relation to a relative percentage difference threshold of 100%: the zones for which this value was greater were classified as area with high yield, whilst the zones for which this value was lower were defined as area with low yield.

The temporal variability of yield pattern over years, expressed as degree of stability, was calculated as temporal variance (yield value recorded at each point mapped within field minus the field mean) over years, according to the method proposed by Blackmore et al. (2003), in order to overcome the limits of the coefficient of variation (Pringle et al., 2003), through the following equation (eq.2):

$$\sigma_i^2 = 1/n * \sum_{k=89}^{k=02} (y_{i,k} - \bar{y}_i)^2 \qquad \text{(eq. 2)}$$

where:

σ_i^2 = the temporal variance at location *i*;

$\bar{y}_k$ = the average yield at year *k*;

y_i = the yield value at location *i* at year *k*;

k = the year over the 1998-2002 period;

n = number of years.

The temporal variance may considerably vary within field by slightly changing the threshold used to determine stable area, as reported by Blackmore: in this study, a limit value of 1 or 2 t ha^{-1} was considered too low for identifying homogeneous area within field practically manageable by farmer, because of the great number of identified zones each of them having a too low surface. Consequently a 2.5 t ha^{-1} threshold was considered reasonable for the studied conditions in order to identify homogeneous sub-regions of field.

By overlying the maps of both relative percentage difference and temporal variance, area characterised by stability of yield and having high yield over years were defined as *HS* area (*HS* – area with high and stable yield over years), whilst area characterised by stability of yield level and having low yield were defined as *LS* area (*LS* – area with low and stable yield over years) respectively. An area characterised by instability and having high or low yield level over years was identified as unstable and defined as *U* area (*U* – area with high or low yield over years), in comparison with the stable area defined as *S* area *(S* – area with stable yield, without considering the yield level attained over years), and obtained by merging the *HS* and the *LS* area.

1.2.7.- Statistical analysis

The statistical differences for yield data of the same crop during the crop rotation were considered. The relationship among all the measured soil physical properties and yield data was investigated for each year and for single crop during the 5-year crop rotation, by developing a correlation matrix and a multiple regression analysis (stepwise forward procedure). The last was performed with a criteria of probability (P) equal to 0.05 for variable addition, for identifying the soil properties influences on yield level. Correlation matrix (*PROC CORR*) and stepwise analyses (*PROC STEPWISE*) were developed in *SAS version 8.0* (*SAS Institute Inc*., 1999). Statistical analysis were developed both for

the complete field and within the homogeneous area identified according to the temporal stability of yield.

1.3.- Results and discussion

1.3.1.- Yield monitoring

Yield pattern resulted variable between different growing seasons for the same crop, attaining an appreciable inter-years variability (Table 1), whilst intra-year spatial variability was detected within field, as shown by the yield maps based on the data collected with the yield monitor system and downloaded at the farmer's PC (Figure 3).

Table 1.- Descriptive statistics for yield row data monitored during the crop rotation (1998-2002). Different letters indicate significant differences between different growing seasons for the same crop (*LSD* test, P≤0.05).

Statistics	**Grain yield (t ha^{-1})**				
	1998	1999	2000	2001	2002
	maize	soybean	maize	wheat	soybean
Mean	11.27 a	4.82 a	9.59 b	7.44	3.84 b
Mode	12.60	4.90	8.13	6.17	3.78
Median	11.81	4.93	9.63	7.45	3.83
standard deviation	± 2.61	± 0.60	± 2.01	± 1.27	± 0.45
Kurtosis	1.29	5.19	1.78	6.30	12.34
Skewness	-0.51	-0.14	0.73	1.01	0.13
Minimum	0.78	0.49	0.84	0.67	0.53
first quartile (Q_1)	10.41	4.64	8.44	6.78	3.69
third quartile (Q_3)	12.91	5.16	11.11	8.23	3.98
Maximum	24.42	8.26	21.41	18.95	6.78
coefficient of variation (*CV*; %)	23.11	12.54	20.95	17.06	11.69

The mean yield was statistically different between growing seasons, and in particular for maize in 2000 the average yield value was 15% (1.68 t ha^{-1}) lower than that monitored in 1998, whilst for soybean in 2002 the average yield obtained was 20% (0.98 t ha^{-1}) lower in comparison with that monitored in 1999. For wheat, the average production monitored within field was slightly lower than the average value generally obtained by the farm, according to the environmental conditions of

the area. The intra-year variations of yield was appreciable, as indicated by values of the range of yield – maximum value minus minimum value of yield – and the coefficient of variation, especially for maize respect to the others crops, generally ranging from a minimum of 11.69 % for soybean in 1999 to a maximum of 23.11 % for maize in 1999, and having over years an average value of 17.07 %, according to that suggested by literature, both for large (Jaynes and Colvin, 1997; Bjarne and Steffen, 2003) and small field scale (Yamagishi et al., 2003).

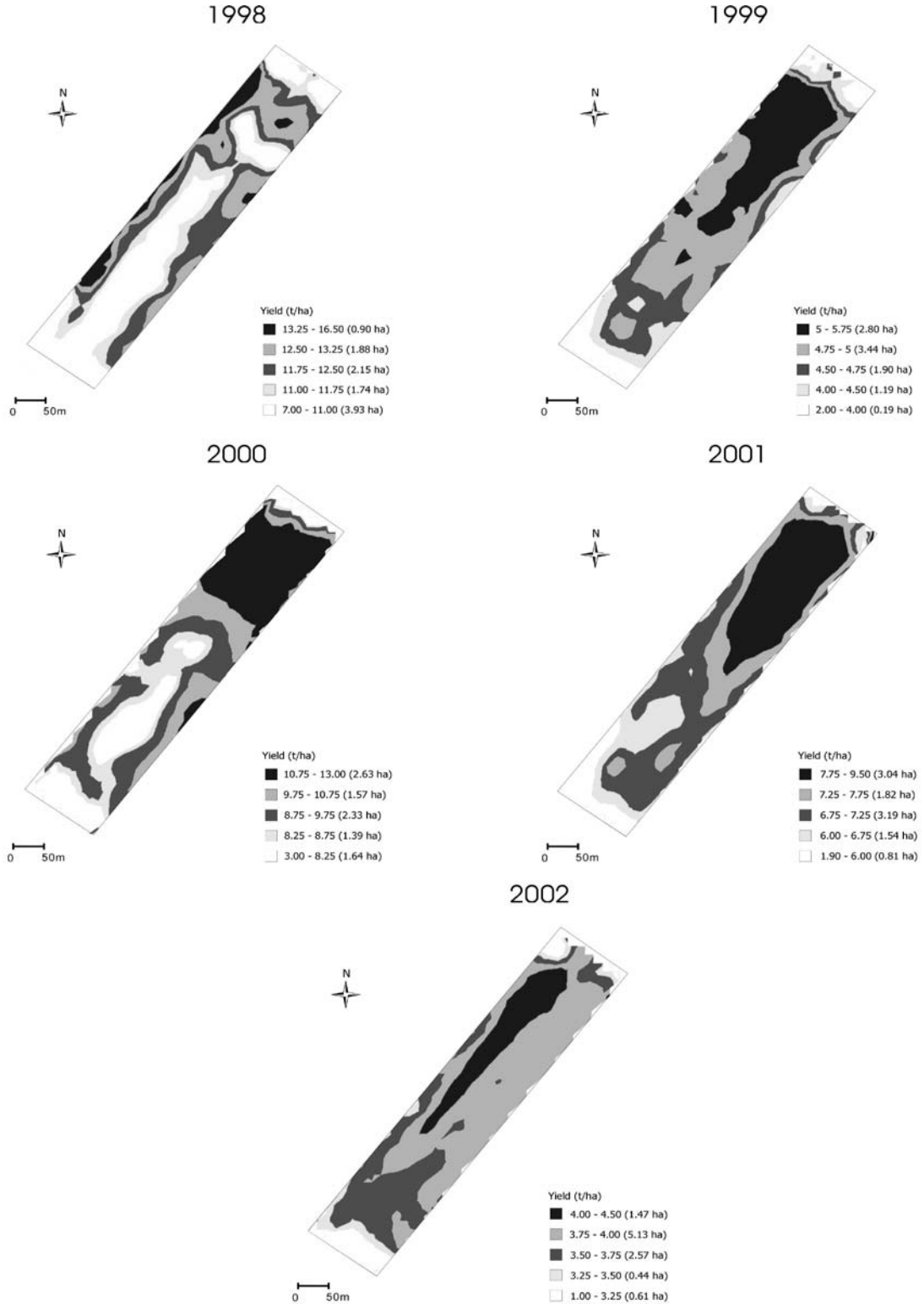

Figure 3.- Yield maps obtained for each crop during the trials period by using the row data collected within field (1998 and 2002: maize; 1999 and 2001: soybean; 2002: wheat).

The yield for maize has a greater range of distribution in both years, with a higher percentage frequency for classes having high yield values in 1998 respect to the distribution detected in 2000, as revealed by the skewness index, which assumed a negative and a positive value in the first and in the second year respectively. In 1998 in fact, the average yield was greater and values were more concentrated in the higher classes of frequency distribution than that collected in 2000 (Figure 4), because of the more homogeneous production obtained within field.

The yield for soybean has an appreciably lower range of variation, especially in 2002, with yield values concentrated in a few classes of percentage frequency, and the shape of frequency distributions indicate a more homogeneous yield level within field in 2002 respect to the data obtained in 1999 growing season, for which the differences of production affecting yield level were significantly marked between different area of field. Par consequence, the frequency distribution of yield was particularly asymmetric in the second year, even if in both growing seasons it was positively skewed (Figure 4).

For wheat, the percentage frequency of distribution has a more regular shape, yield data being homogeneously distributed over different classes, because of the presence within field of area having appreciably greater or lower yield level respect to the average value obtained for the complete field. The frequency distribution in fact was positively skewed, with more frequent values concentrated around the mean class (Figure 4).

The differences of production detected within field for each crop revealed inter- and intra- year variation on yield pattern, and the raisons were probably due to the interaction between the factors – i.e. soil static properties – limiting the yield production between different years and their spatial pattern during the same growing season. In particular, for maize in 1998 yield was greater than that obtained in 2000 because of the greater amount of organic nitrogen distributed with organic manner, and this partially masked the differences of productivity existing within field, as indicated by the correlation matrix performed for yield values (Table 2), whilst climatic conditions could have limited in different way the potential yield level, as indicated by soybean patterns.

The differences detected on yield level for different area of field during the single growing season are evidenced in Figure 5, reporting yield maps having the same classes distribution of values (expressed in t ha^{-1}) for the same crop.

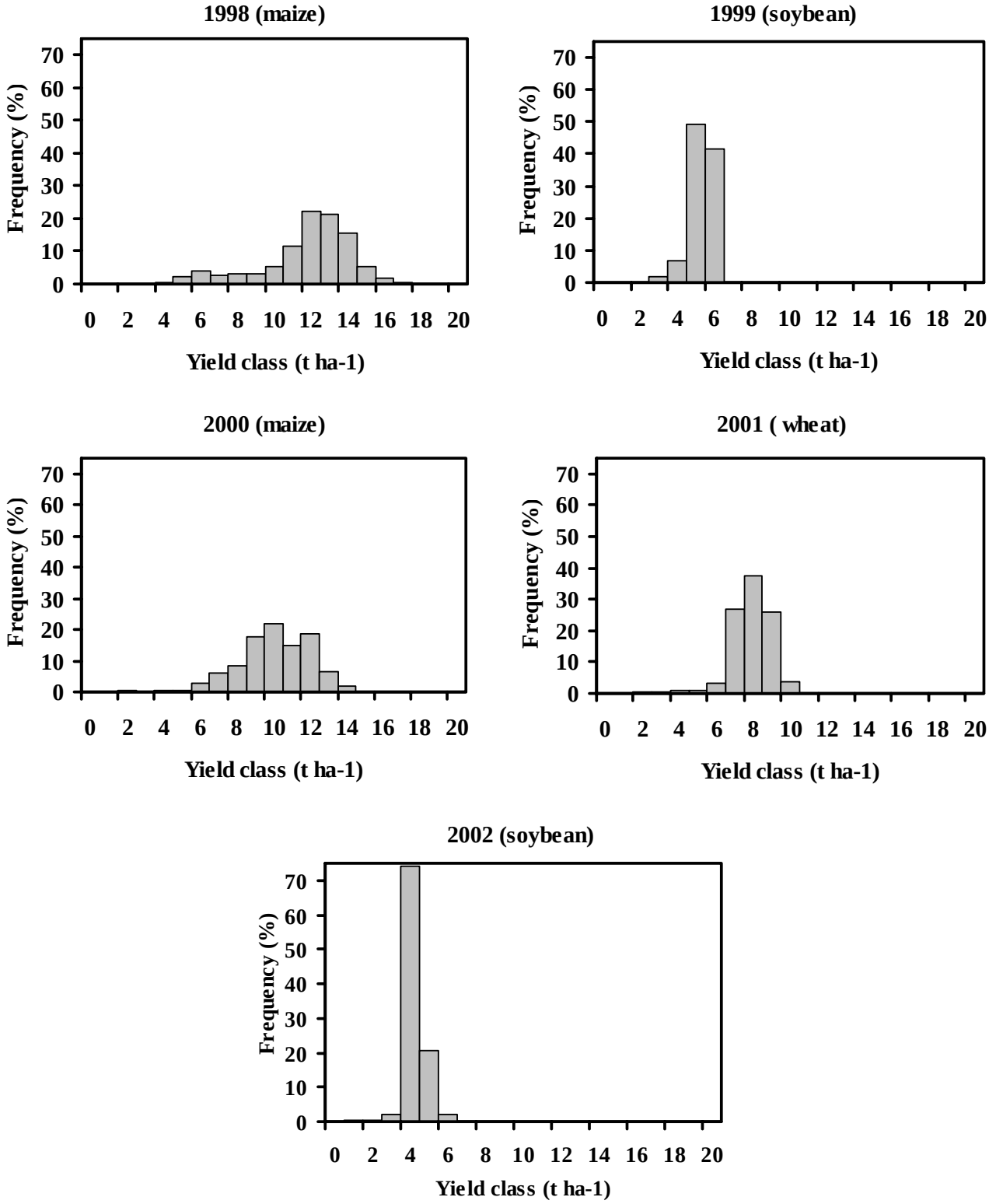

Figure 4.- Frequency distribution of yield values for the 1998-2002 period.

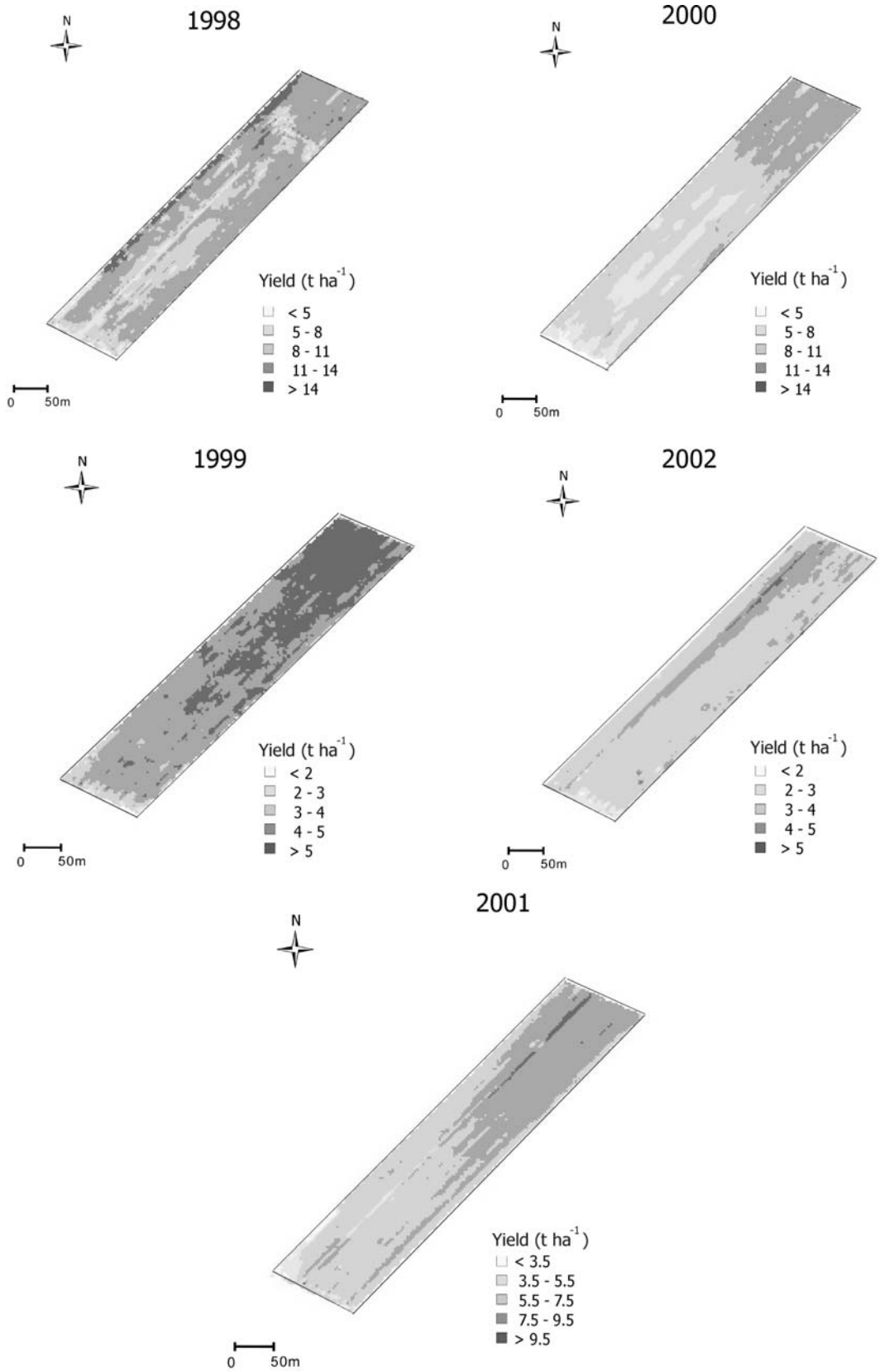

Figure 5.- Yield maps reporting the yield pattern obtained over different growing seasons for the same crop (1998 and 2000: maize; 1999 and 2001: soybean; 2002: wheat).

The relationship among all the yield data during the crop rotation over the years showed a general statistically significant correlation (P<0.01), confirming the existence of different area within field having yield values greater or lower than average in different growing seasons, even if this pattern was not so clear for all crop, as evidenced by the absence of correlations for soybean data, probably due to the action of others limiting factors.

Table 2.- Correlation matrix of yield over the years of crop rotation for the complete field (** = significant at P< 0.01 level of significance; *** = significant at P< 0.001 level of significance).

Years	**1998**	**1999**	**2000**	**2001**	**2002**
1998	1.00	0.29	0.53**	0.54**	0.34
1999		1.00	0.53**	0.51**	0.19
2000			1.00	0.64***	0.53**
2001				1.00	0.51**
2002					1.00

1.3.2.- Climatic data

In regard to the study period, the climatic conditions exerted an appreciable influence on inter-years yield variability in terms of both daily rainfall (mm) and temperature (°C) referred to the complete year, and particularly as regard the growing seasons.

In particular, in relation to the inter-years variability registered for maize, the total annual rainfall ws lower both in 1998 (663 mm) and in 2000 (600 mm) than that referring to the 1989-2002 period (Figure 8), but considering only the monthly rainfall occurred during the growing season (from the date of sowing until that of harvesting), in 1998 it was greater (417 mm) than in 2000 (392 mm) and concentrated particularly in the first part of the period, whilst in 2002 the rainfall was slightly relatively greater during the flowering time, even if the difference between years resulted not statistically significant, except for the data relating to September (Figure 6).

As regards temperature, the annual average value agreed with that relating to the 1989-2002 period, and in particular the average value registered during the growing season (from the date of sowing until that of harvesting) was lower in 1998 (17.6 °C) than in 2000 (18.4 °C), with statistically significant differences between the two years in the first part of the season (April, May and June).

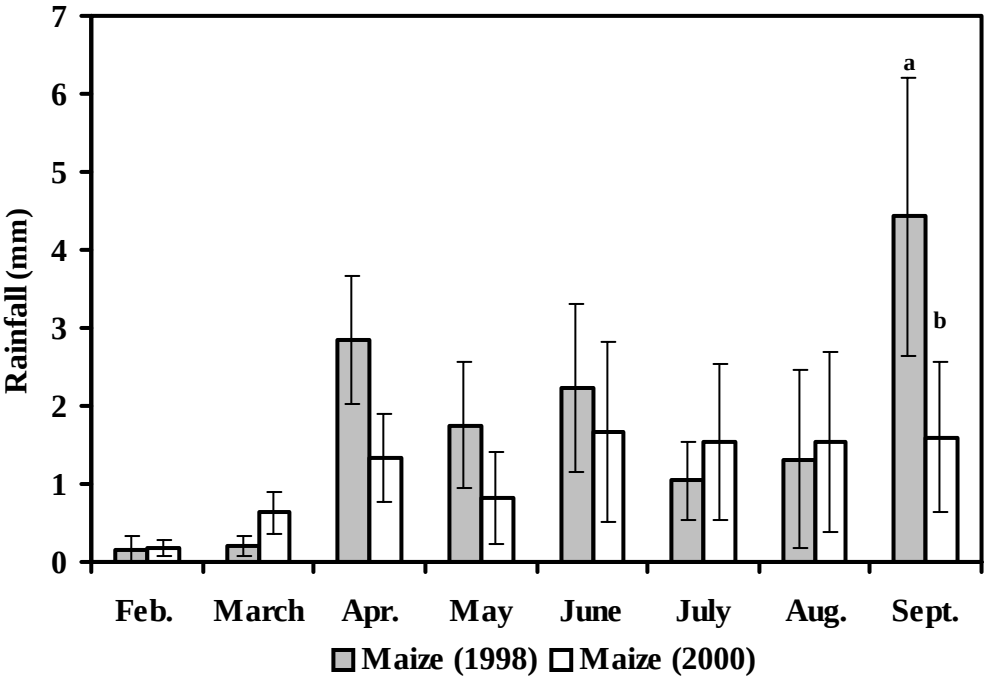

Figure 6.- Average monthly rainfall trend (expressed in mm) measured over maize growing seasons. Vertical bars refer to the standard error of rainfall data registered for single month. Different letters indicate statistically significant differences on rainfall for the same month between different years (LSD test, P≤0.05).

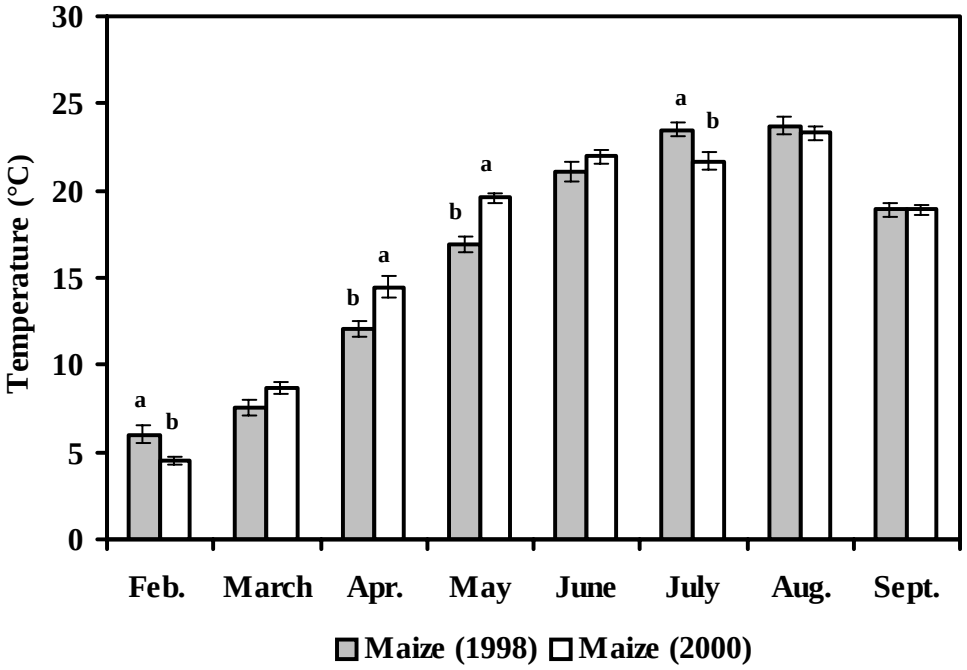

Figure 7.- Average monthly temperature trend (expressed in °C) measured over maize growing seasons. Vertical bars refer to the standard error of temperature values registered for single month. Different letters indicate statistically significant differences on temperature for the same month between different years (*LSD* test, P≤0.05).

The slightly greater rainfall and the lower temperature occurred in 1998 than in 2000, summed to a month longer growing season in the first case, probably limited the yield response in 2000 respect to the 1998 (Figure 7).

As regards the inter-years variability registered for soybean, the total annual rainfall was greater in both years respect to the that referring to the 1989-2002 period (Figure 8), and in particular the annual rainfall was higher in 2002 (870 mm) than in 1999 (800 mm), even if this difference resulted not statistically significant during the growing season. The latter has a different timeframe between the two years, because of the delayed sowing occurred in 2002 (May) respect to the compared growing season (April), a difference that remained constant for all the season, with harvest carried out in September and in October in 1999 and in 2002 respectively, also because of the greater amount of rainfall occurred in September 2002. In fact, during the growing season (from the date of sowing until that of harvesting) the total rainfall was 100 mm greater in 2002 (452 mm) than in 1999 (350 mm), bat the difference regarded above all the month of September (Figure 9).

As regards temperature, the monthly average temperature was not statistically significantly different between the years (Figure 10), with an average lower temperature during the growing season (from the date of sowing until that of harvesting) in 1999 (19.7 °C) than 2002 (21.8°C), except for June and September, for which the difference between seasons was statistically appreciable: in particular, during the latter, being the growing season not completed, the average temperature was lower.

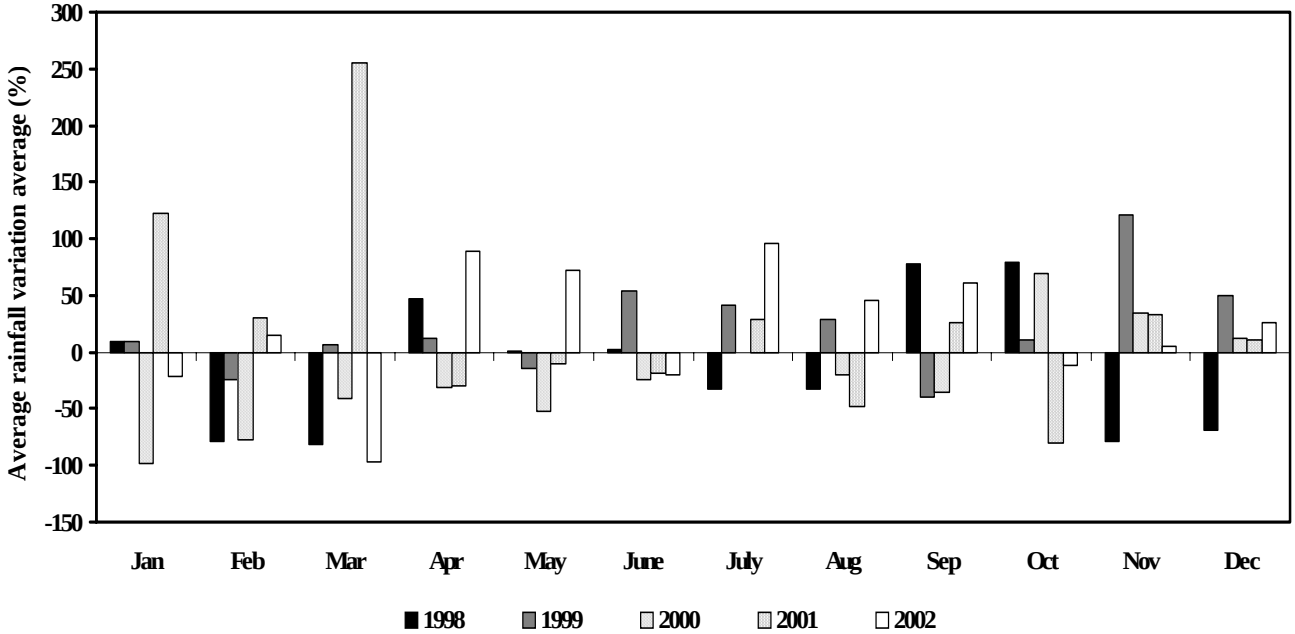

Figure 8.- Relative variation of rainfall for the single years of crop rotation, expressed as percentage average deviation respect to the values referring to the 1989-2002 period.

The slightly lower temperature measured in 1999 and the more favourable rainfall pattern during the growing season (e.g., rainfall measured in June), were probably the causes for a greater yield respect to that obtained in 2002, for which the delayed sowing and the quite appreciable greater within-season variation of the rainfall patter, particularly in the last part of the growing season, probably more penalised the yield, also because of the interrelationships existing among these conditions.

For wheat, the 2001 was characterised by a lower annual rainfall (550 mm) and a greater annual average temperature (15°C), due to the mild temperature occurred in Winter and the high temperature during Summer, respect to the 1989-2002 period, and this probably represented a limiting factor to the yield production respect the average conditions of the area.

1.3.3.- Spatial analysis

The intra-year yield variability was visually analysed by considering the correspondence of area within field reported by maps and having comparable soil physical static properties and attaining a similar level of yield, taking into account the influence exerted by soil properties (Table 3) on hydraulic water limits within field, referred to Mach, which approximately corresponds to the usual sowing time for maize and soybean and to the beginning erect growth for wheat (Figure 11).

Table 3.- Average soil properties and derived hydraulic water limits measured along soil profile.

Investigated layers	**Clay** (%)	**Sand** (%)	**Loam** (%)	**OM** (%)	**LL** ($cm^3\ cm^{-3}$)	**DUL** ($cm^3\ cm^{-3}$)
0÷15 cm	41 ± 3.6	20 ± 8.3	39 ± 6.5	2.80 ± 1.1	0.254 ± 0.04	0.108 ± 0.04
15÷30 cm	40 ± 4.1	20 ± 8.1	40 ± 6.1	2.60 ± 1.3	0.260 ± 0.04	0.115 ± 0.04
30÷45 cm	42 ± 5.1	18 ± 8.6	40 ± 6.5	2.46 ± 1.3	0.247 ± 0.05	0.103 ± 0.05

The field was approximately divided in two zones, oriented according to the principle axle of the field and characterized by different soil static physical properties along the profile – sand and clay content – whilst for the organic matter content the it resulted clearly divided into two zones, having a content of organic matter greater or lower than 3 %. According to the correspondence analysis, these area resulted displaced within field in correspondence of the area having relatively greater (organic matter) or relatively lower (clay content) yield, being localised in the upper part of the field (visually evaluation). As regards the available water content, it being correlated to the soil texture and organic matter content, the field resulted divided in area having different percentage moisture at the same time, and the area having the greatest available water content corresponded to the area characterized by a greater productivity over years.

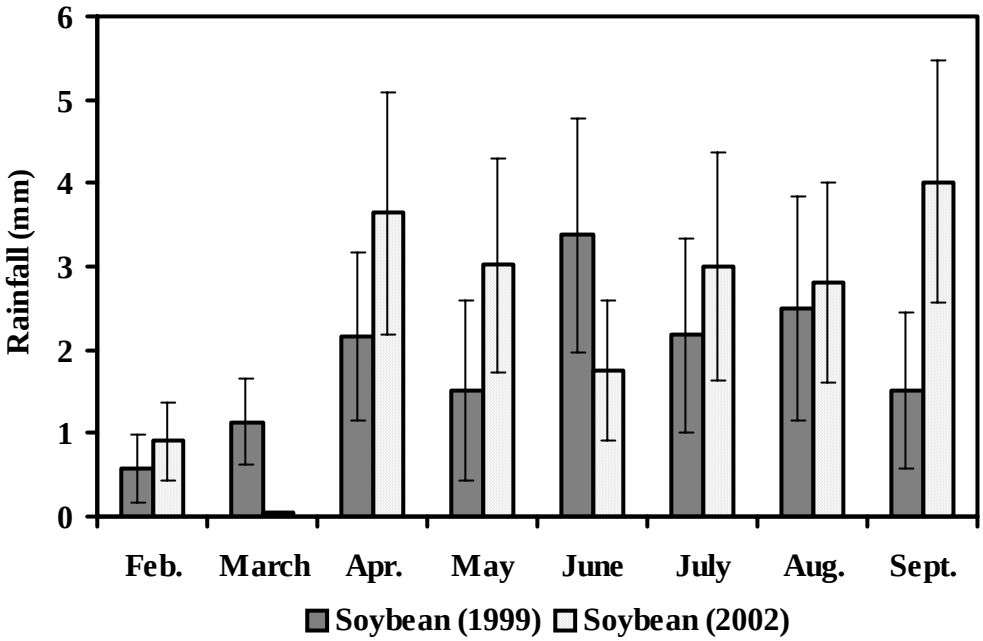

Figure 9.- Average monthly rainfall trend (expressed in mm) measured over soybean growing seasons. Vertical bars refer to the standard error of rainfall data registered for single month.

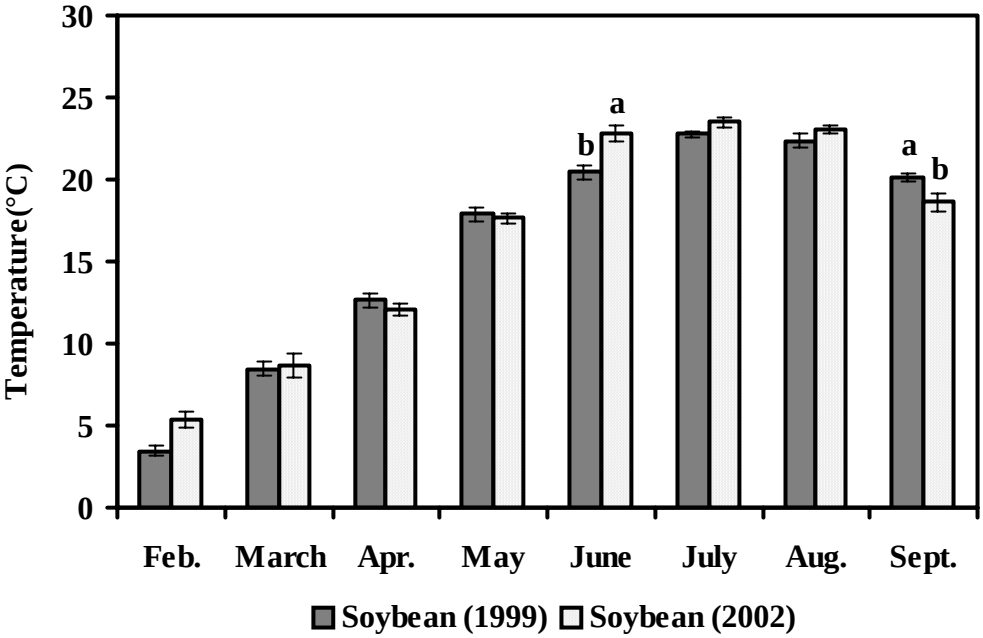

Figure 10.- Average monthly temperature trend (expressed in °C) measured over soybean growing seasons. Vertical bars refer to the standard error of temperature values registered for single month. Different letters indicate statistically significant differences on temperature for the same month between different years (*LSD* test, P≤0.05).

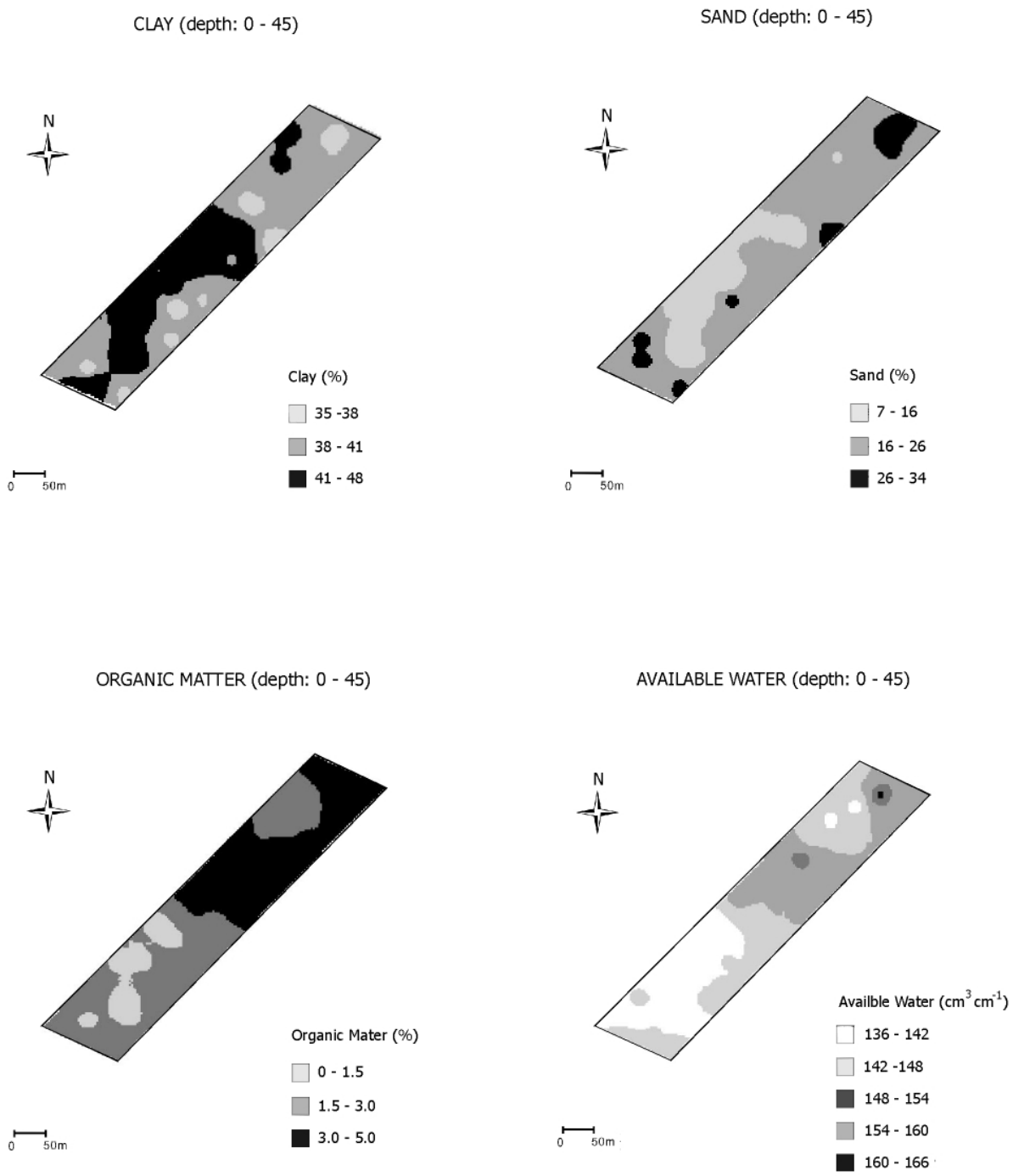

Figure 11.- Soil static physical properties and available water content maps reporting the different values measured within field along the soil profile (0÷45 cm).

1.3.4.- Semivariograms

The relationship between the yield pattern and the soil spatial variability was partially confirmed by the analysis of isotropic semivariograms. For yield the isotropic semivariograms elaborated using the maximum active lag distance (600 m), approximately identified with the length of the field, showed the existence of a spatial structure for yield within field. In particular the semivariograms shape was different for different season, it revealing a partial season influence, but in all year semivariograms showed the presence of "hole" effects, occurring approximately at 120 m interval distance, and it revealed that variance between neighbour mapped locations had lower variance than values measured for yield mapped at greater distance (Figure 12). The same analysis performed by adopting the minimum active lag distance (100 m), amplified the pattern having a spatial structure for each year examined (Figure 13), yield having a range variable from a minimum of 16.2 m to a maximum of 73.2 m for soybean and maize cultivated in 2002 and 1998 respectively, and the exponential model generally fitted the semivariance – except for maize in 2000, with an average range of 50 m (Table 4), and an average value of R^2 greater than 0.80 during the crop rotation. The nugget effect explained approximately the 30 % of semivariance, corresponding to a variance of 0.30 t ha^{-1}, due to the measurements errors, except for maize in 2000 for which the noise was not detected. The level of variation for semivariance – sill values – was quite similar over years, ranging from a minimum of 0.58 t ha^{-1} and a maximum of 0.80 t ha^{-1} for maize in 2000 and 1998 respectively, with an average semivariance of 0.71 t ha^{-1} over years. The values of sill parameter, being appreciably high and revealing the presence of within-field spatial variability for all crops, could justify the adoption of practices at variable intensity, according to that reported by Taylor et al. (2003).

Table 4.- Principal parameters related to isotropic semivariograms of yield, having a 100 m active lag distance.

Crop	Year	Range (m)	Nugget (C_0)	Sill (C_0+C)	C/(C_0+C)	Isotropic model	R^2
maize	1998	73.20	0.34	0.80	0.58	exponential	0.95
	2000	24.10	0.00	0.58	1.00	spherical	0.81
soybean	1999	72.00	0.33	0.79	0.58	exponential	0.95
	2002	16.20	0.21	0.74	0.72	exponential	0.53
wheat	2001	64.80	0.32	0.64	0.50	exponential	0.92

The isotropic semivariograms elaborated for soil physical static properties along the soil profile revealed the presence of a spatial structure within field at the minimum active lag distance used

(200 m) (Figure 13), with an average range of 68 m for soil properties, according to that suggested by literature (McBratney and Pringle, 1999).

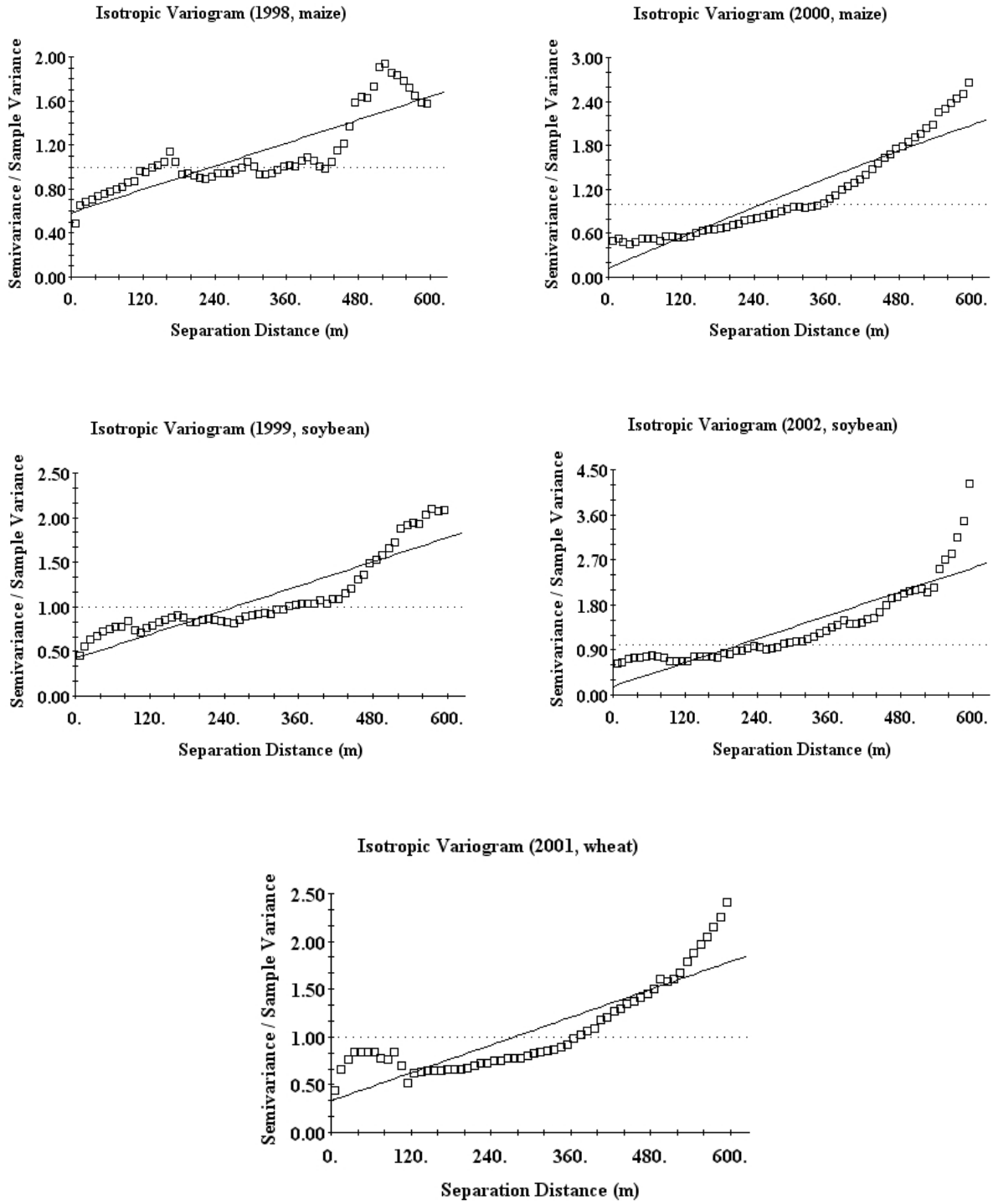

Figura 12.- Isotropic semivariograms of yield obtained with all yield data monitored within field during the crop rotation (1998-2002) and taking into account the maximum lag active distance, approximately corresponding to the length of the field (600 m).

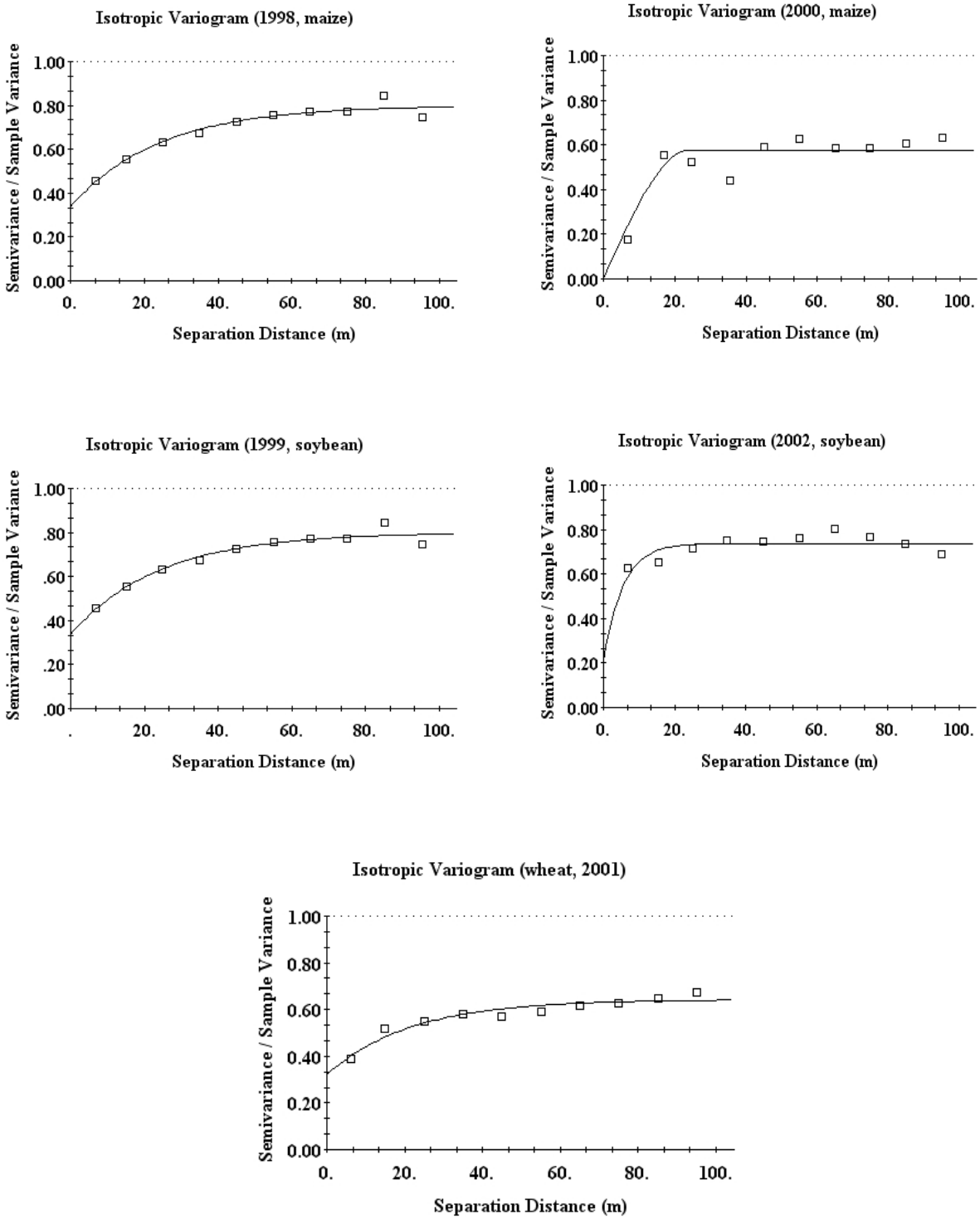

Figura 13.- Isotropic semivariograms of yield obtained by choosing a minimum active lag distance (100 m), reporting the range value for each crop of the rotation.

The range for single properties was close to the average value detected along the profile, soil properties having similar spatial pattern in different depth layers (Figure 14), with a maximum average range for organic carbon (75.5 m), ranging from to 62.6 m to 83.6 m in different layers, and a minimum average value for clay (61.77 m) (Table 5). In all cases the spherical model fitted the semivariance, with a variable value of the coefficient of determination by considering different properties or layers, having for soil characteristics an average value of $R^2 = 0.5$.

For soil properties the nugget effect was very low, whilst sill average values indicates appreciable level of variation only for the organic matter, it ranging from 0.81 % to 0.99 % of variance in organic matter content along the soil profile within field.

Table 5.- Principal parameters related to isotropic semivariograms of soil properties measured along the soil profile.

Soil properties (%)	**Depth (cm)**	**Range (m)**	**Nugget (C_0)**	**Sill (C_0+C)**	**C/(C_0+C)**	**Isotropic model**	**R^2**
	0÷15	50.60	0.001	1.124	0.99	spherical	0.55
clay	15÷30	69.80	0.001	1.095	0.99	spherical	0.69
	30÷45	64.90	0.001	0.992	0.99	spherical	0.45
	0÷15	61.20	0.001	0.938	0.99	spherical	0.37
sand	15÷30	52.50	0.001	0.984	0.99	spherical	0.43
	30÷45	74.60	0.001	1.063	0.99	spherical	0.50
	0÷15	72.40	0.001	0.853	0.99	spherical	0.51
loam	15÷30	73.50	0.001	1.001	0.99	spherical	0.48
	30÷45	75.20	0.001	1.067	0.99	spherical	0.71
	0÷15	62.60	0.001	0.817	0.99	spherical	0.40
organic matter	15÷30	80.30	0.001	0.867	0.99	spherical	0.41
	30÷45	83.60	0.001	0.993	0.99	spherical	0.67

The range values detected for yield were roughly comparable with the values of range for soil static physical properties averaged along the soil profile, supported by greater values of R^2 for model fitting semivariance, revealing the existence of a partial spatial dependence between yield and soil pattern, and this allowed to analyse yield data and soil properties with classical statistical methods.

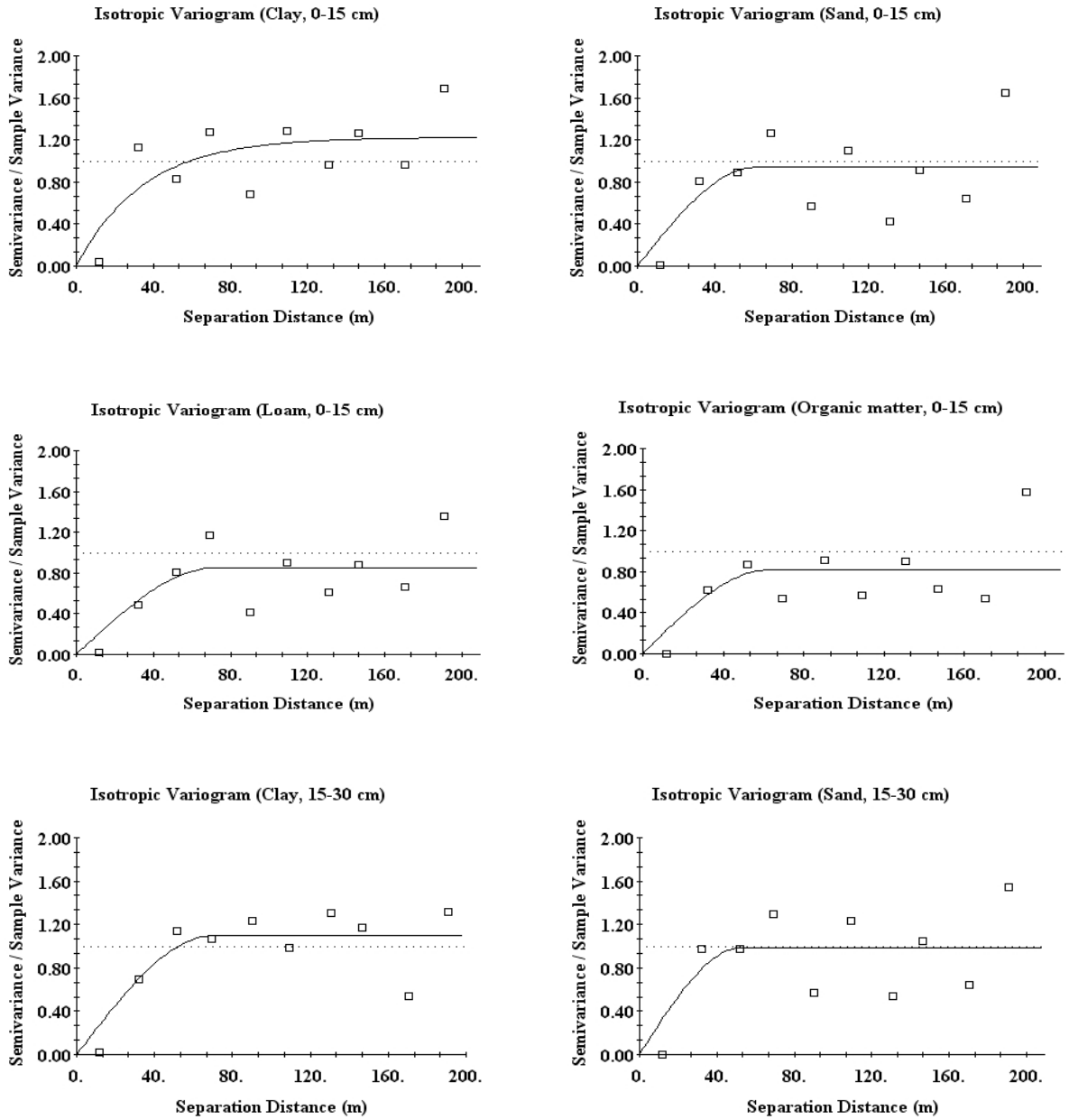

Figura 14.(a)- Isotropic semivariograms of soil static physical properties: data relating to the 0÷15 cm and 15÷30 cm soil layers.

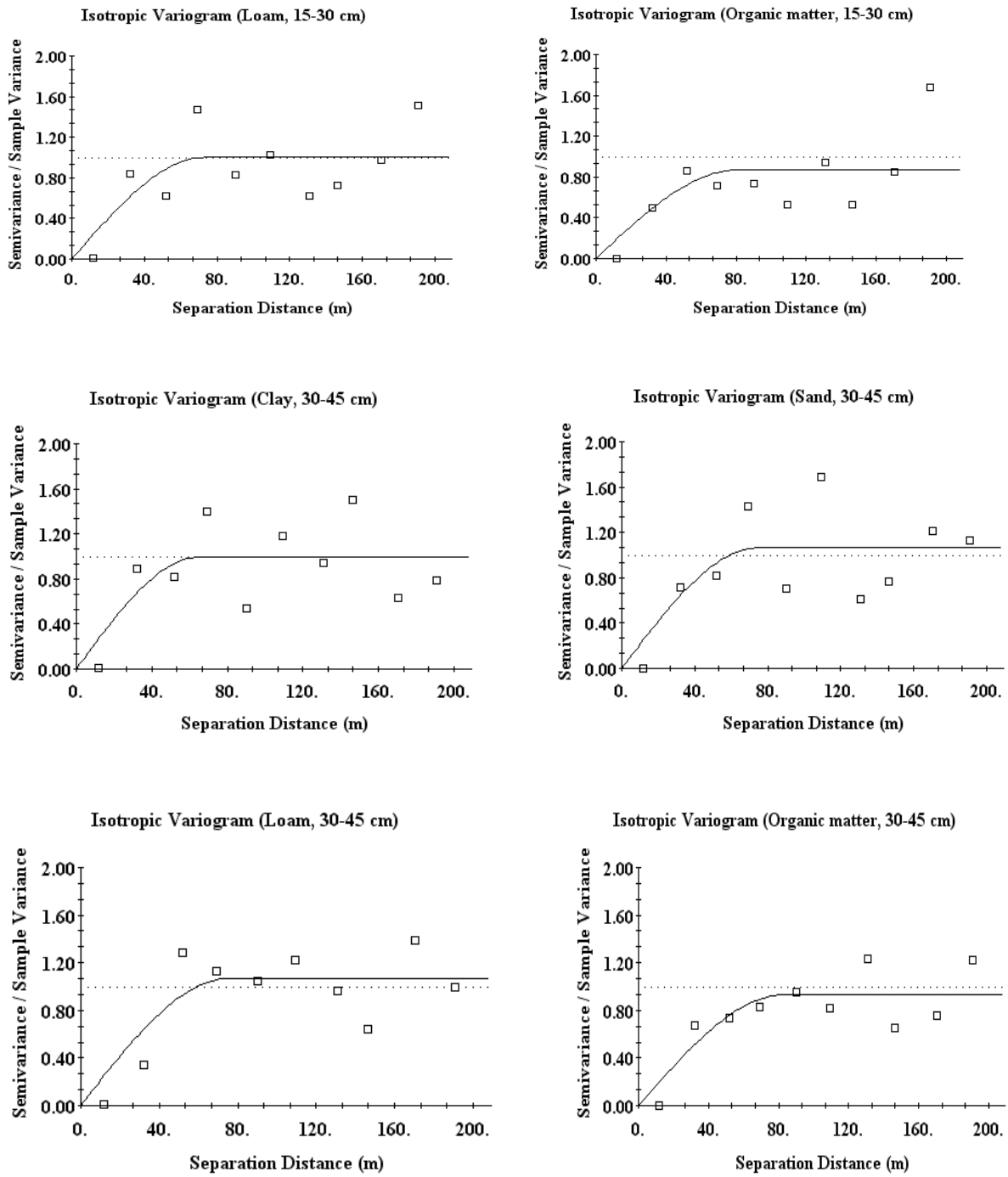

Figura 14.(b)- Isotropic semivariograms of soil static physical properties: data relating to the 30÷45 cm soil layer.

1.3.5.- Statistical analysis within field

A first approach consisted on performing statistical analysis within the complete field, to investigate relationships between yield and soil static physical properties measured along the soil profile within field (Table 3).

Correlation matrix

After developing a correlation matrix between soil properties and yield data, results were different by considering single layer along soil profile and single growing season, even if a general trend roughly showed a more strongly correlation for the upper layer than the others with yield (Table 6). In particular, clay and loam content generally showed a negative correlation, as just revealed by the analysis of correspondence, even if the data were not statistically significant because of the slight differences among different part of the field. In the opposite way, the organic matter content generally resulted positively and statistically correlated with yield of all crops along soil profile, particularly as regards the upper and the medium layers.

Table 6.- Correlation matrix between soil properties and yield within field over years (* = significant at P< 0.05 level of significance; ** = significant at P< 0.01 level significance).

Seasons	**Soil properties (%) for different layers within field**											
	0÷15 cm				**15÷30 cm**				**30÷45 cm**			
	Clay	Loam	Sand	OM	Clay	Loam	Sand	OM	Clay	Loam	Sand	OM
1998	-0.15	-0.29	0.30	0.44**	-0.04	-0.30	0.25	0.36*	-0.24	-0.17	0.27	0.21
1999	0.11	-0.44**	0.31	0.38*	-0.05	-0.29	0.25	0.47**	-0.11	-0.06	0.11	0.33*
2000	-0.02	-0.35*	0.29	0.34*	-0.11	-0.13	0.16	0.36*	-0.38*	0.18	0.09	0.16
2001	-0.13	-0.48**	0.44**	0.51**	-0.37*	-0.23	0.36*	0.43**	-0.32	-0.12	0.28	0.40*
2002	-0.07	-0.16*	0.15	0.05	-0.28	0.14	0.04	0.03	-0.17	0.01	0.10	0.05

Multiple regression analysis

Multiple regression analysis was developed by entering soil properties measured along soil profile, sorted according to the depth. Results showed appreciable difference on the regression model for different crops and considering different growing seasons, with a not clear dependence of yield data on soil properties, but in general model confirmed correlation matrix results, with only clay content and organic matter having an influence on yield variability, generally referring to the upper layers and having a statistically significant negative and positive effect (Table 7). At this purpose, model

explained yield variability with a lower value of the coefficient of determination (average R^2 = 0.23), it ranging from a minimum of 0.15 for clay for maize in 2000 to a maximum of 0.35 for wheat with a model of regression taking into account both clay content (0÷15 cm) – negative influence – and organic matter content – positive influence – measured at the medium layer (15÷30 cm), that was the more frequently variable entered in the model. For the 2002 no variable meeting the 0.05 significance level for entry into the regression model.

1.3.6.- Temporal stability of spatial variability

The analysis of temporal stability, integrating the 5-year spatial pattern (Figure 14) and temporal variance (Figure 15) of yield within field, showed the presence of two stable area, corresponding each one approximately to the 50 % of the field and having statistically higher and lower yield than the average value and lower temporal variance over years (Table 8), and a small area characterised by temporal instability.

Table 7.- Regression models developed for predicting crops yield during crop rotation (1998-2002) within the complete field by considering the soil static physical properties along soil profile (* = significant at a P<0.05 level of significance; ** = significant at a P<0.01 level of significance).

Year	**Variable entered**	**Model (Y = yield)**	**R^2**
1998	OM_0÷15	Y = 8.804 + 0.79 × OM_0÷15	0.19**
1999	OM_0÷15	Y = 4.760 + 010 × OM_0÷15	0.22**
2000	Clay_30÷45	Y = 15.38 –0.14 × Clay_30÷45	0.15**
2001	OM_0÷15	Y = 6.129 + 0.48 × OM_0÷15	0.26**
	Clay_15÷30	Y = 9.394 + 0.44 × OM_0÷15 –0.08 × Clay_15÷30	0.35*
2002	--	--	--

In particular, field resulted divided into two distinct yield zones, having a stable productive trend over years but different yield level (Figure 16). The small area of unstable yield resulted localised particularly along the boundary lines of the field, and probably it depended on errors affecting yield mapping and greater soil compaction due to the traffic of machinery during tillage operations.

Table 8.- Yield data measured during the crop rotation for stable area with high (*HS*) or low (*LS*) yield level. Lower-case letters for the single year (the same crop) indicate statistically significant differences between *HS* and *LS* area, whilst capital letters refer to statistically significant differences regarding the yield data registered for the same crop within a stable areas during crop rotation (*LSD* test, P≤0.05).

Statistics	**Grain yield (t ha^{-1})**									
	1998 (maize)		1999 (soybean)		2000 (maize)		2001 (wheat)		2002 (soybean)	
	HS	*LS*	*HS*	*LS*	*HS*	*LS*	*HS*	*LS*	*HS*	*LS*
mean	12.33aA	10.41bA	5.18aA	4.85bA	11.14aB	8.42bB	8.33a	6.96b	3.97aB	3.89bB
minimum	7.29	7.25	4.77	4.53	9.21	7.06	7.38	5.39	3.62	3.69
maximum	13.61	12.54	5.60	5.13	12.58	10.01	9.09	7.82	4.86	4.38
st.dev.	± 1.76	± 1.62	± 0.23	± 0.19	± 1.18	± 0.92	± 0.49	± 0.66	± 0.30	± 0.23
CV (%)	14.24	15.55	4.36	3.86	10.62	10.95	5.87	9.50	7.57	5.96

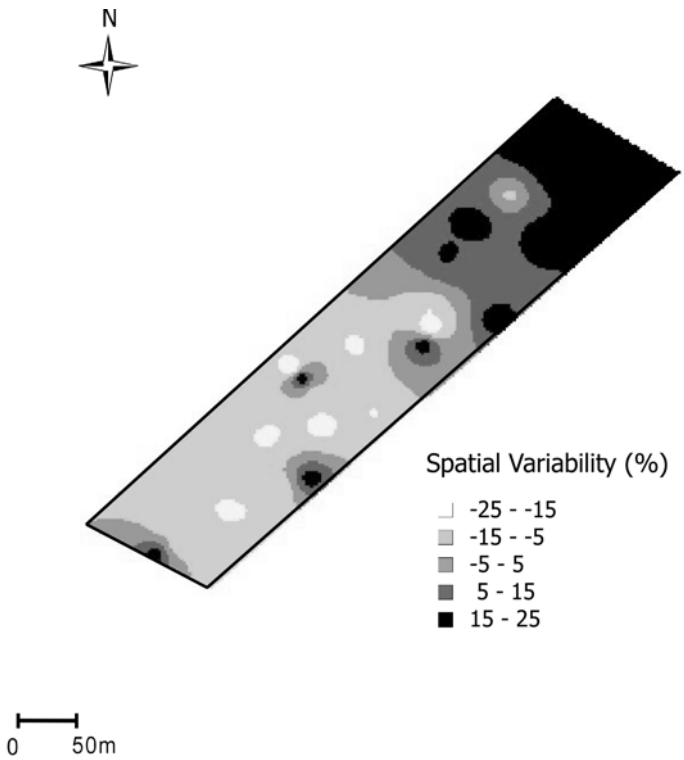

Figure 14.- Spatial pattern of yield over the 5-year crop rotation, expressed as average relative percentage difference from the average value obtained within field.

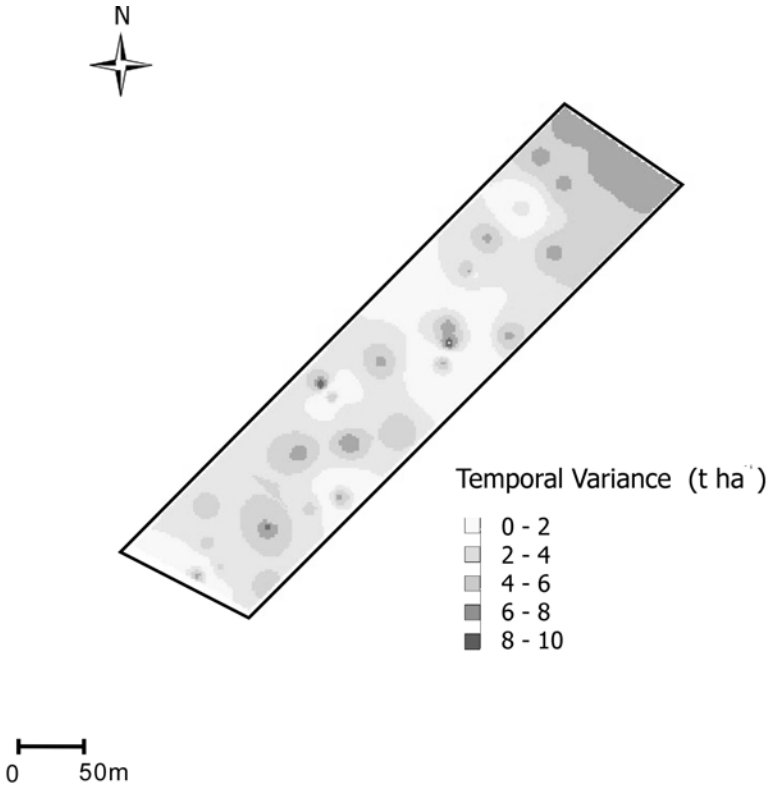

Figure 15.- Temporal variance (t ha^{-1}) detected within field during the 5-year crop rotation.

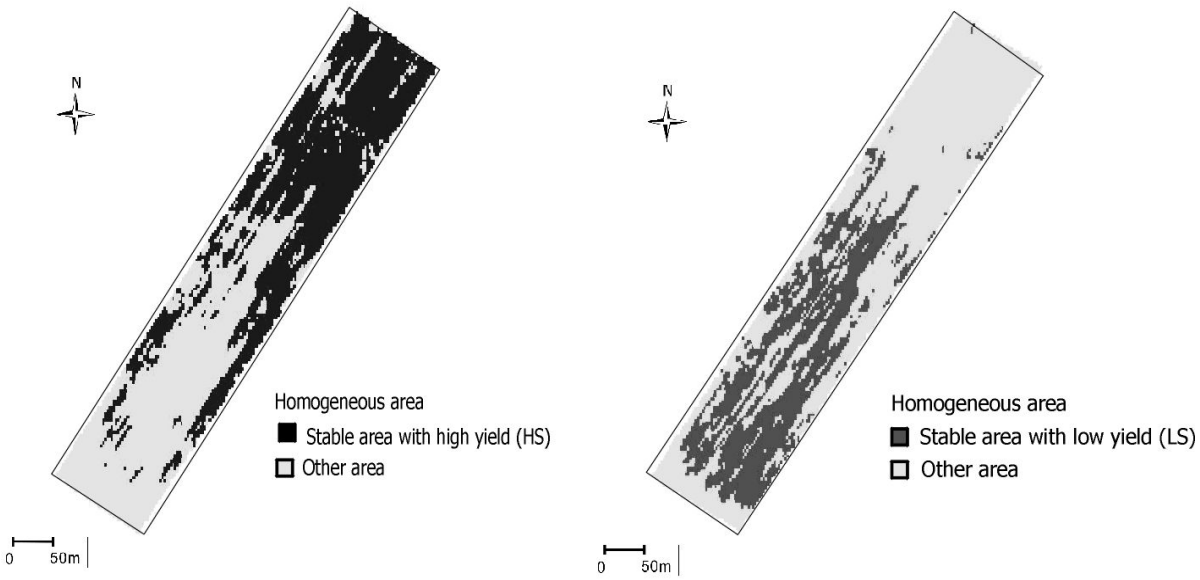

Figure 16.- Temporal stability map, reporting the presence of area within field having different stable level of production, identified as area having high yield (*HS* area) (left) and low yield (*LS* area) (right) pattern over years.

1.3.7.- Statistical analysis within homogeneous area

Based on the identification of homogeneous area within field, according to the temporal stability of spatial variability criteria, statistical analysis – correlation matrix and multiple regression analysis – was repeated for the homogeneous area of the field, based on the different soil properties detected within them along the soil profile (Table 9). In particular, any significant difference was found among average soil properties between stable and unstable area (*S* area vs. *U* area, data not shown) identified within field, and this fact confirmed that yield in unstable area may depends on different factors respect to soil properties, whilst statistically appreciable variations were detected between U area and stable area separated according to the yield level and between *HS* and *LS* area. In general, clay content resulted quite uniformly distributed within field, whilst the organic matter content was statistically different along soil profile, with higher content in *HS* area, having on average a content 1% greater than *LS* area. In particular, in the upper layer sand and loam content were different in all area, whilst the organic matter content was statistically higher in the *HS* area than the others. In the intermediate layer (15÷30 cm) the differences among soil properties were greater for loam and organic matter, whilst sand in the *LS* area was statistically lower than *HS* and *U* area. In the deeper layer (30÷45 cm) texture not showed differences among stable area, whilst the organic matter content was significantly grater in the *HS* area than in the other parts of the field.

Table 9.- Average soil properties measured along soil profile for homogeneous area identified within field. Different letters indicate significant differences between soil properties for the same depth layer (*LSD* test, P≤0.05).

Area	**Soil properties (%) for different layers**											
	0÷15 cm				**15÷30 cm**				**30÷45 cm**			
	Clay	Sand	Loam	OM	Clay	Sand	Loam	OM	Clay	Sand	Loam	OM
HS	39	25 a	35 bc	3.73 a	38	24 a	38 b	3.71 a	40	21	39	3.61 a
LS	41	14 b	45 a	2.39 b	41	14 b	45 a	1.81 bc	44	15	41	1.89 b
U	40	22 ac	38 b	2.29 b	41	22 ab	37 bc	2.40 a	42	17	42	1.89 b

The correlation matrix developed by grouping the areas according to the temporal stability or instability of yield showed similar results respect to the correlation examined for the complete field

(Table 10), confirming the statistically significant existence of stable production levels for the same areas of the field, with a stronger significance (P< 0.01) for stable area respect to that unstable, because of the not uniform production level obtained in the latter, affecting by different and variable limiting factors.

Table 10.- Correlation matrix of yield over years for *S* and *U* area identified within field (* = significant at P< 0.05 level of significance; ** = significant at P< 0.01 level of significance).

Seasons	***S* area**					***U* area**				
	1998	**1999**	**2000**	**2001**	**2002**	**1998**	**1999**	**2000**	**2001**	**2002**
1998	1.00	0.23	0.39*	0.46*	0.05	1.00	0.76*	0.74*	0.63	0.65
1999		1.00	0.58**	0.53**	0.11		1.00	0.60	0.66	0.45
2000			1.00	0.65**	0.27			1.00	0.61	0.78*
2001				1.00	0.17				1.00	0.77*
2002					1.00					1.00

In the opposite way, correlation relationships between yield data were not found by examining the *HS* and *LS* area separated, and this was coherent with the presence of temporal variability: an area having a greater level of production respect to the adjacent within field (intra-year variability) in a specific year could be characterised by a lower production in an other growing season, even if greater respect to the average production obtained for the complete field, without stronger correlation over years (Table 11).

Table 11.- Correlation matrix of yield over years for *HS* and *LS* area identified within field.

Seasons	***HS* area**					***LS* area**				
	1998	**1999**	**2000**	**2001**	**2002**	**1998**	**1999**	**2000**	**2001**	**2002**
1998	1.00	-0.09	0.12	-0.32	0.05	1.00	-0.21	-0.17	0.48	-0.18
1999		1.00	0.40	0.14	-0.20		1.00	-0.29	-0.07	0.22
2000			1.00	0.07	0.09			1.00	0.004	0.35
2001				1.00	0.35				1.00	-0.28
2002					1.00					1.00

The analysis of relationship between soil properties and yield data for the homogenous area identified within field confirmed the importance of negative and positive correlation along soil profile, increasing the level of significance respect to the results found for the complete field, as shown by the greater significance (Table 12), except in 2002, for which any significant relationship was found between yield and soil static physical properties. In particular the organic matter content resulted correlated with yield data along the complete soil profile, with a high value of r coefficient (r = Pearson coefficient), ranging from a minimum of 0.47 to a maximum of 0.69, whilst for clay a significant correlation was found in the intermediate (r = -0.54) and in the deeper layer (r = -0.38), being sand and loam more significantly correlated in the upper and intermediate layers.
For sand in particular, the correlation resulted more marked than that found for the complete field, according to the soil particles distribution within field, being greater content of sand displaced approximately within area having lower content of clay.

Table 12.- Correlation matrix between soil properties and yield for *S* area over years (* = significant at P< 0.05 level of significance; ** = significant at P< 0.01 level significance; *** = significant at P< 0.001 level significance).

Seasons	**Soil properties (%) for different layers in *S* area**											
	0÷15 cm				**15÷30 cm**				**30÷45 cm**			
	Clay	Loam	Sand	OM	Clay	Loam	Sand	OM	Clay	Loam	Sand	OM
1998	-0.28	-0.41*	0.44*	0.39*	-0.05	-0.49**	0.42*	0.34	-0.23	-0.24	0.31	0.35
1999	0.04	-0.54**	0.41*	0.47*	-0.28	-0.34	0.40*	0.61**	-0.09	-0.17	0.17	0.57*
2000	-0.10	-0.45*	0.39*	0.32	-0.24	-0.30	0.35*	0.45*	-0.38*	0.11	0.14	0.43*
2001	-0.22	-0.60**	0.55**	0.69***	-0.54**	-0.36	0.53**	0.67**	-0.33	-0.08	0.25	0.66**
2002	0.09	-0.14	0.07	0.06	-0.36	0.21	-0.004	0.08	-0.03	0.04	-0.007	0.13

Within the unstable area only the organic matter content of the deeper layer resulted correlated with yield data monitored for maize, with a strong statistical significance of correlation, as revealed by the r coefficients (-0.71 and -0.92 in 1998 and 2000 respectively) (Table 13). This result, being different respect to others scenarios considered, may be influenced by the presence of others limiting factors – *i.e.*, inter-relationships among soil factors, climatic conditions and agronomic practices – within these area and the consequently temporal instability of yield, which probably masked the real relationship between yield and soil static physical properties in the studied period.

Table 13.- Correlation matrix between soil properties and yield for *U* area over years (* = significant at P< 0.05 level of significance; ** = significant at P< 0.01 level significance).

Seasons	Soil properties (%) for different layers in *S* area											
	0÷15 cm				15÷30 cm				30÷45 cm			
	Clay	Loam	Sand	OM	Clay	Loam	Sand	OM	Clay	Loam	Sand	OM
1998	0.28	-0.14	-0.02	0.47	0.17	-0.15	-0.03	0.37	-0.33	0.25	-0.001	-0.71*
1999	0.35	-0.09	-0.10	0.32	0.47	0.14	-0.34	0.01	-0.24	0.30	-0.10	-0.48
2000	0.22	-0.25	0.11	0.30	0.24	0.07	-0.17	0.13	-0.45	0.55	-0.18	-0.92**
2001	0.06	-0.40	0.32	-0.03	-0.02	-0.29	0.14	-0.10	-0.40	-0.17	0.38	-0.35
2002	-0.31	-0.33	0.44	-0.17	-0.15	-0.25	0.20	-0.15	-0.53	0.08	0.26	-0.68

The analysis performed for the stable area, grouped in *HS* and *LS* area respectively, showed similar results about correlations between yield data and soil properties respect to that found for the complete field, being only clay and organic matter content correlated with yield. In particular, the correlation was negative for clay and positive for organic matter content respectively, but this result involved only some layers of soil profile for the 2000 and 2001 growing season for both *HS* area (Table 14) and *LS* area (Table 15). This is probably due to the partial influence exerted on yield by soil static physical properties, integrated by the influence of others limiting factors and their interactions, explaining the remaining variability of yield.

Table 14.- Correlation matrix between soil properties and yield for *HS* area over years (* = significant at P< 0.05 level of significance; ** = significant at P< 0.01 level significance).

Seasons	Soil properties (%) for different layers in *HS* area											
	0÷15 cm				15÷30 cm				30÷45 cm			
	Clay	Loam	Sand	OM	Clay	Loam	Sand	OM	Clay	Loam	Sand	OM
1998	0.05	0.10	-0.08	-0.37	0.35	-0.19	-0.07	-0.35	0.21	-0.04	-0.11	-0.37
1999	-0.24	-0.35	0.32	0.19	0.03	-0.31	0.23	0.31	-0.06	-0.21	0.26	0.45
2000	0.02	0.13	-0.09	-0.57*	0.31	-0.03	-0.17	-0.36	-0.05	0.27	-0.25	-0.31
2001	-0.34	-0.54	0.49	0.50	-0.79**	0.09	0.46	0.62	-0.39	-0.17	0.43	0.49
2002	-0.26	-0.14	0.19	-0.18	-0.52	0.45	0.00	-0.18	0.28	-0.11	-0.07	-0.25

The multiple regression analysis performed for the area identified according to the stability criteria and for the stable area divided by considering the level of yield showed results that confirmed that obtained with correlation matrix. In particular, in the first case loam, organic matter and clay content were the variable significantly entered in the regression model to explain the variability of yield, with values of coefficient of determination ranging from a minimum of $R^2 = 0.21$ for model

having single variable to a maximum of R^2 = 0.62 when two variable have been entered in the model for *S* area.

Table 15.- Correlation matrix between soil properties and yield for *LS* area over years (* = significant at P< 0.05 level of significance).

Seasons	**Soil properties (%) for different layers in *LS* area**											
	0÷15 cm				**15÷30 cm**				**30÷45 cm**			
	Clay	Loam	Sand	OM	Clay	Loam	Sand	OM	Clay	Loam	Sand	OM
1998	-0.46	-0.33	0.50	0.47	-0.05	-0.48	0.44	0.18	-0.35	-0.43	0.47	0.31
1999	0.48	-0.17	-0.11	0.03	-0.13	0.09	-0.03	0.18	0.31	-0.09	-0.11	0.11
2000	0.008	0.06	-0.05	-0.31	-0.14	0.19	-0.11	-0.52*	-0.50*	0.30	0.08	-0.21
2001	-0.10	-0.10	0.13	0.38	-0.08	-0.11	0.12	-0.07	-0.06	0.04	0.004	0.22
2002	0.44	0.05	-0.27	-0.008	0.03	0.27	-0.24	-0.04	-0.21	0.24	-0.04	0.18

The percentage of variability explained by the multiple regression resulted variable for different growing seasons, but in general greater than that explained considering the complete field (Table 16). For the unstable area a few significant model were found, only yield of maize being explained, according to the matrix correlation results, and the level of statistical significance was lower than for area characterised by temporal stability.

As regards stable area, only in 2000 and 2001 for *HS* area and in 2001 in 2002 for *LS* area regression models were found, having a statistical significance degree lower than that found by considering the complete stable area identified within field (Table 17). In particular, only organic matter and clay content were entered into the model at a 0.05 significance level, explaining in general the 62% of variability with the clay content, that resulted negatively correlated, and only the 30% of variability with the organic matter content, resulted negatively correlated, probably because the spatial pattern of soil static physical properties was one of the factors but not the exclusive influencing yield variability within field, and consequently they partially explained yield variability in some parts of the field but not in the others, with different degree of statistic significance, according to the suggestions reported by literature (Sudduth et al., 1996; Mallarino et al., 1999).

Table 16.- Regression models developed for predicting crops yield for the homogeneous stable and unstable area identified within field over the 1998-2002 season, by considering the static physical properties of the soil layers (0÷15 cm, 15÷30 cm and 30÷45 cm, respectively) (* = significant at a P<0.05 level of significance; **= significant at a P<0.01 level of significance; *** = significant at a P<0.001 level of significance).

Year	**Variable entered**	**Model (Y = yield) for stable yield area (*S*)**	**R^2**
1998	Loam_15÷30	Y = 17.24 – 0.14 × Loam_15÷30	0.24**
1999	OM_15÷30	Y = 4.67 + 0.12 × OM_15÷30	0.37**
2000	Loam_0÷15	Y = 14.32 - 0.12 × Loam_0÷15	0.21*
	Loam_30÷45	Y = 11.97 - 0.23 × Loam_0÷15 + 0.17 × Loam_30÷45	0.48**
2001	OM_0÷15	Y = 6.05 + 0.52 × OM_0÷15	0.48***
	Clay_15÷30	Y = 9.80 + 0.45 × OM_0÷15 – 0.09 × Clay_15÷30	0.62**
2002	--	--	--
Year	**Variable entered**	**Model (Y = yield) for unstable yield area (*U*)**	**R^2**
1998	OM_30÷45	Y = 12.79 – 1.54 × OM_30÷45	0.51*
1999	--	--	--
2000	OM_30÷45	Y = 13.02 - 2.28 × OM_30÷45	0.85**
2001	--	--	--
2002	--	--	--

Table 17.- Regression models developed for predicting crops yield during the crop rotation (1998-2002) for the homogeneous *HS* and *LS* area identified within field by considering the static physical properties along soil profile (* = significant at a P<0.05 level of significance; ** = significant at a P<0.01 level of significance).

Year	**Variable entered**	**Model (Y = yield) for high and stable yield area (*HS*)**	**R^2**
1998	--	--	--
1999	--	--	--
2000	OM_0÷15	Y = 14.412 – 0.87 × OM_0÷15	0.32*
2001	Clay_15÷30	Y = 11.825 – 0.09 × Clay_15÷30	0.62**
2002	--	--	--
Year	**Variable entered**	**Model (Y = yield) for low and stable yield area (*LS*)**	**R^2**
1998	--	--	--
1999	--	--	--
2000	OM_15÷30	Y = 9.73 – 0.7 × OM_15÷30	0.27*
2001	--	--	--
2002	--	--	--

1.4.- Conclusions

In this study, the within-field spatial and temporal variability of yield were considered in a 5-year crop rotation, by analysing the monitored yield data. Yield resulted affected by inter-years and intra-year variability, the first being principally explained by the differences on cropping management and the variability of climatic conditions registered over years, the second partially corresponding to the spatial patter of soil static physical properties – i.e. soil particle size and organic matter content – measured within field.

According to these results, the effects of soil static physical properties on temporal stability of spatial variability of yield was analysed by developing correlation matrix between yield data and soil properties and by elaborating regression models, for both the complete field and the identified homogeneous management area. Among soil properties investigated along soil profile clay and organic matter contents resulted negatively and positively correlated with yield pattern, respectively.. Anyway, the magnitude of this influence resulted statistically variable for different growing seasons and crops, but also for the different area identified within field. In particular, the significance of the relationships between soil properties and yield data resulted greater for the *S* area, whilst it decreased by considering the stable area with the same production. The reason of that was probably due to only the partial influence of soil spatial pattern on yield, it being one of limiting factors existing within field. Furthermore, the same temporal stability of yield may be influenced by the presence of others limiting factors, classical analysis not taking into account the complex inter-relationships existing between soil properties and climatic conditions for the limited studied period.

Further study is needed and also dynamic soil properties should be considered to more completely explain the yield variability existing within field. Par consequence, the next step of this study is to apply simulation model to crop growth, in order to consider the long-term intra-year and inter-years variability of yield and then identify stable homogeneous area within field, in which apply variable rate application.

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– Sezione 2 –

Determinazione e simulazione della variabilità spaziale e della stabilità temporale della resa in una rotazione di mais, soia e frumento

Riassunto

La possibilità di eseguire gli interventi colturali a dosaggio variabile rappresenta una interessante prospettiva per l'azienda agricola, soprattutto grazie ai progressi avutisi nel settore delle tecnologie applicate al settore agricolo negli ultimi decenni. Nell'ambito della caratterizzazione iniziale dell'azienda, tale opportunità deve però accompagnarsi alla messa a punto di metodiche in grado di consentire l'individuazione delle aree omogenee esistenti all'interno dell'appezzamento, a partire dai dati raccolti sullo status della coltura e delle proprietà del suolo.

Il presente lavoro ha preso in considerazione una metodologia per l'identificazione delle aree omogenee all'interno dell'appezzamento nelle quali poter eseguire interventi colturali ad intensità variabile, sulla base delle mappe di produzione precedentemente collezionate. In particolare, per tale obiettivo si è fatto ricorso all'impiego di un *S*istema *I*nformativo *G*eografico per la gestione dei dati di produzione e di un modello si simulazione per l'analisi della variabilità nel lungo periodo della resa sulla base dell'influenza delle condizioni climatiche. Lo studio è stato condotto presso un'azienda privata situata in provincia di Rovigo, Italia, in un appezzamento coltivato a mais (*Zea mays*, L.), soia (*Glycine max*, L.) e frumento (*Triticum aestivum*, L.) in rotazione quinquennale, e le zone omogenee sono state individuate in accordo con la stabilità temporale della variabilità spaziale della resa all'interno del campo. In particolare, per ciascuna coltura le zone maggiormente produttive e dotate di maggiore stabilità temporale sono risultate coincidere con la parte più settentrionale dell'appezzamento, anche se per ciascuna coltura le zone stabili sono risultate comunque caratterizzate da superficie e dimensioni differenti. La sovrapposizione delle mappe di stabilità relative a ciascuna coltura ha quindi consentito d'individuare una zona stabile, avente una resa maggiore rispetto alle zone vicine del campo, per la quale la superficie (1,27 ha) è risultata inferiore di circa il 50% rispetto alla medesima zona omogenea individuata sulla base dei dati di resa raccolti nel corso dei 5 anni di rotazione. Tale risultato, dovuto probabilmente alla diversa

incidenza delle condizioni ambientali sulle prestazioni produttive di colture differenti, ha evidenziato come l'utilizzo di strumenti informativi geografici e di modelli di simulazione sia uno strumento molto valido per consentire all'azienda di individuare con un'elevata accuratezza le zone da gestire in maniera differenziata.

***Parole chiave*:** frumento; mais; modelli di simulazione; resa; soia; stabilità temporale; variabilità spaziale; zone omogenee.

Abbreviazioni: *HS area* – area con resa alta e stabile nel tempo; *LS area* – area con resa bassa e stabile nel tempo.

– Section 2 –

Assessing and simulating spatial variability and temporal stability of yield in a maize-soybean-wheat crop rotation

Abstract

The principal aspect farmer has to consider before applying technical factors at variable rate is the identification of homogeneous management area within field. This study analysed a methodology to identify homogeneous area within field, according to the stability of yield, and regarded a 5-year crop rotation – maize (*Zea mays*, L.), soybean (*Glycine max*, L.) and wheat (*Triticum aestivum*, L.) – in a private farm situated in Rovigo, NE Italy. Based on intra-year and inter-years variability affecting yield data, the crop growth and yield process were simulated over a 15-years period (1989-2003) by using *G*eographical *I*nformative *S*ystem to manage row yield data and the modules of *DSSAT v.3.5*, to take into account the influence of environmental conditions. By considering and overlying the long-term spatial variability and the temporal variance maps of maize, wheat and soybean, field resulted divided into two stable area, having different yield level and displaced according to the principle axle of the field. The final map reporting the multiple-crop temporal stability of spatial variability of predicted yield showed a stable area, having greater yield than the remnant part of the field, corresponding to an area of 1,27 ha. This area, localised in the upper part of the field and having an appreciable surface to adopt variable rate technologies, resulted lower than that found by considering only the 5-year crop rotation, covering only the 15.6 % of the surface area, with a decrease of almost the 30% of the *HS* area, mainly because of the different long-term temporal variance assumed by different crops. Contrarily, the identified stable area having a lower predicted yield than the average of the field and named *LS,* resulted greater than that identified for the crop rotation. In conclusion, results showed that a combination of GIS tools and crop growth simulation models can be useful to identify long-term temporal stability of spatial variability within homogeneous area having different yield variability before adopting variable rate technologies.

Keywords: maize; management zones; simulation model; soybean; wheat; yield spatial variability; yield temporal stability.

Abbreviations: *HS area* – stable area with high yield; *LS area*– stable area with low yield.

2.1.- Introduction

The presence of within-field spatial and temporal variability on yield patterns is well recognised by authors and documented in several studies carried out in the last years (Eghball and Varvel, 1997; Blakmore et al., 2003), specifying the influences exerted by spatial variability of limiting factors on the yield level obtained in the field (Cahn et al., 1994; Cambardella et al., 1994).
Despite to that fact, generally a field was traditionally considered as a homogeneous productive unit, despite to the spatial variability affecting numerous factors (e.g. soil properties and attributes, nutrient availability, etc.) within field, and in general agronomic practices were uniformly adopted: the management of the crop in fact is usually based on the average yield level obtained with the precedents crops (Stafford et al., 1996), but the uniform applications of inputs is resulted inefficient both in terms of environmental impact and in terms of productive costs (Stafford, 1993).
The alternative management strategy proposed by Precision Agriculture is that the spatial variability within field could be differently managed, according to the soil properties and attributes of each homogeneous area of the field (Lark, 2001) and taking into account the influence exerted by the climatic conditions on yield level over years (Dobermann et al., 2003; Kravchenko et al., 2003). Precision Agriculture in fact can be considered an opportunity for farmers to obtain economic benefits in relation to the intensity of the spatial variability detected within field (Godwin et al., 2003), whilst an increase of the efficiency in crop management could also reduce the pressure exerted by agricultural production systems on the environment (Thrikawala et al., 1999; Wang et al., 2003; Hamel et al., 2004).

The presence of within-field variability represents the basic assumption to apply concepts proposed by Precision Agriculture, and yield monitoring and mapping in fact is one of the most largely used technologies currently employed in site-specific crop management to obtain information about the within field yield variability and consequently to identify homogeneous zones to manage at variable intensity. Since the introduction of yield monitor, the availability of yield data was accompanied by various studies oriented to the analysis and the correction of different errors affecting row data (Blackmore and Marshall, 1996), and various methods were consequently proposed to filter the row data collected within field (Han et al., 1997; Beck et al., 2001) and to reduce the noise regarding the estimated values (Han et al., 2004). Additionally the development in electronics and computer/microprocessor technologies provides the basis for a rapid transfer of these innovative

solution to the crop management for the adoption of spatially variable rate application (Earl et al., 2000; Adamchuk et al, 2004), but a step not always so clear for farmers is the interpretation of the information contained in the yield map, although some solutions have been proposed to identify the within-field magnitude and spatial pattern variability of yield, in order to measure the effectively manageable variability according to the technical and the economic aspects (Cassel et al., 2000; Pringle et al., 2003). This has direct implications on the identification of homogeneous area characterised by a stable yield level that could be managed at variable intensity of input application (Zhang and Han, 2002), fields having greater temporal stability being characterised by the highest potential for measuring variability and its consequent variable management (Pierce and Nowak, 1999). In particular, the variability affecting yield is characterised by a spatial pattern within field (Nielsen et al., 1999) and its temporal stability over years (Stafford, 1999), the same limiting factors exerting different spatial and temporal influence on yield (Machado et al., 2000; Machado et al., 2002).

Yield at any point in a field is a result of genetics, plant population, management and weather, that set the yield potential of the population of plants for the particular season, and temporal integration of stresses that reduce yield from the potential during the season (Batchelor et al., 2002). At this regards, the largely used coefficient of variation is not an appropriate parameter to quantify the magnitude of variability within field, because of its non-spatial meaning and the impossibility of a clear distinction between manageable and unmanageable variability within field (Blackmore et al., 2003; Pringle et al., 2003). Furthermore, the analysis of intra-field variation over years may be influenced by the type of crop considered, because of the different relationship existing on spatial yield variability for different crops and the best results are obtainable by considering several years with different crops (Joernsgaard and Halmoe, 2003).

In this framework, advances in technologies such as GIS tools represent a fundamental instrument to manage the monitored yield data, by overlying several yield maps referring to different crops and growing seasons (Neményi et al., 2003), in order to understand the within-field spatial pattern and temporal variability of yield, achieving the objective of identifying homogeneous and stable management zones. For the same reasons, the application of crop growth simulation model could be useful to analyse spatial and temporal yield variability. Traditional analytical techniques in fact have failed to explain the causes for yield variability because the dynamic temporal interaction among multiple limiting factors can not be taken into account. In particular, process-oriented crop

growth model simulate the effects of genetics, management, whether and stresses on crop performance, by daily considering the temporal interaction and different management inputs on plant growth and yield processes (Basso et al., 2001) (Jones et al., 2003).
Crop model are an interesting tool for understanding yield variability (Jones et al., 2003), and consequently for variably managing field operations, according to the possibility to perform site-specific practices created by advances in technology, leading to a better control on production cost and to a more sustainable environment (Cora et al., 1999).

The main objectives of this study are ***(i)*** to verify the accuracy of simulation model in predicting the yield pattern for the considered crops – *i.e.*, maize (*Zea mays,* L.), soybean (*Glycine max,* L.) and wheat (*Triticum aestivum,* L.) – ***(ii)*** and to determine the within-field temporal stability of spatial variability of long-term predicted yield, accounting also the climatic conditions influences, in order to identify stable management zones where adopt variable rate technologies.

2.2.- Material and methods

2.2.1- Site description and climatic data

The data for this research were obtained from a 8-ha flat field, situated near Rovigo (44° 4’ 12” N, 11° 47’ 22” E, 6 m a.s.l.), NE Italy, during a 5-year rotation (1998-2002). Soil was clay, according to the USDA particles-size distribution limits. The climate of the area (data relating to the 1989-2002 period) is characterised by an annual average rainfall of 700 mm, distributed mostly in autumn and spring. The annual average temperature is 13.3 °C, with a monthly maximum of 23.5 °C in July and a minimum of 3.2 °C in January (Figure 1).

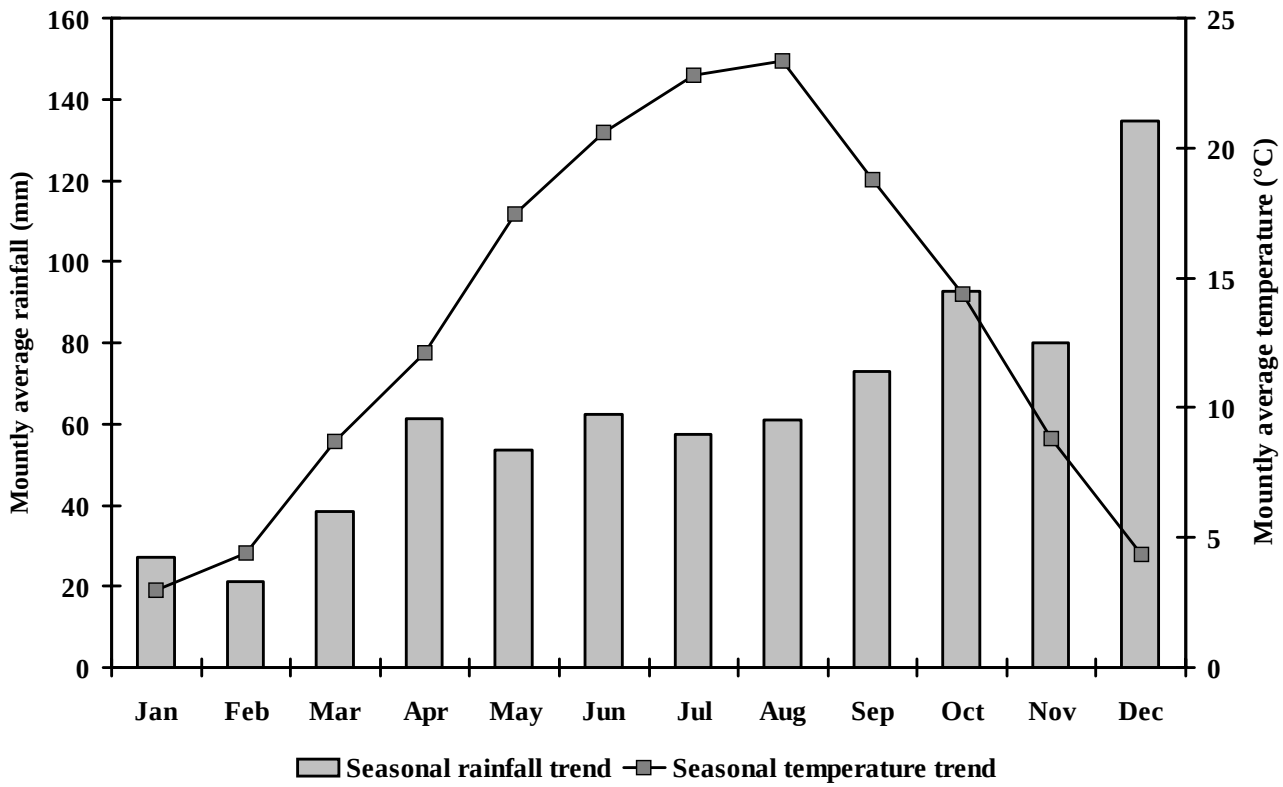


Figure 1.- Monthly total rainfall (mm) and average temperature (T °C) long-term trend (1989-2002) in the area where the study was carried out.

2.2.2.- Agronomic management

The study regarded a 5-year crop rotation, consisting on maize (*Zea mays*, L.) in 1998 and 2000, soybean (*Glycine max*, L.) in 1999 and in 2002, and wheat (*Triticum aestivum*, L.) in 2001. The farming system adopted during the crop rotation generally consisted on reducing tillage intensity according to soil characteristics and crop species and on adopting integrated strategies in the weed control. The specific agronomic practices adopted during the crop rotation are reported below for each crop.

Maize

In 1998 soil was tilled in August with a subsoiler and a rear mounted hitch disk harrow at a depth of 35 cm and 15 cm respectively, in order to incorporate the organic fertilizer (having a total of 112 N kg ha^{-1}, 37 P kg ha^{-1} and 150 kg ha^{-1}), applied with a manure spreader, whilst in 2000 tillage practices consisted of subsoiling and disk harrowing in October. Seedbed preparation was performed in both year by using a S-tines harrow in January and in March, whilst only in 2000 rotary harrowing was performed in March. The *Pregia* (in 1998) and *PR34F02* (in 2000) cultivars were sown with a planter (0.75 cm rows) in March 23 and in March 17, respectively. The seeding rate consisted of 28.4 kg ha^{-1} and 37.3 kg ha^{-1} of seeds (8.1 plants m^{-2}) in 1998 and 2000, respectively.

In 1998 mineral fertilisers (57 P kg ha^{-1} and 63 K kg ha^{-1}) were distributed before seedbed preparation with a double spinner disk, and after sowing 185 N kg ha^{-1} was applied in May with a pneumatic distributor. In 2000 44 P kg ha^{-1} was distributed before tillage with a double spinner disk, whilst 159 N kg ha^{-1} was applied in April 21 (85 N kg ha^{-1}) and in May 11 (74 N kg ha^{-1}), with a pneumatic distributor. In both years weed control was performed through the combination of herbicide application, distributed with a field sprayer in April and in May, and row crop cultivation by using a weeder in May. Harvest was carried out in September 18 and in August 23 in 1998 and 2000 respectively.

Soybean

In 1999 soil tillage was performed with a subsoiler in September 19 and with a rear mounted hitch disk harrow in November 24, at a depth of 35 cm and 15 cm respectively, whilst in 2002 subsoiling and disk harrowing were performed in July 2 and September 21, respectively. Only in 2002 S-tines harrow was used in November 17. In both years seedbed preparation was performed in March with rotary hoe to obtained weeds emergence. Their suppression was then achieved with herbicide in April in 1999, whilst in 2002 the same purpose was attained with a twice use of rotary hoe in April

and May. The *Loria* (in 1999) and *Bio-Nikir* (in 2002) cultivars were sown with a planter (0.75 cm rows) in April 26 and in May 30, in 1999 and 2002 respectively. The seeding rate consisted of 59 kg ha^{-1} (1999) and 49.5 kg ha^{-1} (2002) of seeds (30-35 plants m^{-2}). Only in 1999, 50 P kg ha^{-1} and 50 K kg ha^{-1} were applied in November with a double spinner disk. Weed control was performed in 1999 through the combination of herbicide application (in April 28, in May 25 and in June 18) and row crop cultivation, by using a weeder for two times in May, whilst in 2002 it was achieved by using a tined weeder and a weeder in June and July. Harvest was carried out in September 27 and in October 10 in 1999 and 2002 respectively.

Wheat

Seedbed was directly prepared on September 2000 with a rear mounted disk harrow at a depth of 15 cm. The *Amarok* cultivar was sown with a grain drill on October 23, with a 204 kg ha^{-1} seeding rate (approximately 450 seeds m^{-2}). The field was fertilised before sowing with 50 P kg ha^{-1}, whilst N fertilisers was applied after sowing (45 kg ha^{-1} in February 17, 45 kg ha^{-1} in March 12, and 136 kg ha^{-1} in April at the beginning) with a double spinner disk. Weed control was achieved by herbicide application in Marc 19 with a field sprayer. Harvest was carried out in June 25.

For each crop cultivars sown were chosen according to the best genetic characteristic for the environmental conditions of the experimental area.

2.2.3.- Yield monitoring

Yield monitor data were recorded by using a *New Holland TX 64* combine having a yield monitor system (grain mass flow sensor and capacity moisture sensors, placed in the upper part of the clean elevator) and a *Trimble AgGPS 132* receiver, having real-time differential correction (*OMNISTAR* signal) for the site coordinates determination. In particular, the row yield data, expressed as dry matter (0% grain moisture), were downloaded in *SMS software version 3.0*^{TM} (*AgLeader Tecnology, Inc*.) to obtain yield maps, and then were imported in *ArcView, version 3.2*^{TM} (*ESRI*, 1999). The layer referring to the annual yield map was overlaid to that reporting the sampling locations, and yield grain data was derived at each sampled point.

2.2.4.- Criteria for identification of management zones

The identification of homogeneous management zones was carried out by considering the temporal stability of spatial variability of yield obtained within field during the crop rotation. The spatial variability of yield was analysed in *ArcView version 3.2*^{TM}, by calculating for each year the relative percentage difference of yield from the average yield level obtained at each point mapped within field, according to the suggestions of Blackmore (2000), with the following equation (eq.1):

$$\bar{y}_i = \left[1/n * \sum_{k=1}^{n} y_{i_k}\right] \qquad \text{(eq.1)}$$

where:

$\bar{y}_i$ = mean of the y_i values;

y_i = interpolated yield value (t ha^{-1}) at location *i*;

n = number of years.

The final map reporting the area with different yield was performed by overlying the single map reporting the relative percentage difference of yield. Different zones were then classified in relation to a relative percentage difference threshold of 100%: the zones for which this value was greater were classified as area with high yield, whilst the zones for which this value was lower were defined as area with low yield.

The temporal stability of yield spatial pattern over years, was calculated as temporal variance (yield value recorded at each point mapped within field minus the field mean), according to the method proposed by Blackmore et al. (2003), in order to overcome the limits of the coefficient of variation (Pringle et al., 2003), with the following equation (eq.2):

$$\sigma_i^2 = 1/n * \sum_{k=89}^{k=02} (y_{i,k} - \bar{y}_i)^2 \qquad \text{(eq. 2)}$$

where:

σ_i^2 = the temporal variance at location *i*;

$\bar{y}_k$ = the average yield at year *k*;

y_i = the yield value at location *i* at year *k*;

k = the year over the 1998-2002 period;

n = number of years.

Because of the temporal variance variability within field may result appreciably variable by slightly changing the threshold used to determine stable area, as reported by Blackmore, a threshold value of 2.5 t ha^{-1} was considered, for identifying homogeneous area within field practically manageable by farmer.

By overlying the map of relative percentage difference and that of temporal variance, area characterised by stability of yield and having high yield over years were defined as *HS* area (*HS* – area with high and stable yield over years), whilst area characterised by stability of yield level and having low yield were defined as *LS* area (*LS* – area with low and stable yield over years) respectively. An area characterised by instability and having high or low yield level over years was classified unstable and defined as *U* area (*U* – area with high or low yield over years).

2.2.5.- Crop growth model

The long-term (15 years) pattern of yield grain was simulated over the 1989-2002 period, by validating the model using the monitored data, in order to increase the accuracy of the homogeneous management area defined within field, accounting the climatic conditions and the pattern of different crops, as suggested by literature (Boydell and McBratney, 2002; Joernsgaard and Halmoe, 2003). Simulation was performed by using *CROPAGRO* model (Boote et al., 1998) for soybean and *CERES* model for maize (Jones and Kiniry, 1986) and wheat (Ritchie and Otter, 1985). These models are parts of the *DSSAT 3.5* (*Decision Support System for Agrotechnology Transfer*) (Hoogenboom et al., 1994), that provides several tools for model application, using a minimum database relating to the factors required to run the crop models and validate the outputs, as reported below.

Weather dataset

It includes the daily values of incoming solar radiation (MJ m^{-2} day^{-1}), maximum and minimum air temperature (ºC), and rainfall (mm), measured during the period used for the prediction at the Rosolina weather station (*Arpav* – Centro Meteorologico di Teolo, Padova, Italy), situated in Rovigo, Italy.

Soil dataset

It includes soil classification, surface slope, permeability, drainage and soil properties measured along the soil profile, as percentage sand, silt, and clay content, bulk density, organic carbon and water limits. In particular, soil properties – i.e., soil texture, organic matter – were determined after collecting soil samples at 35 locations randomly displaced within field with an undisturbed soil core sampler (*Eijkelkamp*, Glesbeek, NL). The hydrometer method was used to determine the textural characteristics of the soil. The organic matter content was calculated by using the Walkley-Black method (Walkley and Black, 1934). Undisturbed soil cores 8-cm in diameter ware collected and the bulk density was determined after oven-drying at 105°C to constant weight. Soil water limits were calculated using the procedure suggested by Ritchie et al. (1999). All the measurements were made at three soil depth layers (0-15 cm, 15-30 cm, 30-45 cm) (Table 1), and sampling locations displaced within field were grouped according to the temporal stability criteria. A portable *Trimble 132* receiver was used to localise each point within field.

Genetic coefficients dataset

It includes the genetic parameters required to simulate the crop growth in the experimental area according to the peculiar crop genotype, and it was supplied by the producers for the cultivars used in the crop rotation.

Table 1.- Soil properties and hydraulic water limits of field averaged by values measured within field and entered in the model to predict yield data at each sampled location

Investigated layers	**Clay** (%)	**Sand** (%)	**Loam** (%)	**OM** (%)	**Bulk density** (g cm^{-3})	**LL** (cm^3 cm^{-3})	**DUL** (cm^3 cm^{-3})
0÷15 cm	40 ± 3.6	20 ± 8.3	39 ± 6.5	2.80 ± 1.1	1.26 ± 0.14	0.254 ± 0.04	0.108 ± 0.04
15÷30 cm	40 ± 4.1	20 ± 8.1	40 ± 6.1	2.60 ± 1.3	1.31 ± 0.11	0.260 ± 0.04	0.115 ± 0.04
30÷45 cm	42 ± 5.1	58 ± 8.6	40 ± 6.5	2.46 ± 1.3	1.25 ± 0.13	0.247 ± 0.05	0.103 ± 0.05

Management and experimental data

It includes all the information referring to the farming system suited by the farmer during the crop cycle (*e.g.*, planting date, planting density, row spacing, planting depth, crop variety, irrigation, fertilizer practices and rates, etc.). At this regard, specific farming practices and timeframe used as input for model simulation, referring to each crop of the investigated 5-year crop rotation, are that adopted by farm and previously described.

2.2.6.- Annual simulation and long-term scenarios

The model performance was evaluated for each crop by using the Root Mean Square Error (*RMSE*) (Basso et al., 2001), according to the following equation (eq. 3):

$$RMSE = \left[1/n * \sum_{i=1} (y_i - \hat{y}_i)\right]^{1/2} \qquad \text{(eq. 3)}$$

where:

y_i = yield value measured at location *i*, referring to the yield map;

$\hat{y}_i$ = yield value predicted at location *i*;

n = number of comparisons.

The model validation for each crop was performed by compare the predicted yield data with the yield data collected during the crop rotation collected with the yield monitor system.

In particular, to minimize the *RMSE* values for the complete field and obtain an average percentage difference between predicted and measured values of yield within the stable area identified for the 5-year crop rotation, the validation of model was performed according to the suggestions of the farmer, resumed in following assumptions:

- soil profile resulted different for the two stable area, *HS* area being characterised by a deeper exploitable soil profile than *LS* area, because of the presence in the latter of a greater soil strength in the deeper layer caused by a similar clay content and a lower organic carbon percentage;
- the volume available for root growth was different within field, the greater volume corresponding to the *HS* area (0÷60 cm), respect to the *LS* area (0÷45 cm);
- during period of the growing season having higher or lower rainfall than the annual average stresses were more relevant for *LS* area because of the slower water infiltration and the

impendence of capillary water ascendance respectively. Consequently, the water balance was differently entered into the input model to simulate different environmental condition.

After validating model, it was run to simulate the yield grain data, that were finally used to analyse the long-term temporal stability of spatial variability of yield.

2.2.7.- Simulated long-term temporal stability

Based on long-term predicted yield data, the identification of long-term temporal stability of spatial variability of yield for the 1989-2002 period was performed in *ArcView version 3.2*^{TM}, after importing the predicted yield data. Spatial and temporal variability of yield were determined separately for different crops, according to the method previously described, in order to increase the accuracy of the estimation and the variability due to the presence of different crops in the crop rotation (Bjarne and Steffen, 2003). In particular, the spatial variability of yield was calculated by interpolating the long-term predicted yield values and by averaging the annual data. The temporal variance was determined for each crop by averaging the predicted annual temporal variance in the considered long-period.

The temporal stability of spatial variability was determined for each crop was calculated by overlying the maps of spatial variability and temporal variance of yield. In particular, for maize and wheat a threshold of 10% was considered to identify the area within field having yield greater than the long-term average value – *i.e,.* yield 10% greater than average value – whilst yield values ≤ than a percentage spatial variability of 10% were classified as lower yield. A threshold of ± 2.42 t ha^{-1} and ± 1.40 t ha^{-1} – calculated as the average variance affecting yield over years within the complete field – was used to identify area being characterised by temporal stability over years for maize and wheat respectively. For soybean thresholds of 20% and ± 0.84 t ha^{-1} were used for identifying spatial and temporal pattern respectively.

By overlying the map of relative percentage difference and that of temporal variance, area characterised by temporal stability of spatial variability of yield and having high yield level were defined as long-term *HS* and *LS* area, according to the stability criteria.

After calculating the stable map pattern for each crop, these ware overlaid to identify a long-term stable map, reporting the homogeneous area having high or low yield production and lower temporal variance of spatial variability of yield.

Statistical analyses and *ANOVA multivariate* were developed in *SAS version 8.0* (*SAS Institute Inc*., 1999).

2.3.- Results and discussion

2.3.1.- Yield monitoring

Yield pattern was different between different growing seasons for the same crop, it attaining different level of production (Table 2), whilst an appreciable intra-year spatial variability was detected within field, as shown by the yield maps based on the data collected with the yield monitor system and downloaded at the farmer's PC (Figure 2).

Table 2.- Descriptive statistics for yield row data monitored during the crop rotation (1998-2002). Different letters indicate significant differences between different growing seasons for the same crop (*LSD* test, P≤0.05).

Statistics	**Grain yield (t ha^{-1})**				
	1998	1999	2000	2001	2002
	maize	soybean	maize	wheat	soybean
mean	9.69 a	4.14 a	8.25 b	6.40	3.30 b
mode	10.84	4.22	6.99	5.30	3.25
median	10.16	4.24	8.28	6.40	3.30
standard deviation	± 2.24	± 0.52	± 1.73	± 1.09	± 0.39
kurtosis	1.10	4.47	1.53	5.41	10.61
skewness	-0.51	-0.14	0.73	1.01	0.13
minimum	0.67	0.42	0.72	0.58	0.46
first quartile (Q_1)	8.95	3.99	7.26	5.83	3.17
third quartile (Q_3)	11.10	4.44	9.56	7.07	3.43
maximum	21.00	7.10	18.41	16.29	5.83
coefficient of variation (*CV*; %)	23.11	12.54	20.95	17.06	11.69

The mean yield was statistically different in different growing seasons, and in particular for maize in 2000 the average yield value was 15% (1.68 t ha^{-1}) lower than that monitored in 1998, whilst for soybean in 2002 the average yield obtained was 20% (0.98 t ha^{-1}) lower in comparison with that monitored in 1999. For wheat, the average production monitored within field was slightly lower than the average value generally obtained by the farm, according to the environmental conditions of the experimental area. The intra-year variations of yield was appreciable, as indicated by values of both the range of yield – maximum value minus minimum value of yield – and the coefficient of variation, especially for maize respect to the others crops, generally ranging from a minimum of 11.69% for soybean in 1999 to a maximum of 23.11% for maize in 1999, and having over years an average value of 17.07%, according to that suggested by literature, for both large (Jaynes and Colvin, 1997) and small field scale (Yamagishi et al., 2003).

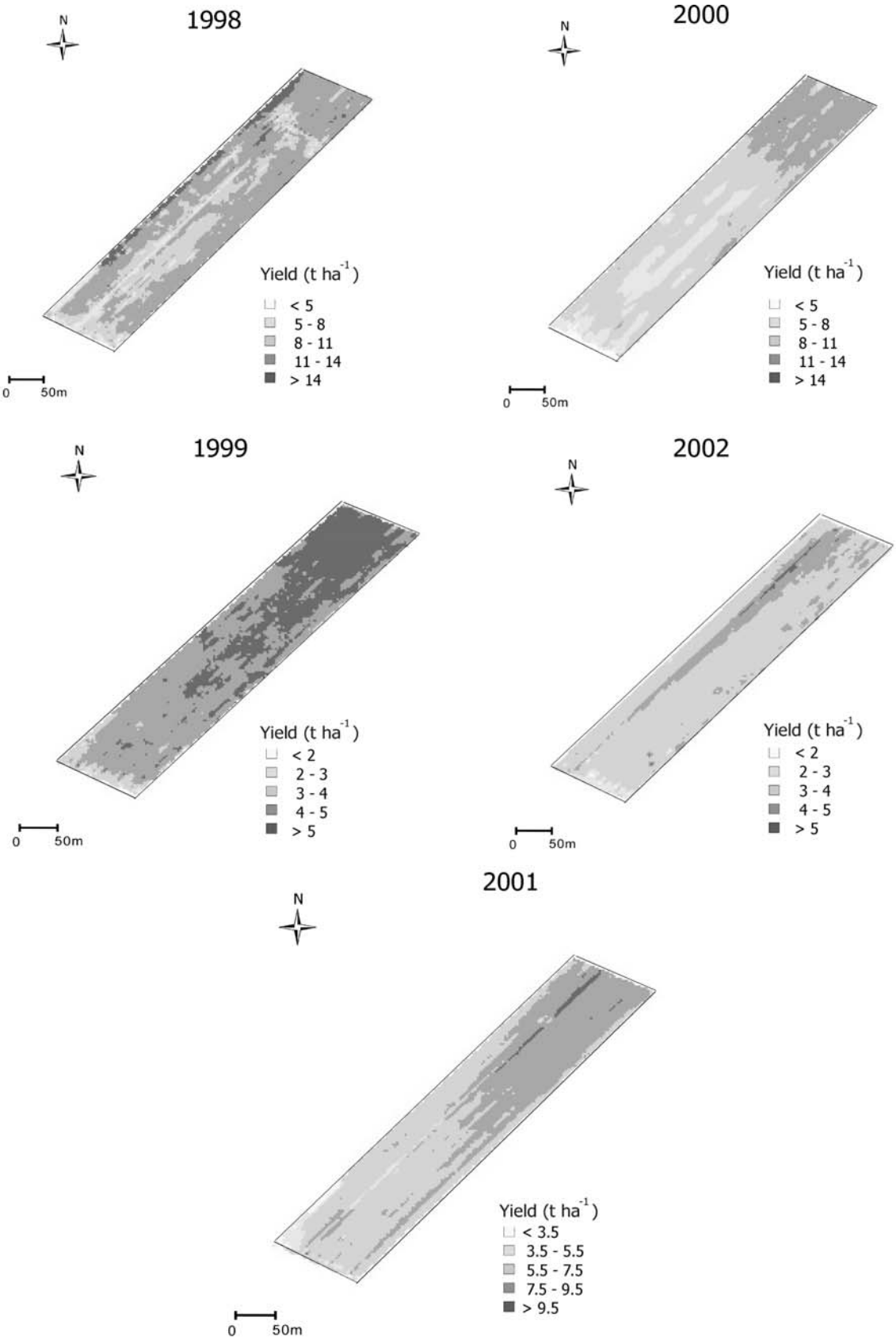


Figure 2.- Yield maps reporting the yield pattern obtained over different growing seasons for the same crop (1998 and 2000: maize; 1999 and 2001: soybean; 2002: wheat).

2.3.2.- Temporal stability of spatial variability

The analysis of temporal stability, integrating the 5-year spatial pattern (Figure 3) and temporal variance (Figure 4) of yield within field, showed the presence of two stable area, corresponding each one approximately to the 50 % of the field and having statistically higher or lower yield than the average value and lower temporal variance over years (Table 3). A small area characterised by temporal instability (*U* area) corresponded to the boundary of the field and was not considered in the analysis. In particular, field resulted divided into two distinct yield zones north-south oriented, having a stable productive trend over years but different yield level (Figure 5). The small area of unstable yield resulted localised particularly along the northern and southern boundary lines of the field, and probably it depended on errors affecting yield mapping and greater soil compaction due to the traffic of machinery during tillage operations.

Table 3.- Yield data measured during the crop rotation for stable area with high (*HS*) or low (*LS*) yield level. Different lower-case letters for the single year (the same crop) indicate statistically significant differences between *HS* and *LS* area, whilst different capital letters refer to the statistically significant differences regarding the yield data registered for the same crop within *HS* or *LS* areas during crop rotation (LSD test, P≤0.05).

Statistics	**Grain yield (t ha^{-1})**									
	1998 (maize)		1999 (soybean)		2000 (maize)		2001 (wheat)		2002 (soybean)	
	HS	*LS*	*HS*	*LS*	*HS*	*LS*	*HS*	*LS*	*HS*	*LS*
mean	10.60aA	8.95bA	4.45aA	4.17bA	9.58aB	7.24bB	7.16a	5.98b	3.41aB	3.42bB
minimum	6.27	6.24	4.10	3.90	7.92	6.07	6.35	4.64	3.11	3.17
maximum	11.70	10.78	4.82	4.41	10.82	8.61	7.82	6.73	4.18	3.77
st.dev.	± 1.51	± 1.39	± 0.20	± 0.16	± 1.01	± 0.79	± 0.42	± 0.57	± 0.26	± 0.20
CV (%)	14.24	15.55	4.36	3.86	10.62	10.95	5.87	9.50	7.57	5.96

2.3.3.- Annual simulation

The unstable area identified within field according to the stability criteria was not entered into the model, because of the small surface area covered, but sampled locations displaced within them were entered in the nearest *HS* or *LS* area displaced within field. Consequently yield data were predicted for the homogeneous *HS* and *LS* area identified within field, with variable Root Mean Square Error

(Table 4), being different by considering different growing seasons for the same crop cultivated and the different area identified within field and attaining an average value of 1.43 t ha^{-1} during the crop rotation.

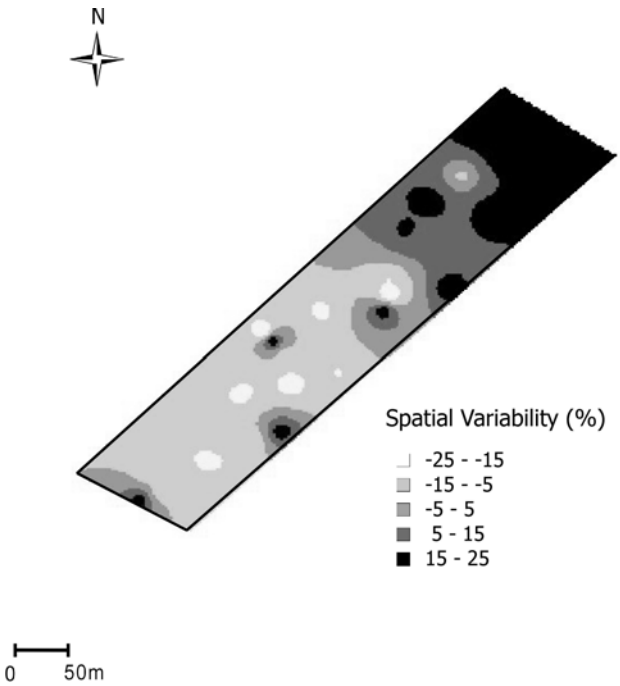


Figure 3.- Spatial pattern of yield over the 5-year crop rotation, expressed as average relative percentage difference from the average yield obtained within field.

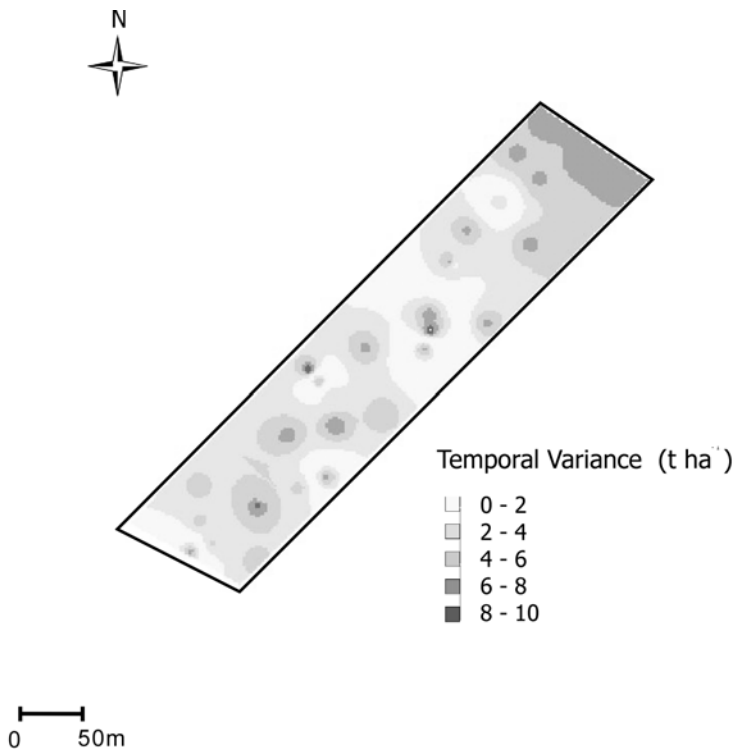


Figure 4.- Temporal variance (t ha^{-1}) revealed during the 5-year crop rotation within field.

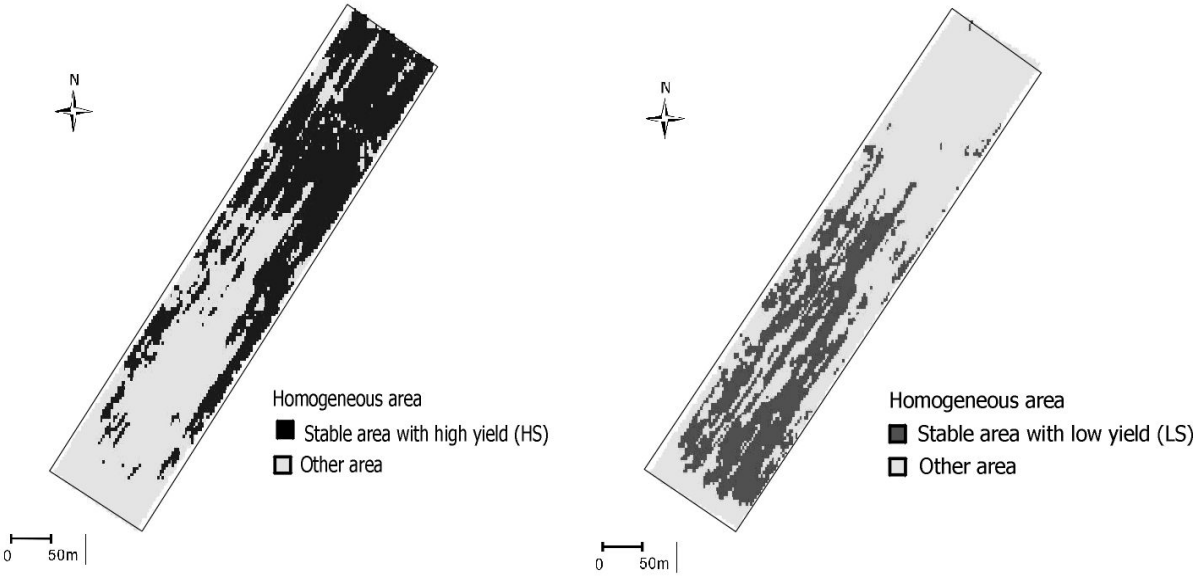


Figure 5.- Temporal stability map, reporting the presence of area within field having different stable level of production, identified as area having high yield (*HS* area) (left) and low yield (*LS* area) (right) pattern over years.

Table 4.- Predicted long-term pattern of yield and root mean square error for the homogeneous stable area (*HS* and *LS* area) and the complete field.

Scenarios	*Crop*	**Year**	***HS* area**		***LS* area**		*Complete field*	
			model runs	*RMSE* (t ha^{-1})	model runs	*RMSE* (t ha^{-1})	model runs	*RMSE* (t ha^{-1})
1	maize	1998	16	1.94	19	2.24	35	2.11
	maize	2000	16	1.74	19	2.11	35	1.95
2	wheat	2001	16	1.10	19	0.80	35	0.95
3	soybean	1999	16	1.40	19	1.37	35	1.38
	soybean	2002	16	0.53	19	0.92	35	0.76

Maize

The *RMSE* was relatively greater for maize (2.11 t ha^{-1} and 1.95 t ha^{-1} in 1998 and 2000 respectively), and lower for soybean cultivated in 2002 (0.76 t ha^{-1}). The same pattern was found for the comparison between predicted and measured yield data for the *HS* and *LS* area, whilst maize and wheat showed greater values in *HS* area and soybean in *LS* area respectively.

Consequently, the difference between the predicted and the measured value of yield resulted statistically significant for maize only in 1998 within the complete field (Table 5) (Figure 6), the simulated production being lower than measured, a result subsequently found for the *HS* and the *LS* area in the same growing season, whilst considering the stable area the predicted data were greater than measured in *LS* area in 2000 (Figure 7 and 8). Despite the statistically significant differences described, the percentage difference for the two growing seasons was lower in both year than the threshold of 15% (12% in 1998 and 2.6% in 1998 and 2000 respectively), the limit used to consider acceptable the performance of the simulation model.

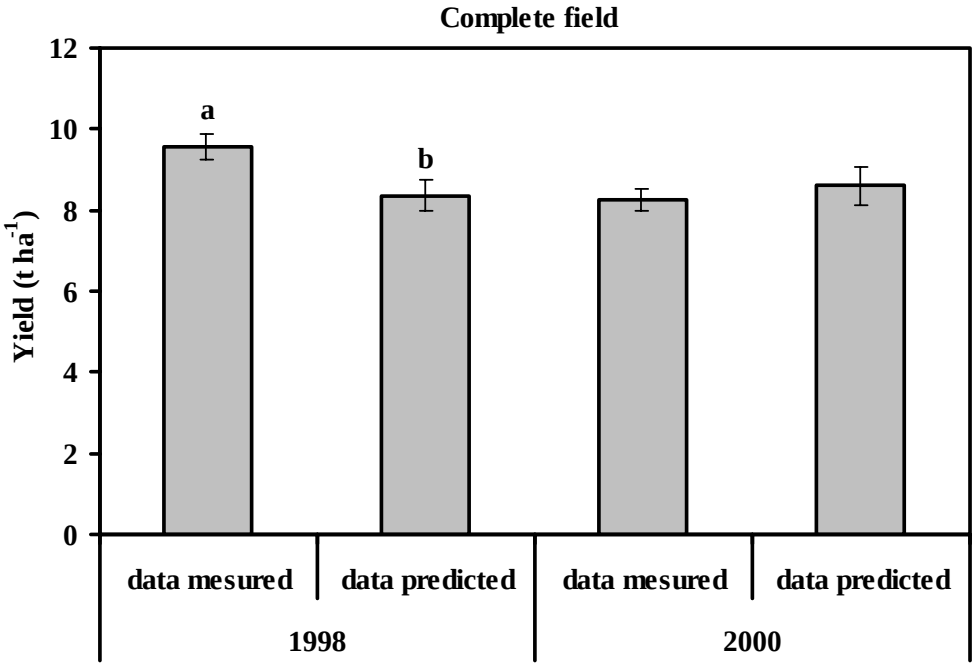


Figure 6.- Measured and predicted data for maize within the complete field. Vertical bars refer to the standard error of yield data. Different letters indicate statistically significant differences between measured and predicted yield data for the same growing season (*LSD* test, P≤0.05).

Wheat

The difference between predicted and measured yield value for wheat was slightly statistically significant because of the over-estimated yield data (Table 5), within both the complete field (Figure 9) and the stable area identified according to the level of yield obtained (Figure 10 and 11), but the average percentage difference between the predicted and the measured yield data was appreciably lower (8%) than 15%, and the accuracy of the simulation was considered acceptable.

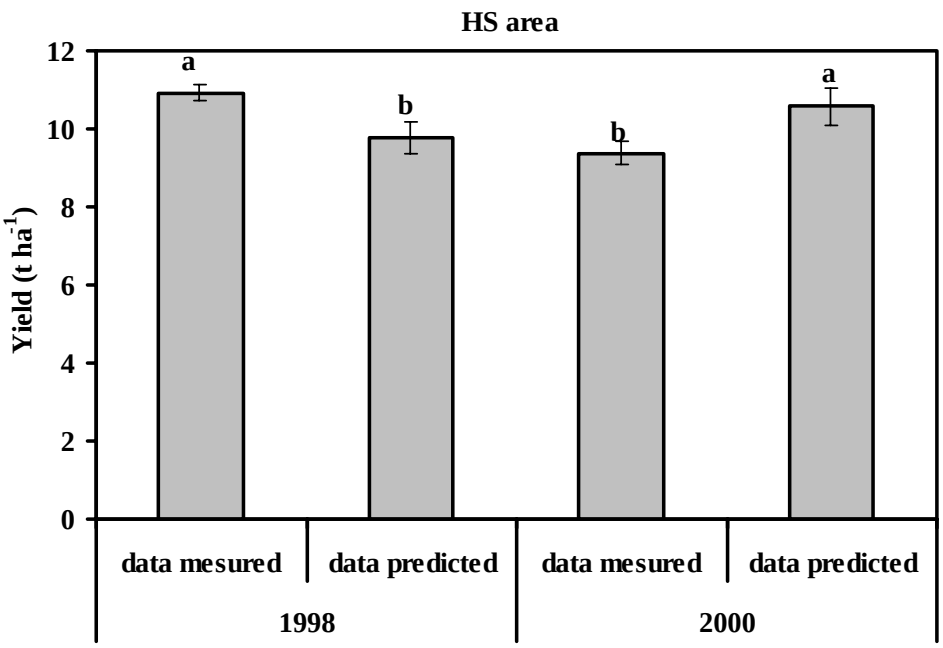


Figure 7.- Measured and predicted data for maize within *HS* area. Vertical bars refer to the standard error of yield data. Different letters indicate statistically significant differences between measured and predicted yield data for the same growing season (*LSD* test, P≤0.05).

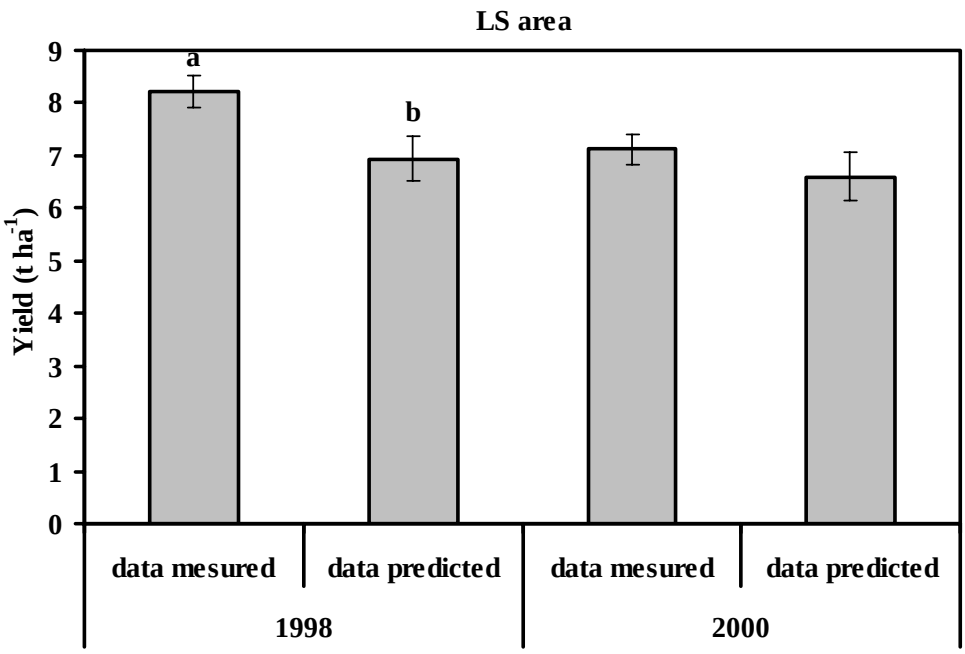


Figure 8.- Measured and predicted data for maize within *LS* area. Vertical bars refer to the standard error of yield data. Different letters indicate statistically significant differences between measured and predicted yield data for the same growing season (*LSD* test, P≤0.05).

Soybean

The differences between predicted and measured yield value for the complete field for soybean were appreciably significant and negligible in 1999 and 2002 respectively (Table 5) (Figure 12). In particular, the difference was statistically significant for the 1999 in all the scenarios considered, both for the complete field and the identified stable area, as confirmed by the percentage difference between the predicted and the measured yield data, being twofold greater than the threshold limit of 15%, and consequently by the root mean square error. Despite to that, in 2002 this difference was generally lower (12%) and appreciable only for the *LS* area, being negligible for the *HS* area (Figure 13 and 14).

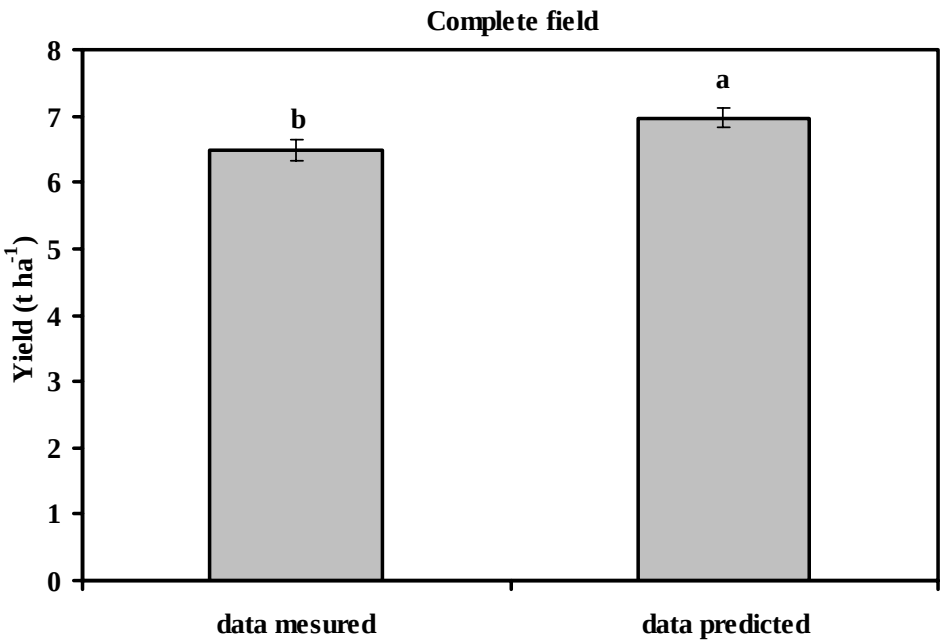


Figure 9.- Measured and predicted data for wheat within the complete field. Vertical bars refer to the standard error of yield data. Different letters indicate statistically significant differences between measured and predicted yield data (*LSD* test, P≤0.05).

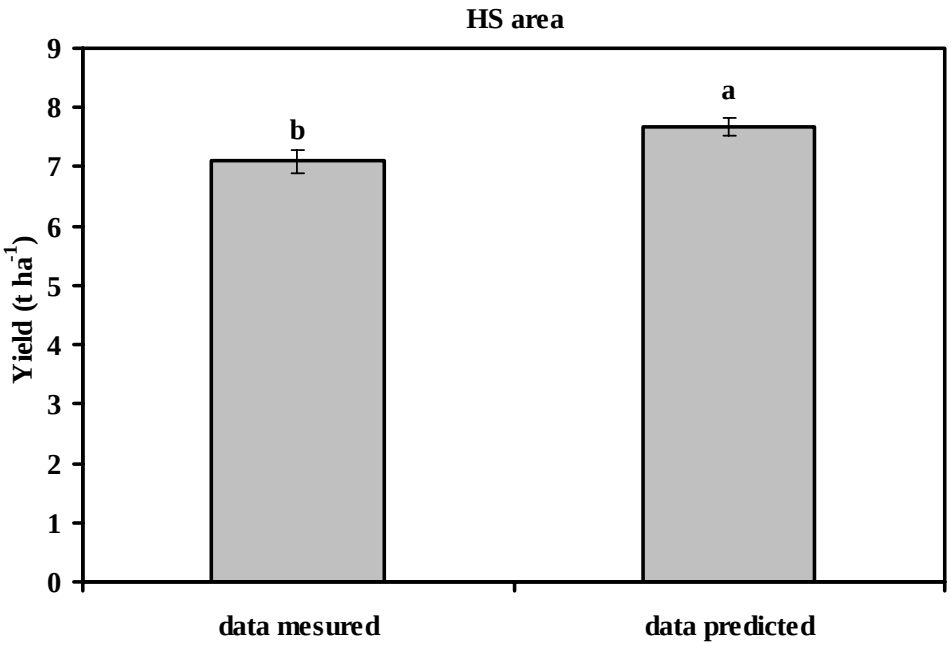


Figure 10.- Measured and predicted data for wheat within *HS* area. Vertical bars refer to the standard error of yield data. Different letters indicate statistically significant differences between measured and predicted yield data (*LSD* test, P≤0.05).

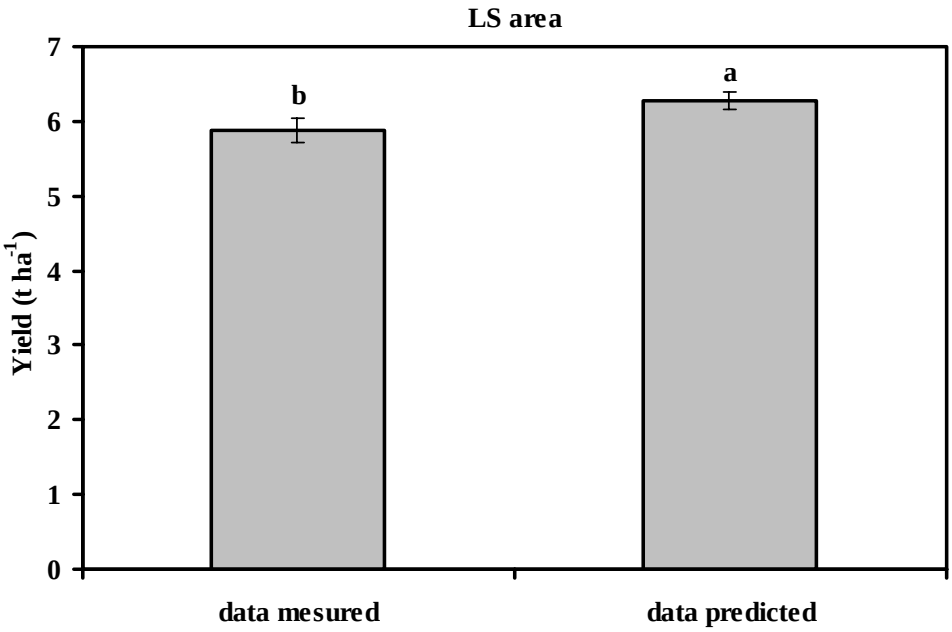


Figure 11.- Measured and predicted data for wheat within *LS* area. Vertical bars refer to the standard error of yield data. Different letters indicate statistically significant differences between measured and predicted yield data (*LSD* test, P≤0.05).

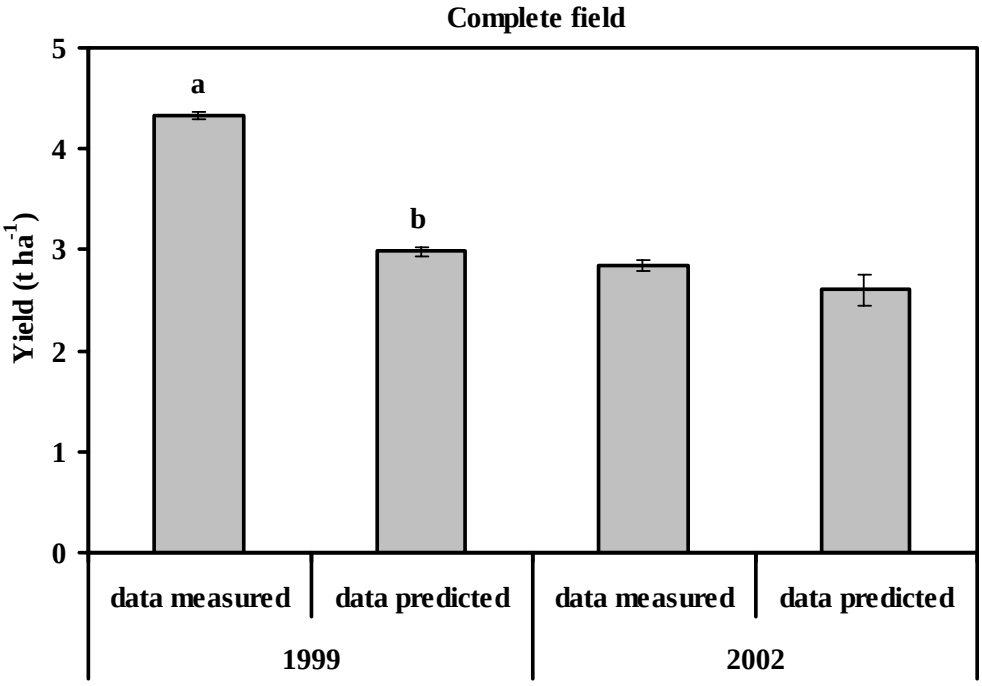


Figure 12.- Measured and predicted data for soybean within the complete field. Vertical bars refer to the standard error of yield data. Different letters indicate statistically significant differences between measured and predicted yield data for the same growing season (*LSD* test, P≤0.05).

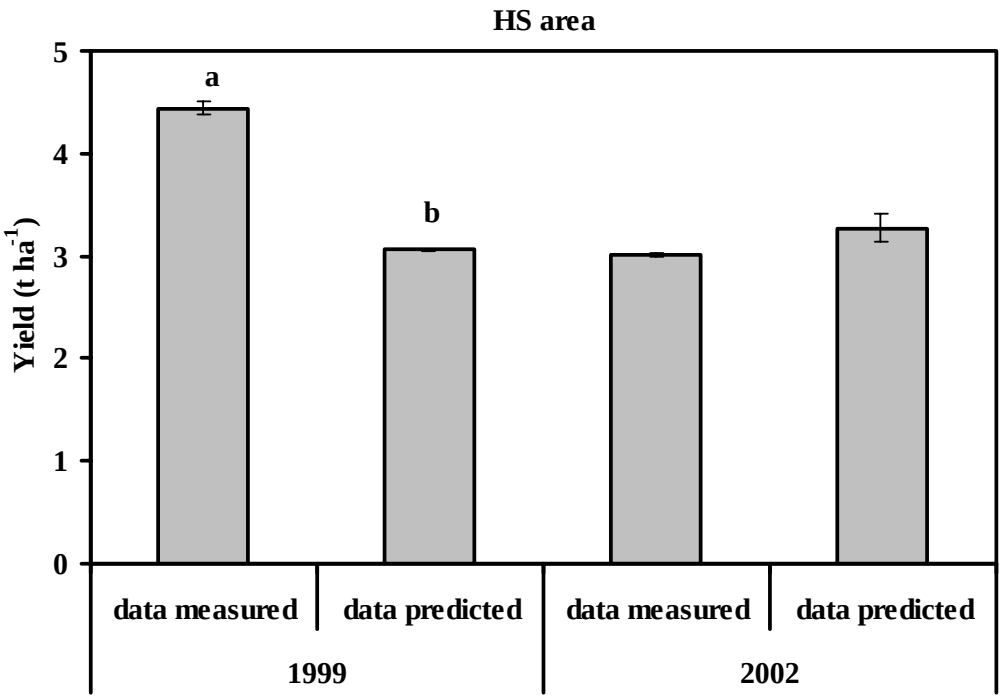


Figure 13.- Measured and predicted data for soybean within *HS* area. Vertical bars refer to the standard error of yield data. Different letters indicate statistically significant differences between measured and predicted yield data for the same growing season (*LSD* test, P≤0.05).

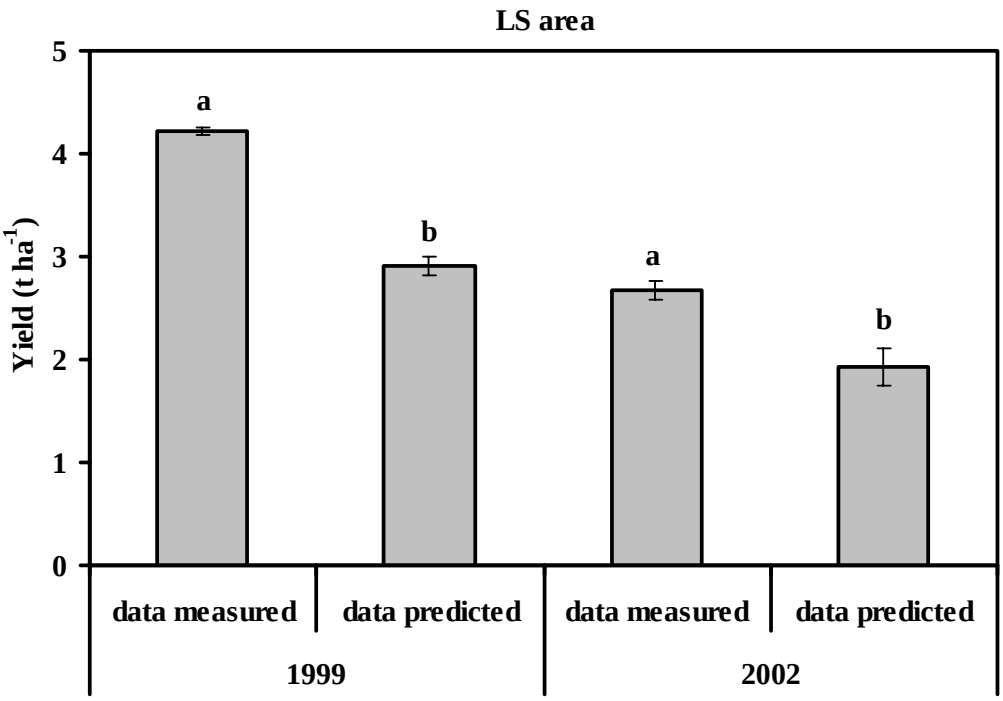


Figure 14.- Measured and predicted data for soybean within *LS* area. Vertical bars refer to the standard error of yield data. Different letters indicate statistically significant differences between measured and predicted yield data for the same growing season (*LSD* test, P≤0.05).

Table 5.- Predicted and measured annual yield data for single crop analysed during the 5-year crop rotation (* = significant at P< 0.05 level of significance; ** = significant at P< 0.01 level of significance; *** = significant at P< 0.001 level of significance).

Area	**Data**	**maize**				**soybean**				**wheat**	
		1998		2000		1999		2002		2001	
		mean	dev.st.	mean	dev.st.	mean	dev.st.	mean	dev.st.	mean	dev.st.
field	measured	9.56	± 1.78	8.26	± 1.68	4.33	± 0.23	2.84	± 0.33	7.10	± 0.75
	predicted	8.36**	± 2.19	8.59	± 2.79	2.98***	± 0.30	2.60	± 0.96	7.67*	± 0.57
HS area	measured	10.92	± 0.77	9.38	± 1.24	4.44	± 0.25	3.01	± 0.08	5.88	± 0.68
	predicted	9.78**	± 1.56	10.59*	± 1.91	3.06***	± 0.02	3.27	± 0.55	6.28*	± 0.51
LS area	measured	8.20	± 0.93	7.13	± 1.26	4.22	± 0.16	2.68	± 0.39	6.49	± 0.93
	predicted	6.94**	± 0.88	6.60	± 1.99	2.91***	± 0.40	1.93***	± 0.78	6.97*	± 0.88

In general, the predicted data resulted slightly greater or lower than the measured values, but the percentage difference between them was acceptable, except for soybean cultivated in 1999, probably because of the residual effect of organic matter distributed in 1998 for supplying the elements requirements of maize, that was not taken into account by the simulation model. Anyway, based on the data obtained for the different annual scenarios, the performance of the prediction of yield data resulted acceptable, according to the values of root mean square error, and the long-term

simulation was performed, to take into account the partial influence on inter-years variability of yield of the within-field soil properties pattern and the climatic conditions.

2.3.4.- Soil properties spatial pattern

The field resulted approximately divided in two zones, north-south oriented and characterized by different soil static physical properties along the profile, the differences on sand and clay content between stale area being statistically significant and negligible respectively, whilst for the organic matter content the it resulted clearly divided into two zones, having a content of organic matter greater or lower than 3%. In particular soil properties resulted distributed within field approximately according to the homogeneously productive area, even if that explained the yield variability only in some cases, according to the suggestions reported in literature (Mallarino et al., 1999), probably because of the inter-relationships among soil properties and external factors and the their influence on dynamic soil attributes, as for example the hydraulic water limits and the derived available water content during the growing season (Figure 15). In particular, any statistically significant difference was found on clay content measured along the soil profile in homogeneous area, whilst the sand percentage and the organic matter content resulted statistically different in the upper layers and along the complete soil profile respectively. In the deeper layer (30÷45 cm) texture not showed differences among stable area, whilst the organic matter content was significantly grater in the *HS* area than in the other parts of the field (Table 6).

Table 6.- Average soil properties measured along soil profile for homogeneous area identified within field. Different letters indicate significant differences for the same soil attribute measured at each layer between different stable area (*LSD* test, P≤0.05).

Area	*Soil properties (expressed in %) for different layers*											
	0÷15 cm				**15÷30 cm**				**30÷45 cm**			
	Clay	Sand	Loam	OM	Clay	Sand	Loam	OM	Clay	Sand	Loam	OM
HS	39	25 a	35 b	3.73 a	38	24 a	38 b	3.71 a	40	21	39	3.61 a
LS	41	14 b	45 a	2.39 b	41	14 b	45 a	1.81 b	44	15	41	1.89 b

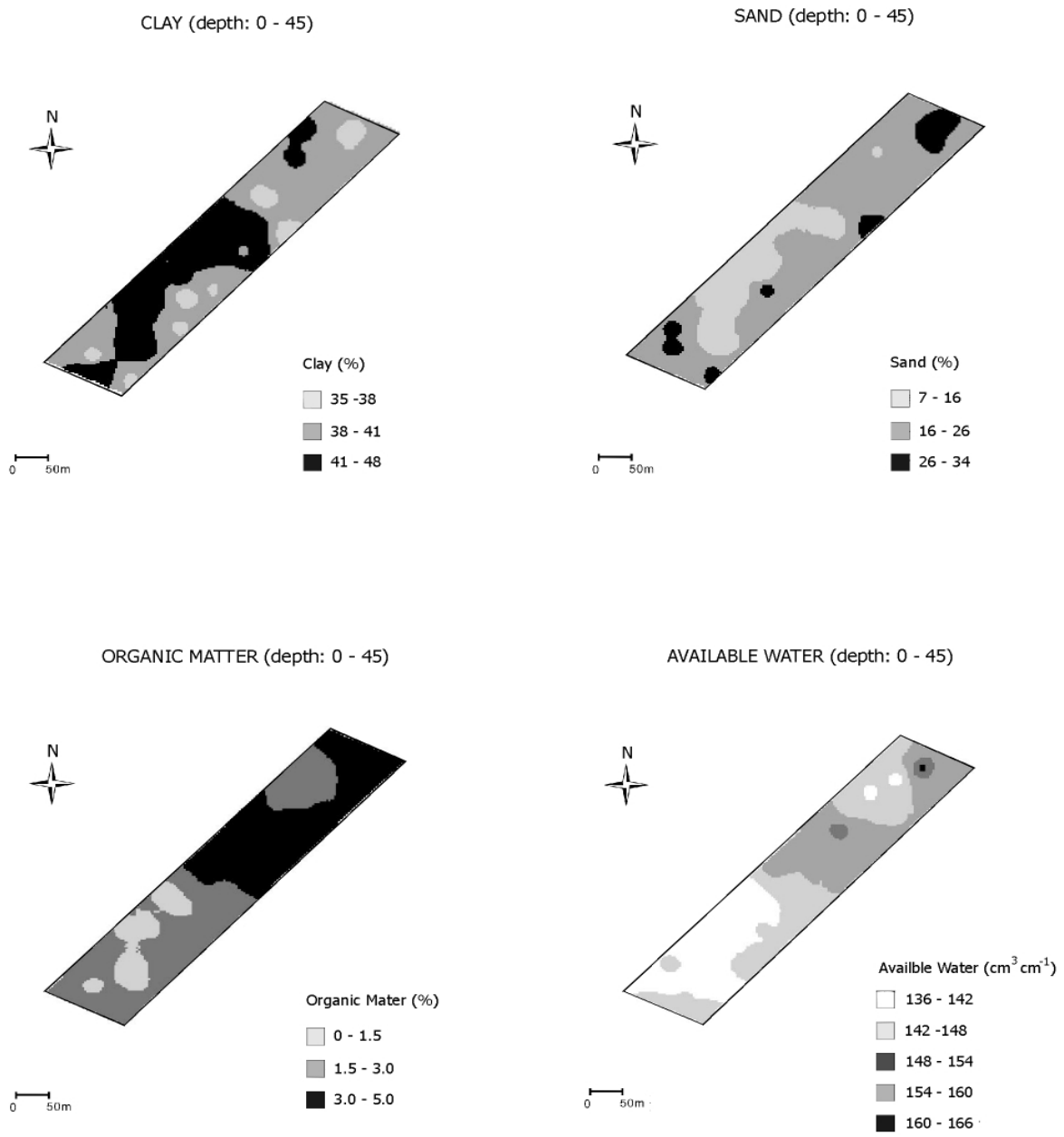


Figure 15.- Soil static physical properties and available water content maps reporting the different values measured within field along the soil profile (0÷45 cm).

2.3.5.- Climatic data

Climatic conditions resulted appreciably variable during the simulated period, both in terms of annual total rainfalls (mm) and average temperature (°C) values during the long-term period. In

particular, rainfalls resulted largely variable and characterised by a close standard deviation within the same year, increasing the differences between different growing seasons (Figure 16).

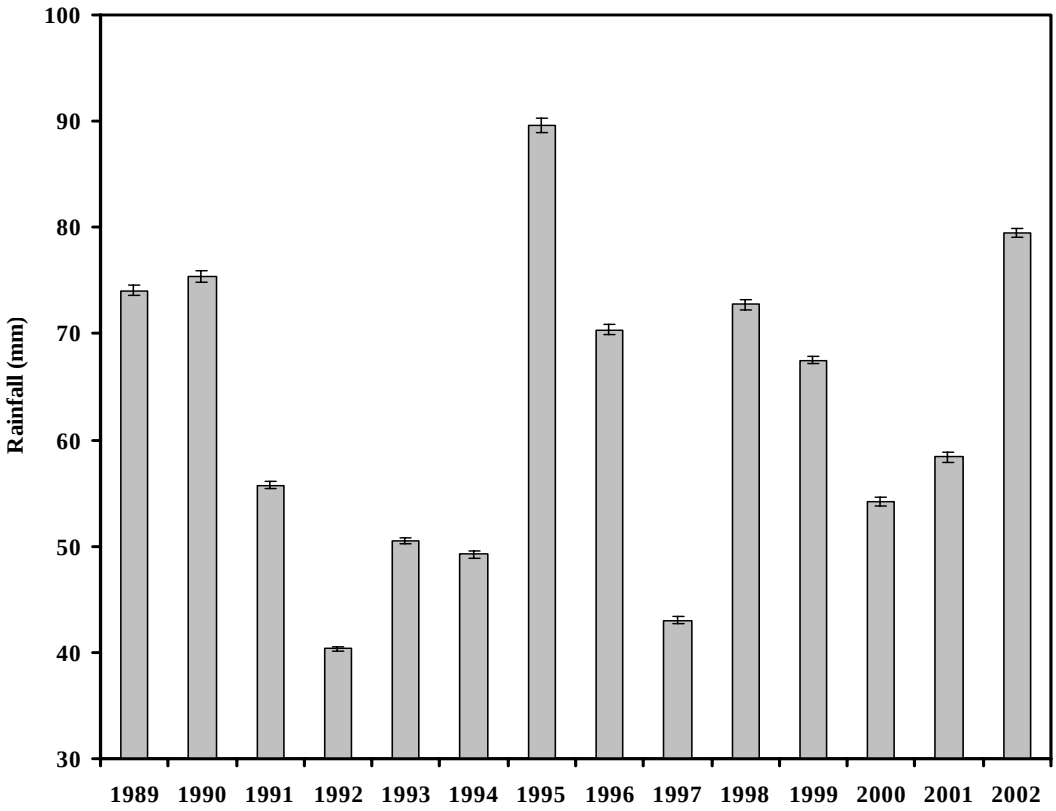


Figure 16.- Long-term trend (1989-2002) of the average rainfall (mm) occurred in the studied area during the growing season (March-October). Vertical bars refer to the standard errors for the measured data.

In particular, in some years the lack of rainfall resulted very appreciable during the growing season, as shown by the Figure 18a and Figure 18b, respect to the average measured in the growing season.

Average annual temperature resulted variable over years, with a considerable standard deviation for each year, and consequently, despite to some cases of particular greater or lower values, differences in the long-term period resulted less accentuated (Figure 17). In particular, during some growing season temperature resulted potentially particular favourable for crop growth, as for example in

1995 and in 1997, but the more important aspect was the combination of rainfall amount and temperature values. For example, as regards the cited years – i.e., 1995 and 1997 – the first was potentially more favourable for yield than the second, because of the relatively lower temperature and the greater rainfall occurred respect to the long-term average (Figure 19a and Figure 19b).

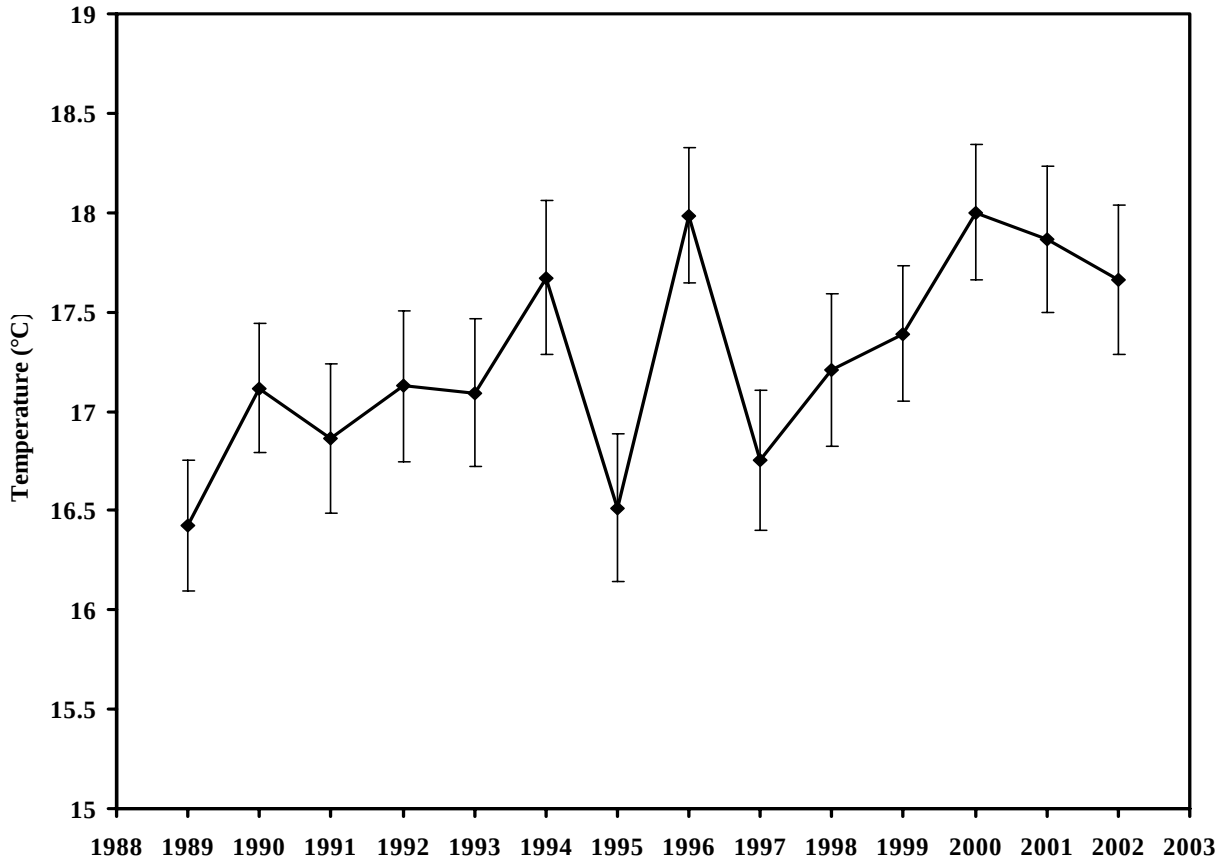


Figure 17.- Long-term (1989-2002) average temperature (°C) registered for the studied area during the growing season (March-October). Vertical bars refer to the standard errors for the measured data.

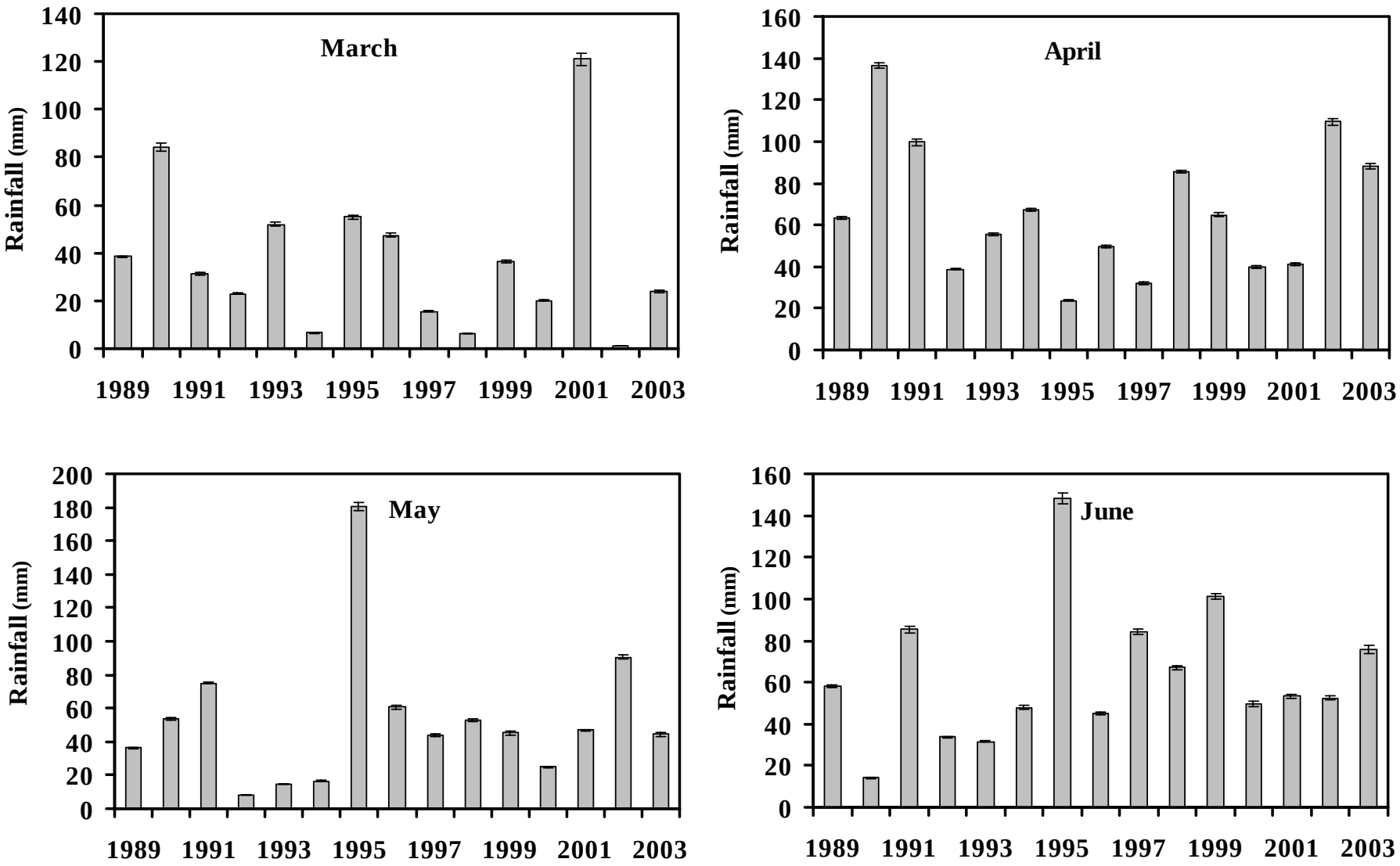


Figure 18.(a)- Monthly rainfall amount occurred in the studied period over years (March-June). Vertical bars refer to the standard errors.

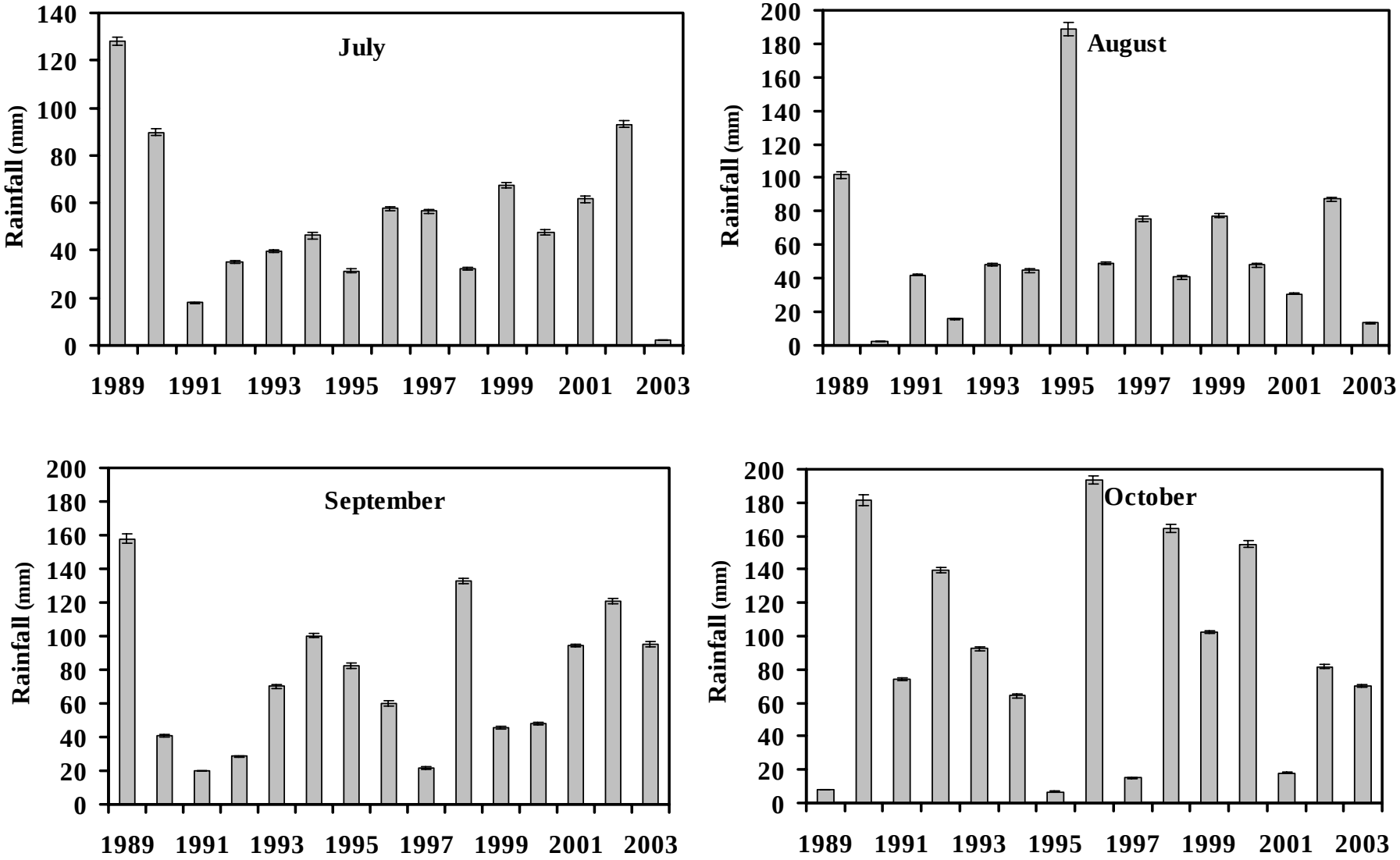


Figure 18.(b)- Monthly rainfall amount occurred in the studied period over years (July-October). Vertical bars refer to the standard errors.

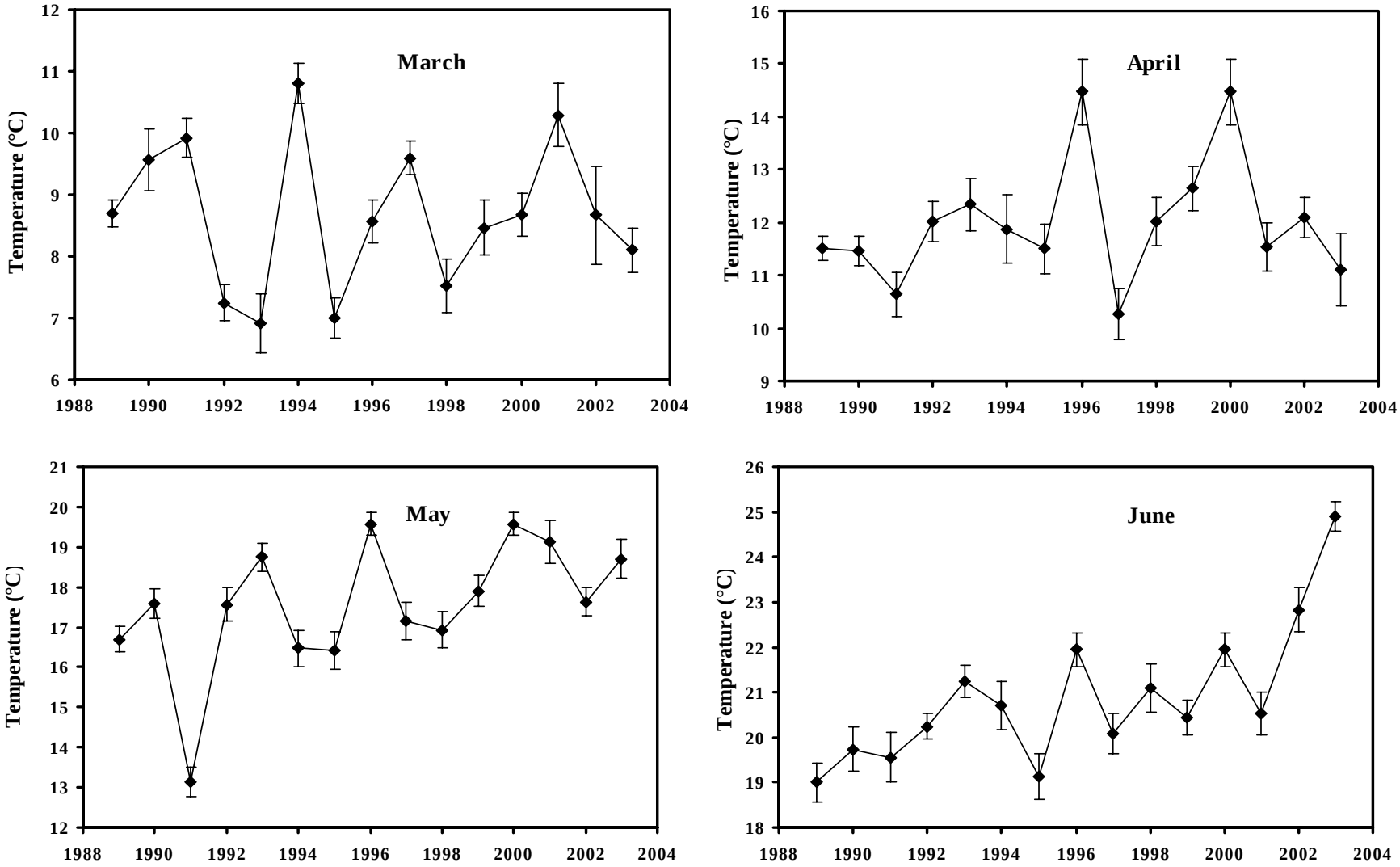


Figure 19.(a)- Monthly temperature registered in the studied period over years (March-June). Vertical bars refer to the standard errors.

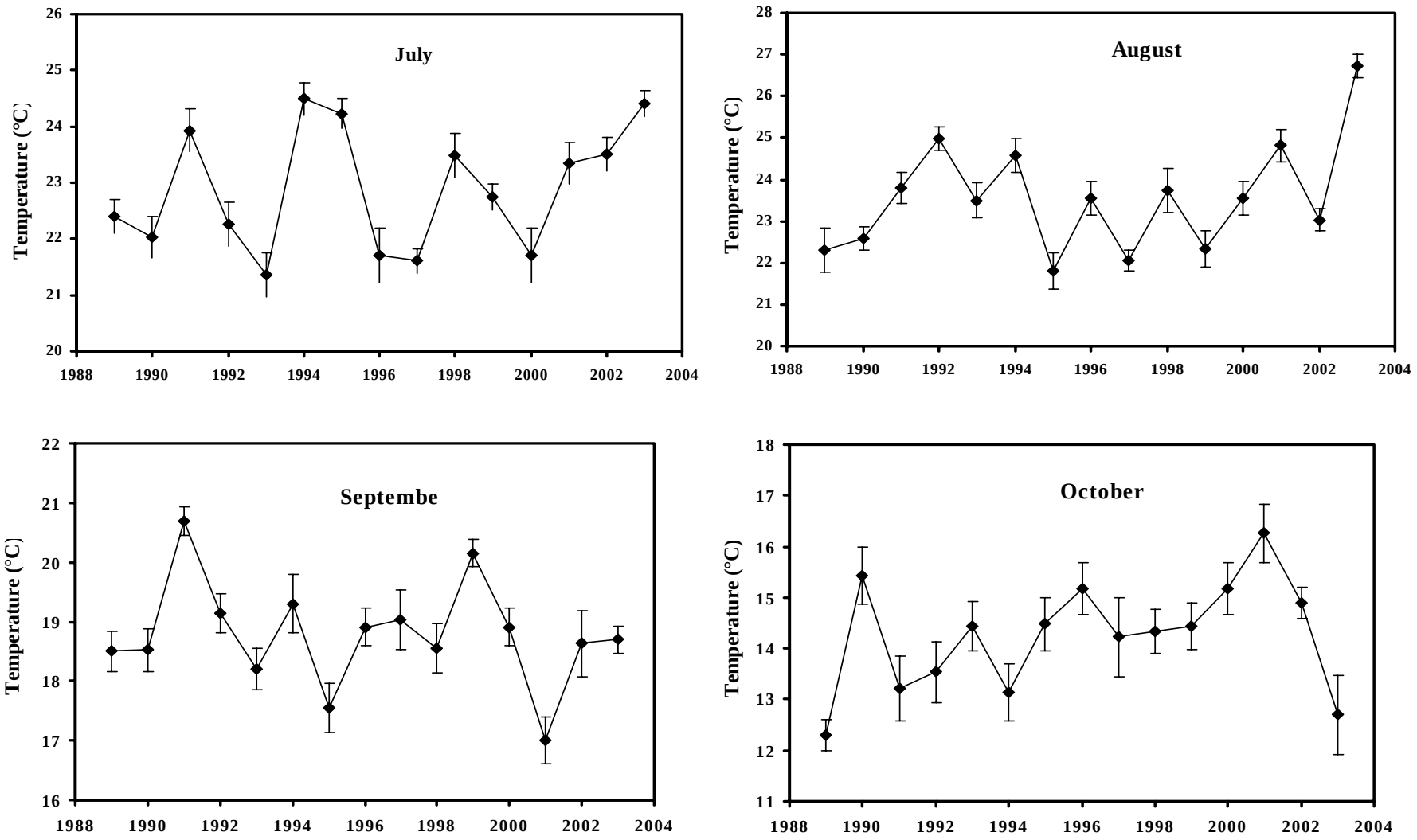


Figure 19.(b)- Monthly temperature registered in the studied period over years (July-October). Vertical bars refer to the standard errors.

2.3.6.- Long-term scenarios

The predicted long-term yield pattern showed statistically appreciable differences on yield data obtained in different years, according to the climatic conditions occurred in the studied area, with a considerable intra-year variability measured for some growing season, with different pattern for different crops, and a similar pattern between *HS* and *LS* area for different crops.

Maize

For maize, the long-term predicted yield showed a variable response to climatic conditions, with higher yield for years having greater rainfall and lower average temperature values (Figure 20). The intra-year variability was also appreciable for some growing seasons, as revealed by the variable standard deviation of yield data, it attaining a maximum of ± 4.19 t ha^{-1} in 1992 (Table 7(a)).

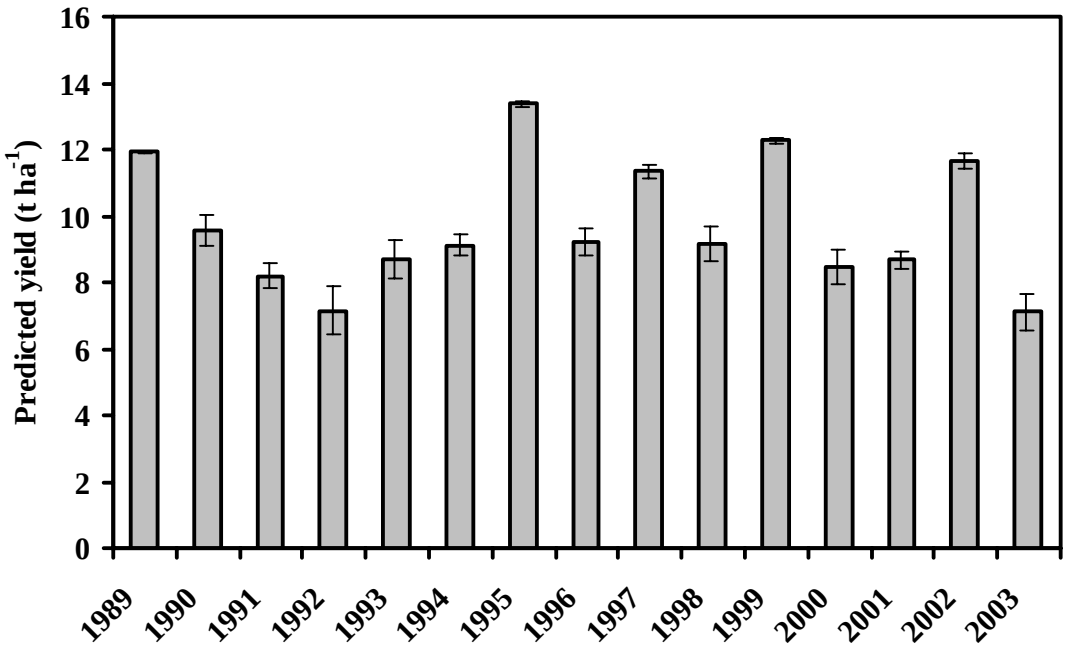


Figure 20.- Long-term predicted yield data for maize. Vertical bars refer to the standard errors of the yield data.

In particular, the predicted yield was statistically different between the stable area identified within field, *HS* area having greater yield than *LS* area (Figure 21), except for the 2002 growing seasons, in

which the opposite situation was found, with a low probability respect to the long-term scenario, probably because the favourable climatic conditions, especially as concerned greater rainfall, occurred during the growing season reduced the differences existing between the two area of the field.

The function of cumulative probability (*P*) ranged for maize in a large interval of yield, with a probability of 50% to obtain a predicted yield value slightly greater than 9 t ha^{-1}, and a low probability to obtained an average predicted yield greater than 12 t ha^{-1}, whilst the probability to obtain a yield lower than 8.5 t ha^{-1} in the long-term scenario was more appreciable (Figure 22).

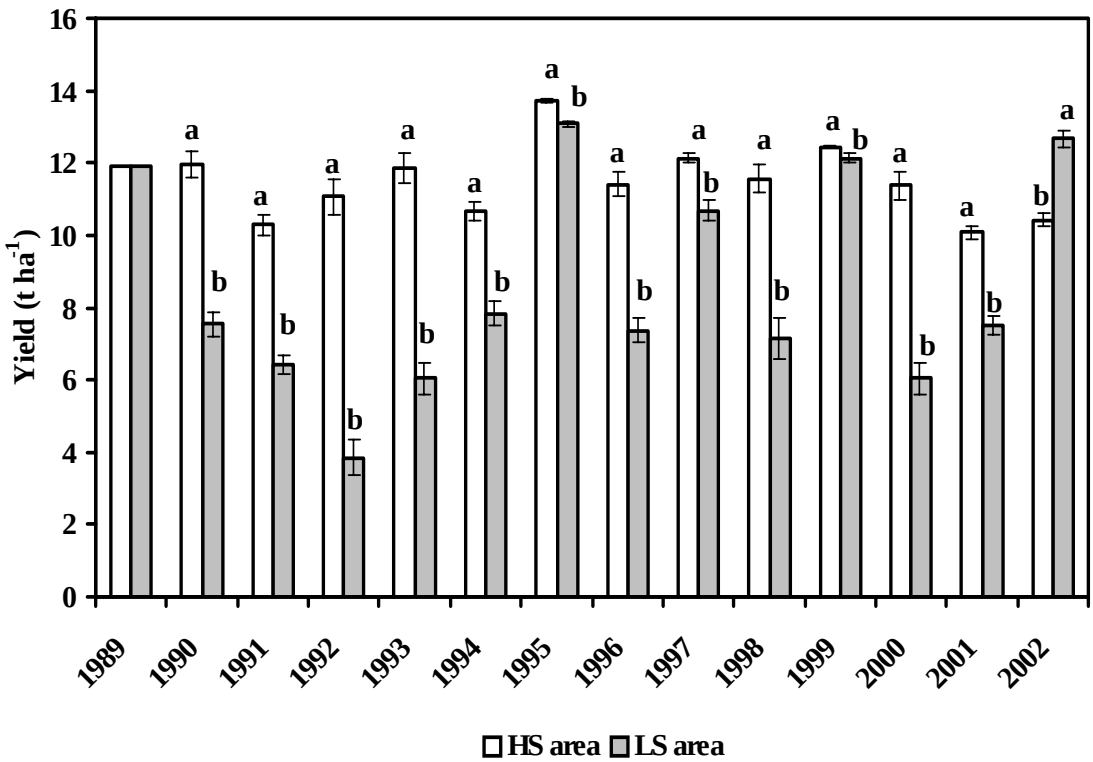


Figure 21.- Predicted yield data for maize in *HS* and *LS* area identified within field. Vertical bars refer to standard errors of yield data. Different letters indicate statistically significant differences between *HS* and *LS* area for each growing season (LSD test, P≤0.05).

Table 7(a).- Statistics for the predicted long-term yield values of maize.

Statistics	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
mean	11.92	9.56	8.20	7.15	8.70	9.12	13.37	9.21	11.34	9.17	12.27	8.47	8.68	11.65
st.dev.	0.03	2.67	2.23	4.19	3.42	1.92	0.45	2.50	1.17	3.05	0.41	3.19	1.62	1.42
variance	0.00	7.11	4.96	17.58	11.70	3.70	0.20	6.23	1.38	9.33	0.17	10.20	2.61	2.00
kurtosi	14.75	-1.97	-1.98	-2.07	-1.99	-1.00	-0.37	-1.97	0.46	-1.10	1.91	-2.04	-1.44	-1.97
skewness	-0.28	-1.03	-1.06	-1.05	-1.04	-093	-0.88	-1.01	-0.77	-0.91	-0.47	-1.02	-0.98	0.98
minimum	11.78	5.82	5.25	2.73	3.92	5.36	12.21	5.70	8.43	2.30	11.16	4.06	5.64	10.26
maximum	11.93	12.30	10.55	11.57	12.26	10.92	13.76	11.74	12.25	11.95	12.47	11.74	10.27	13.29
quartile (Q_1)	11.93	7.35	6.30	3.20	5.82	8.16	13.00	7.04	11.04	7.01	12.47	5.59	7.64	10.26
quartile (Q_2)	11.93	7.63	6.69	3.70	6.29	9.13	13.57	8.09	11.90	10.16	12.47	6.12	8.12	11.90
quartile (Q_3)	11.93	12.30	10.55	11.57	12.26	10.92	13.76	11.74	12.25	11.95	12.47	11.74	10.27	13.28
CV(%)	0.025	27.89	27.17	58.61	39.34	21.08	3.33	27.09	10.35	33.32	3.37	37.70	18.63	12.15

Table 7(b).- Statistics for the predicted long-term yield values of wheat.

Statistics	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
mean	7.28	8.78	3.21	3.09	4.91	10.98	6.06	6.71	7.83	9.17	2.09	8.63	8.31	2.68
st.dev.	1.63	0.46	1.61	1.33	2.04	0.03	1.70	1.60	1.63	1.25	1.41	1.55	0.48	1.34
variance	2.66	0.22	2.59	1.76	4.17	0.00	2.88	2.55	2.66	1.57	1.99	2.42	0.23	1.79
kurtosi	-1.85	-0.34	-1.59	-1.61	-1.85	-0.41	-1.78	-2.06	-1.90	-1.87	-1.71	-1.84	-1.57	-1.17
skewness	--	--	--	--	--	-0.10	--	0.90	--	-0.91	0.90	-1.11	--	--
minimum	5.38	8.09	1.55	1.61	2.59	10.94	3.89	5.12	6.08	7.24	0.64	6.41	7.45	1.44
maximum	9.97	9.97	6.33	5.51	8.45	11.04	9.11	8.63	10.50	11.03	4.93	11.05	8.90	5.74
quartile (Q_1)	5.67	8.41	1.80	1.91	2.99	10.96	4.50	5.23	6.26	8.01	0.83	7.20	7.85	1.52
quartile (Q_2)	6.79	8.73	2.18	2.19	3.37	10.98	5.64	5.30	7.55	9.29	1.06	8.04	8.34	1.67
quartile (Q_3)	8.90	9.14	4.55	4.28	6.83	11.00	7.72	8.41	9.41	10.42	3.44	10.19	8.79	3.66
CV(%)	22.41	5.28	50.07	42.94	41.60	0.26	27.99	23.81	20.83	13.65	67.34	18.01	5.78	50.03

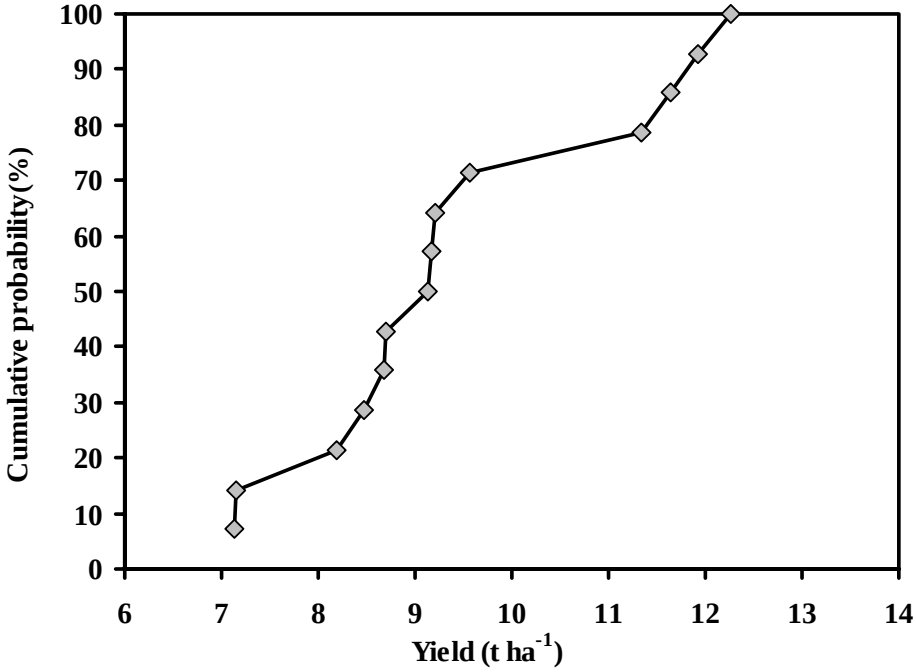


Figure 22.- Cumulative probability function for predicted yield of maize.

Wheat

For wheat, the long-term predicted yield showed a variable response over the considered period (Figure 23), with an average yield of 6.41 t ha^{-1}, annual data ranging from a maximum yield value of 11.04 t ha^{-1} in 1994 to a minimum of 0.64 t ha^{-1} in 1999 (Table 7(b)). The intra-year variability was considerable, particularly for some growing seasons, as revealed by the variable standard deviation of yield data and the coefficient of variation, it varying from a minimum of 0.26% to a maximum of 67.34% in the cited years respectively.

As regards the stable area identified within field, the differences between *HS* and *LS* area resulted statistically significant over the considered long-term period, with an appreciable greater yield measured for *HS* area than the respective *LS*, except in 1994, for which the average yield was the more homogenous within field and the differences between areas were negligible (Figure 24), by generally confirming the importance of the influence exerted by climatic conditions and the different results obtainable by varying soil properties.

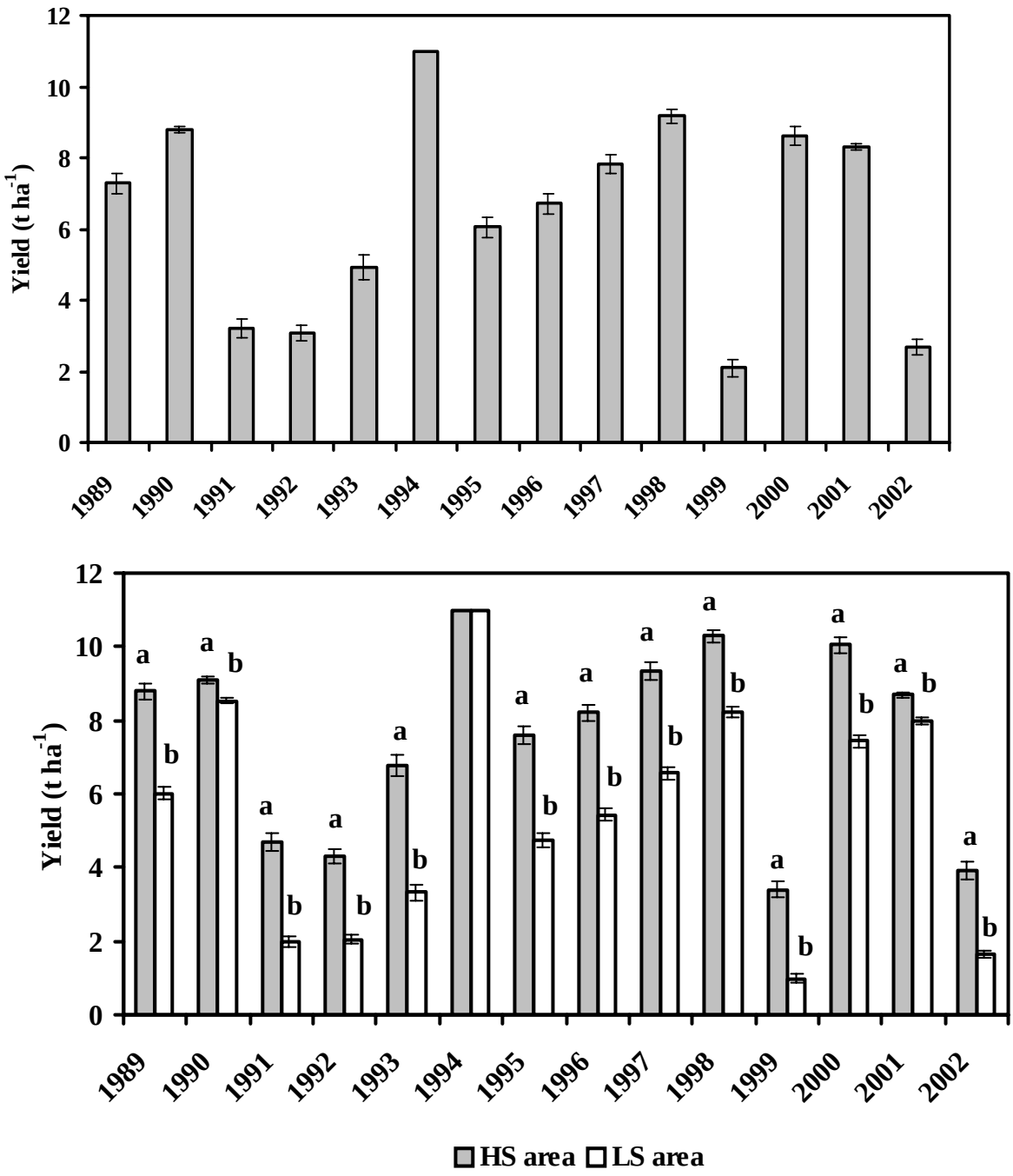
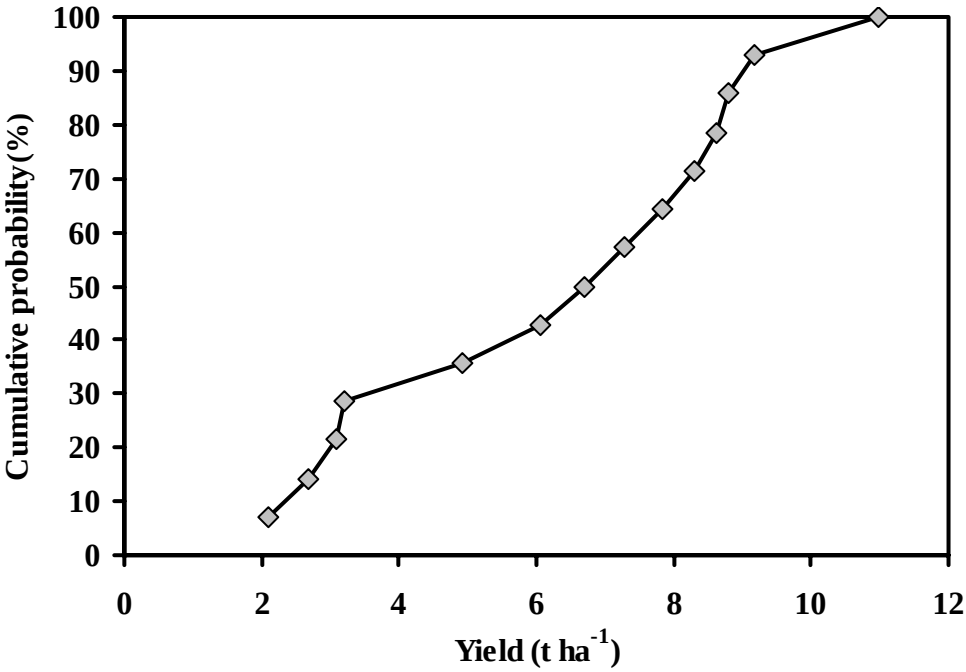


Figure 23.- Long-term predicted yield data for wheat. Vertical bars refer to the standard errors of the yield data.

Figure 24.- Predicted yield data for wheat in *HS* and *LS* area identified within field. Vertical bars refer to standard errors of yield data. Different letters indicate statistically significant differences between *HS* and *LS* area for each growing season (*LSD* test, P≤0.05).

The function of cumulative probability (*P*) for wheat showed a large interval of variation of yield, with a probability of 50% to obtain a predicted yield value of around 7 t ha^{-1}, whilst the probability to obtain a yield lower than 3 t ha^{-1} or greater than 10 t ha^{-1} were not frequently, the more probable



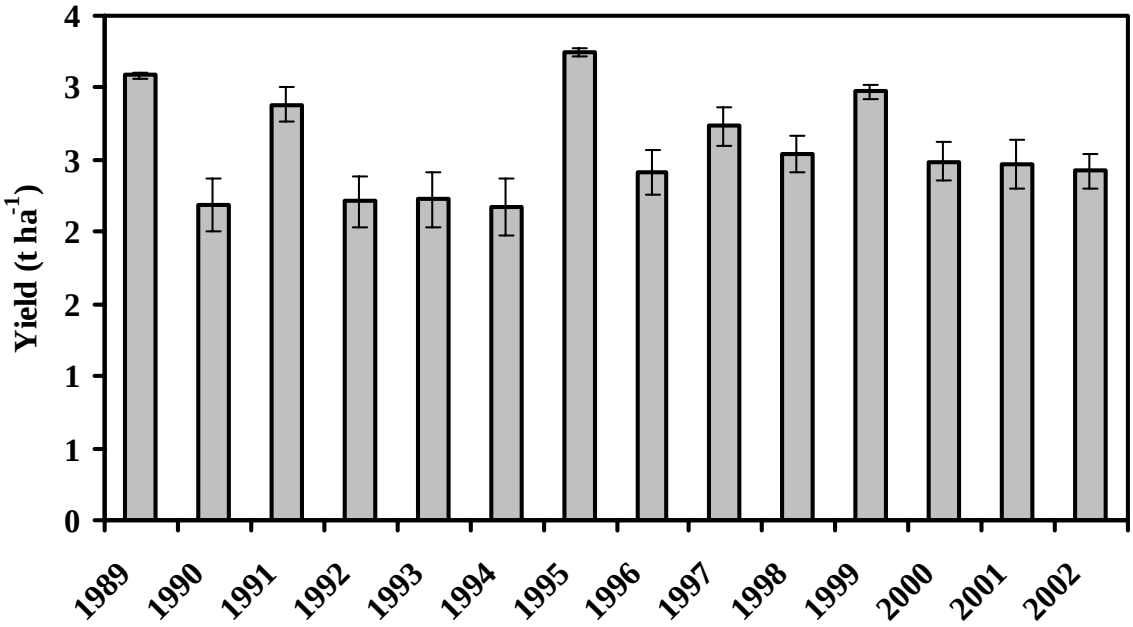
yield data varying from 5 t ha^{-1} (*P* = 35%) to 9 t ha^{-1} (*P* = 90%) (Figure 25).

Figure 25.- Cumulative probability function for predicted yield of wheat.

Soybean

For soybean, the long-term predicted yield showed a variable response over the considered period (Figure 26), with an average yield of 2.56 t ha^{-1}, annual predicted data ranging from a maximum

yield value of 3.41 t ha^{-1} in 2001 to a minimum of 0.30 t ha^{-1} in 1994 (Table 8). The intra-year variability was considerable, particularly for some growing seasons, as revealed by the variable standard deviation of yield data and the coefficient of variation, it varying from a minimum of 5.55% in 1995 to a maximum of 55.31% in 1994 respectively. As regards the stable area identified within field, the differences between *HS* and *LS* area resulted statistically significant over the complete considered long-term period, the yield measured in *HS* area being generally statistically appreciably different respect to that obtained in *LS* area, the long-term average being slightly



greater than 1 t ha^{-1}. In particular, the differences detected were appreciable for the growing seasons having lowest rainfall, as for example the 1992 or the 1994 (Figure 27).

Figure 26.- Long-term predicted yield data for soybean. Vertical bars refer to the standard errors of the yield data.

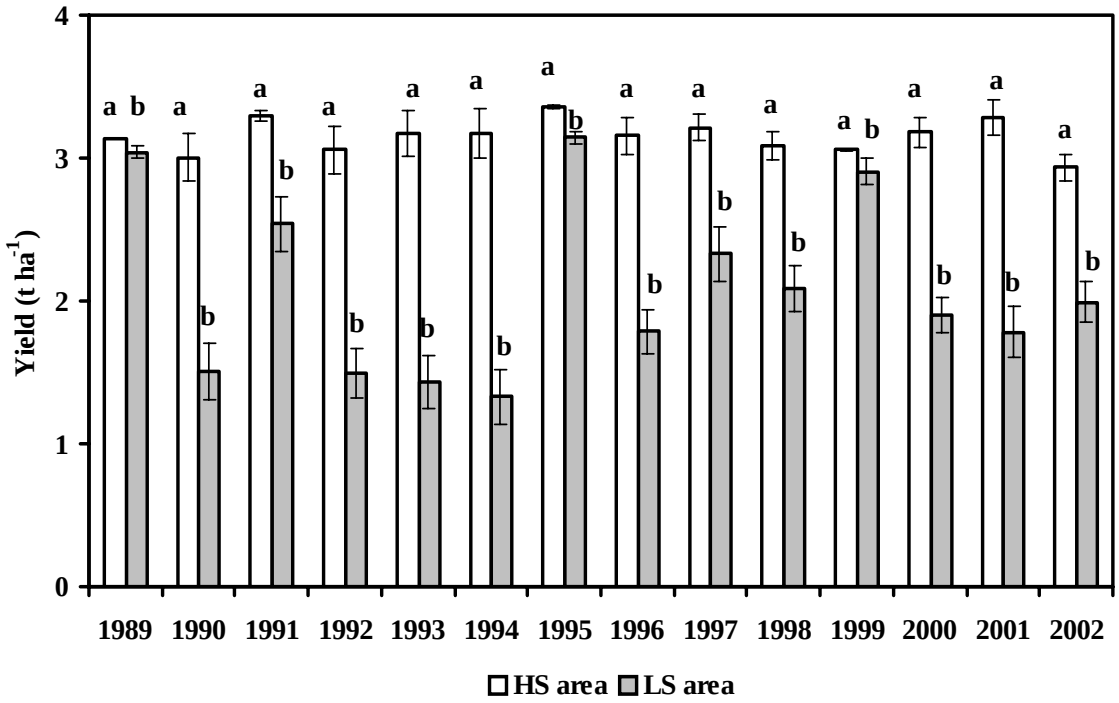


Figure 27.- Predicted yield data for soybean in *HS* and *LS* area identified within field. Vertical bars refer to standard errors of yield data. Different letters indicate statistically significant differences between *HS* and *LS* area for each growing season (*LSD* test, P≤0.05).

Table 8.- Statistics for the predicted long-term yield values of soybean.

Statistics	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
mean	3.08	2.19	2.89	2.21	2.23	2.17	3.24	2.41	2.73	2.54	2.98	2.49	2.47	2.42
st.dev.	0.13	1.09	0.72	1.06	1.14	1.20	0.18	0.91	0.79	0.76	0.30	0.80	1.00	0.69
variance	0.02	1.18	0.52	1.12	1.29	1.45	0.03	0.83	0.62	0.57	0.09	0.64	1.01	0.48
kurtosi	8.72	-1.29	2.50	-1.62	-1.70	-1.64	1.85	-1.60	0.65	-0.39	3.99	-1.94	-1.27	-0.38
skewness	-0.38	-0.90	-0.63	-0.96	-0.97	-0.98	-0.74	-0.96	-0.73	-0.84	-0.30	-1.00	-0.94	-0.90
minimum	2.62	0.36	0.99	0.51	0.42	0.30	2.69	0.83	0.78	0.87	2.01	1.22	0.55	0.87
maximum	3.14	3.17	3.34	3.23	3.33	3.36	3.38	3.29	3.31	3.18	3.28	3.29	3.41	3.04
quartile (Q_1)	3.10	1.53	2.77	1.51	1.46	1.43	3.15	1.78	2.60	2.19	3.06	1.77	1.84	2.20
quartile (Q_2)	3.13	2.52	3.34	1.89	1.75	1.81	3.37	2.34	3.23	2.76	3.07	2.05	2.33	2.35
quartile (Q_3)	3.13	3.17	3.34	3.23	3.33	3.35	3.38	3.29	3.31	3.18	3.07	3.29	3.41	3.02
CV (%)	4.10	49.64	25.05	47.94	51.01	55.31	5.55	37.79	28.80	29.74	10.06	32.30	40.70	28.58

The function of cumulative probability (*P*) calculated for soybean showed a relatively close interval of variation of yield (Figure 28), the more probable predicted yield ranging from a minimum slightly lower than 2.5 t ha^{-1} (*P* = 30%) to a maximum of around 3 t ha^{-1} (*P* = 75%÷90%), whit a probability of 50% to obtain an average predicted yield value close to the value of 2.5 t ha^{-1}.

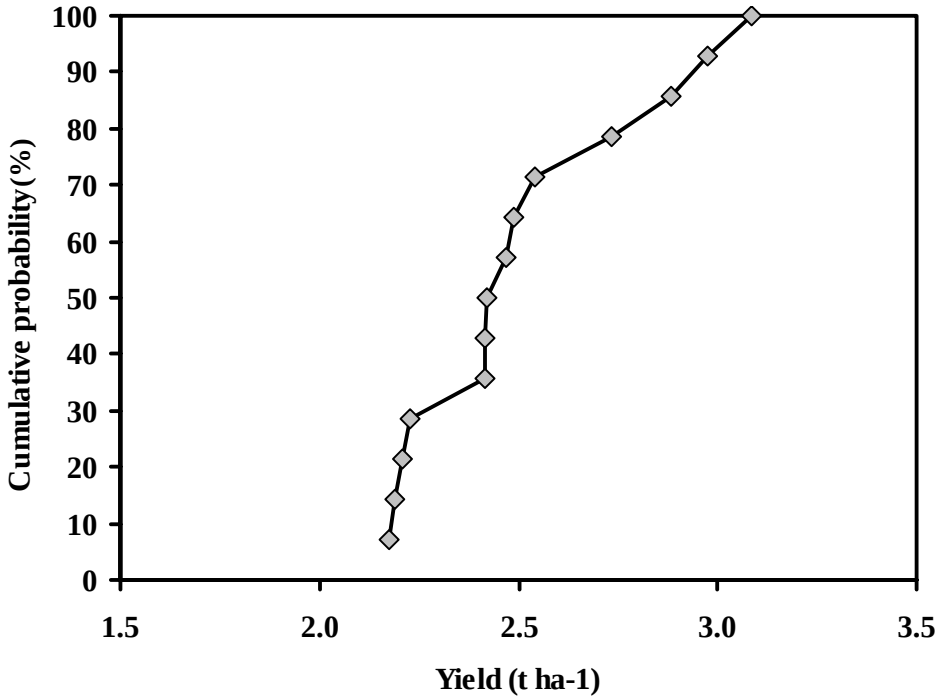


Figure 28.- Cumulative probability function for predicted yield of soybean.

In general the long-term predicted yield resulted variable for all crops considered, confirming the statistically significant influence of climatic data on the average yield level, whilst for different stable area identified within field – i.e., *HS* and *LS* area – the difference was appreciable, because of the partially influence of different soil properties, in particular when climatic conditions were not favourable for crop growth.

2.3.7.- Simulated long term temporal stability

In general, the field resulted characterised by the presence of a greater part having lower values of yield respect to that detected in the upper part of the field. The latter, in general was characterised by a greater temporal variance of yield, especially in the final part of the field, probably because of the presence of limiting factors or the errors done during yield monitoring.

In particular, for maize the long-term spatial variability of predicted yield values showed the presence of two area, having a yield greater than 11 t ha^{-1} and oriented according to the principal axle of the field, that covered almost the 50% of the complete field (Figure 29). A similar area covering the remnant part of the field showed a lower long-term production. The temporal variance pattern resulted more irregular within field, being divided into a lot of small area having different temporal variance on yield level (Figure 30).

Based on both the spatial pattern and the temporal variance of yield, the long-term temporal stability of spatial variability of yield showed the presence of two clearly distinct area, characterised by temporal stability and having a different level of production, identified as *HS* and *LS* area. In particular, *HS* area covered the 32.6% of the field, corresponding to 2.64 ha, the remnant part being identified with the *LS* area (5.45 ha) (Figure 31).

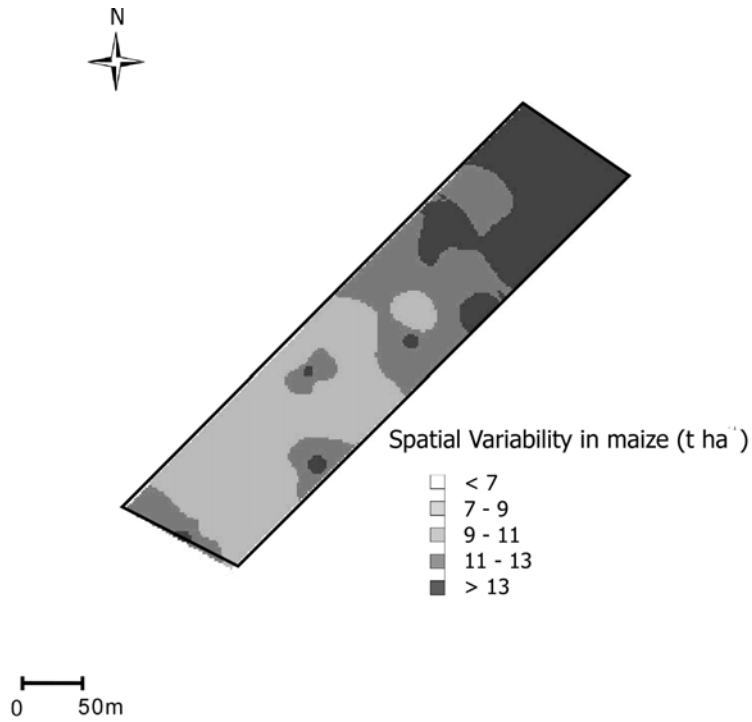


Figure 29.- Predicted long-term spatial variability of yield within field in maize.

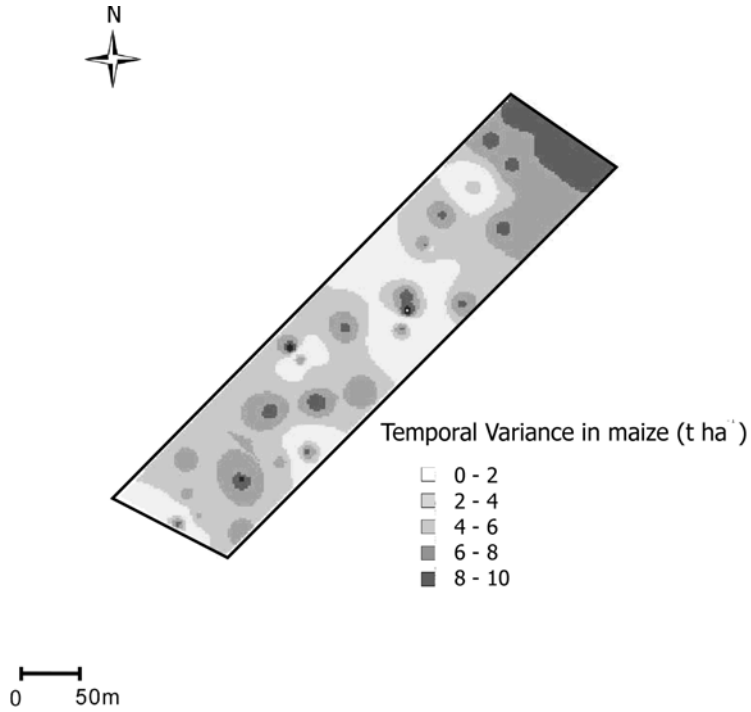


Figure 30.- Predicted long-term temporal variance of yield within field in maize.

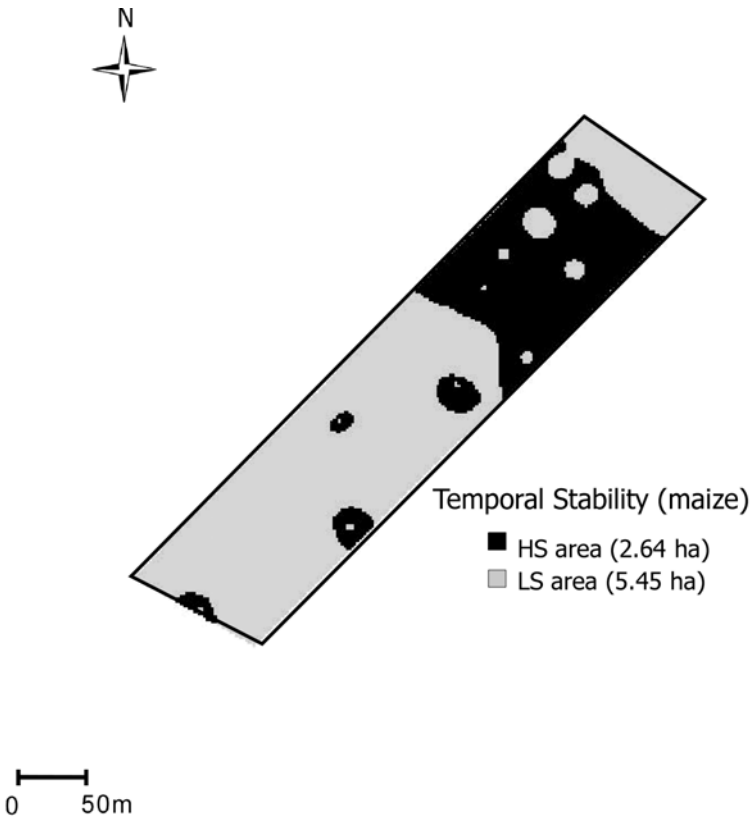


Figure 31.-Temporal stability of spatial variability of the long-term predicted yield within field in maize.

For wheat the long-term spatial variability of predicted yield values showed the presence of more different area than that found for maize, even if the field resulted roughly divided into two parts, having a yield lower or greater than 6 t ha^{-1} respectively, oriented according to the principal axle of the field. In particular, an area having the highest spatial variability was found in the north-eastern part of the field (Figure 32).

The temporal variance map showed an almost uniform pattern of differences regarding yield data, with an area having the highest variance displaced in the part of the field having the greater values of spatial variability (Figure 33).

Based on both the spatial pattern and the temporal variance of yield, the long-term temporal stability of spatial variability of yield showed the presence of two clearly distinct area, characterised by temporal stability and having a different level of production, identified as *HS* and *LS* area. In particular, *HS* area covered a surface area of 2.30 ha (28.4% of the field), whilst *LS* area was greater and involved the remnant part of the field (2.79 ha) (Figure 34).

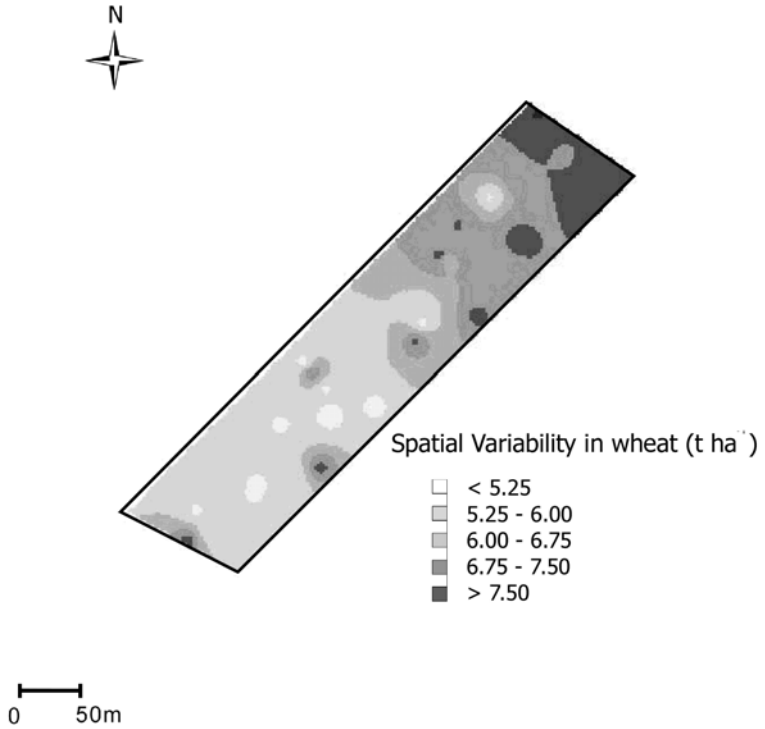


Figure 32.- Predicted long-term spatial variability of yield within field in wheat.

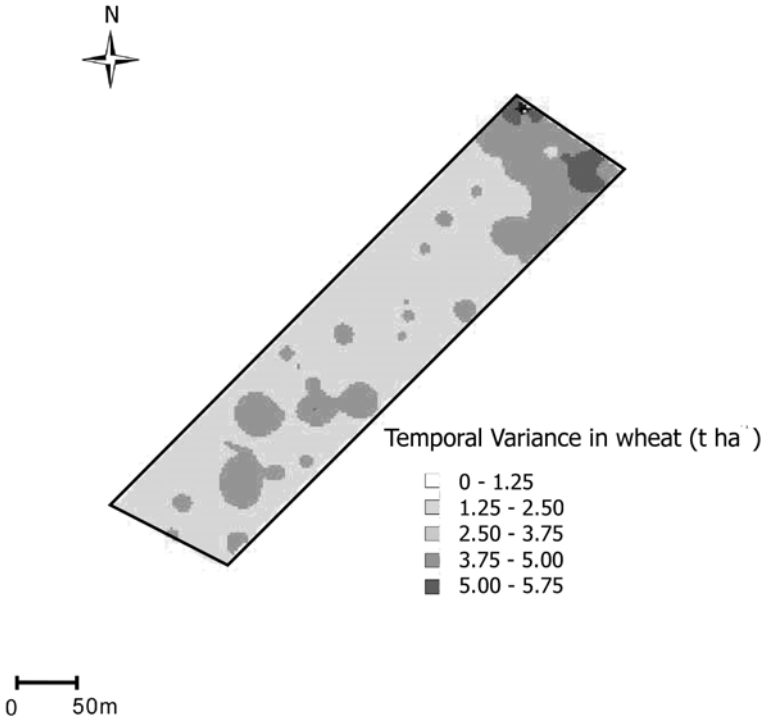


Figure 33.- Predicted long-term temporal variance of yield within field in wheat.

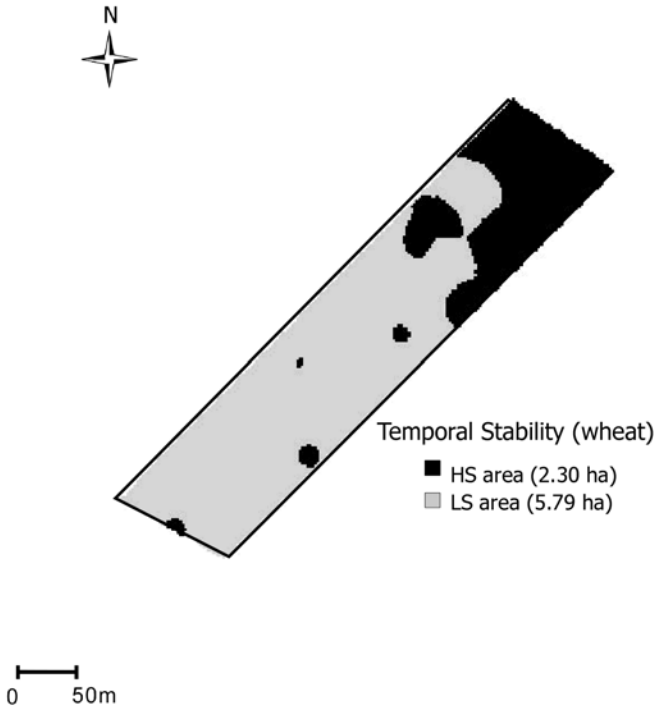


Figure 34.- Predicted long-term temporal stability of spatial variability in wheat.

For soybean the long-term spatial variability of predicted yield values showed a more clear distinct presence of two area within field, having a yield greater or lower than 2.2 t ha^{-1}, that could be

considered the threshold to identified *HS* and *LS* area. Furthermore, the *HS* area, being greater than that detected for maize and wheat, was more uniform than *LS* area, being characterised by the presence of small cells having different yield values (Figure 35). The temporal variance map showed the presence of two area, divided according to the values of yield. The more stable area involved almost the 75% of the complete field, the remnant part corresponding to the upper area, having greater values of temporal variance also for the precedent crops (Figure 36). Based on both the spatial pattern and the temporal variance of yield, the long-term temporal stability of spatial variability of yield showed the presence of a smaller area, having high values of yield and relatively lower temporal variance in the upper part of the field, whilst the remnant part of the field had lower value of yield. In particular, *HS* area covered a surface area of 2.10 ha (26% of the field), whilst *LS* area was greater and involved the remnant part of the field (7.99 ha) (Figure 37).

By considering and overlying the temporal stability maps of single crops, the temporal stability of spatial variability of yield was calculated for the complete field, corresponding to an area of 1,27 ha (Figure 38). This area resulted appreciably lower than that found by considering only the 5-year crop rotation, covering only the 15.6 % of the surface area, with a decrease of almost the 30% of the *HS* area, mainly because of the different long-term temporal variance assumed by different crops.

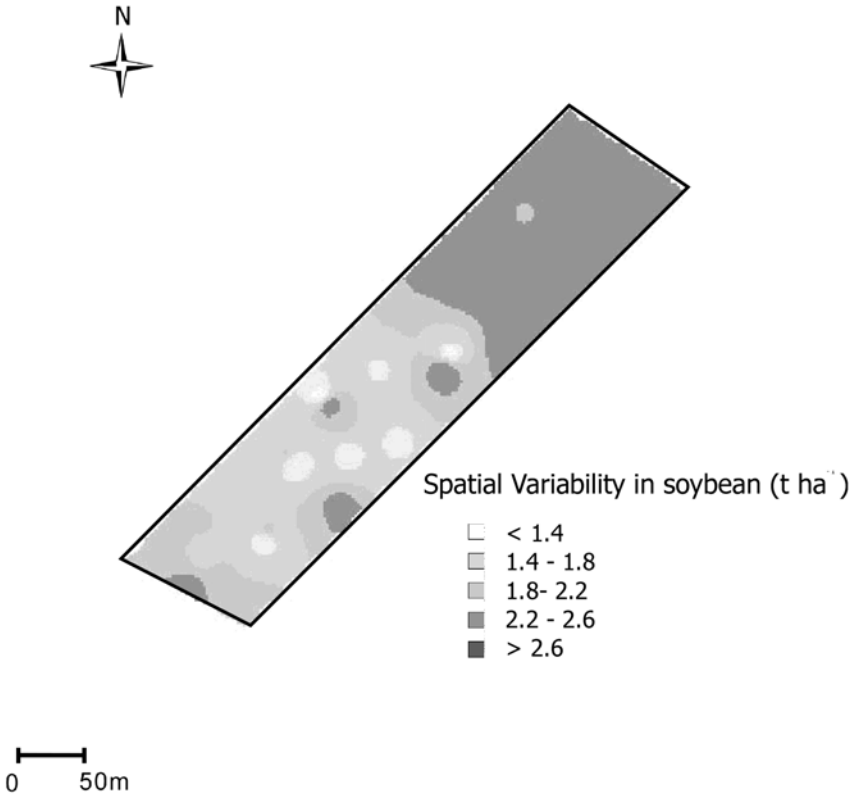


Figure 35.- Predicted long-term spatial variability of yield within field in soybean.

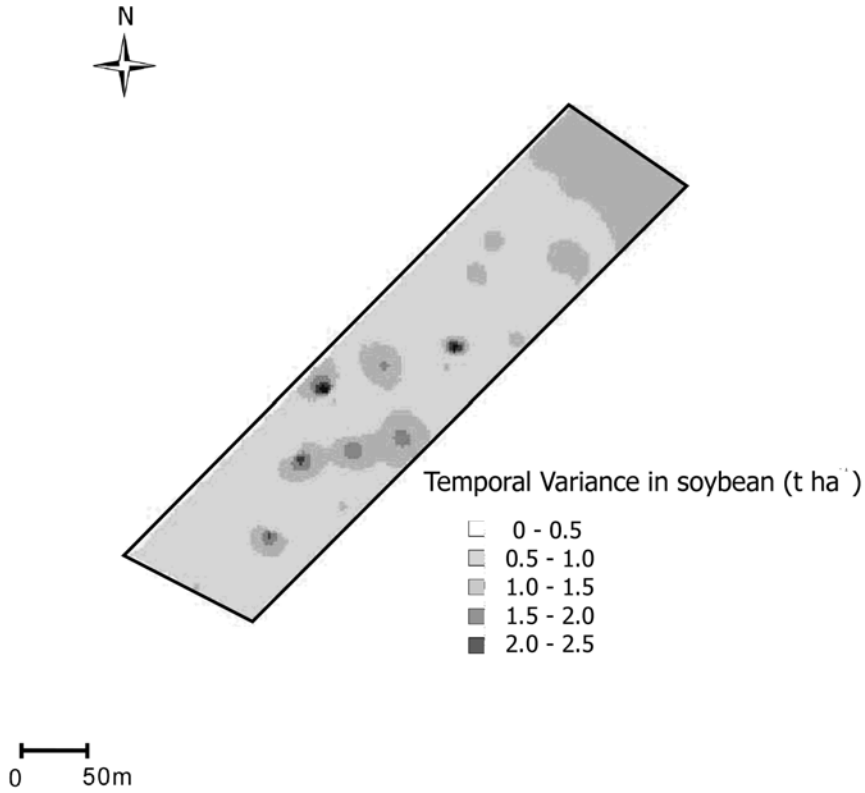


Figure 36.- Predicted long-term temporal variance of yield within field in soybean.

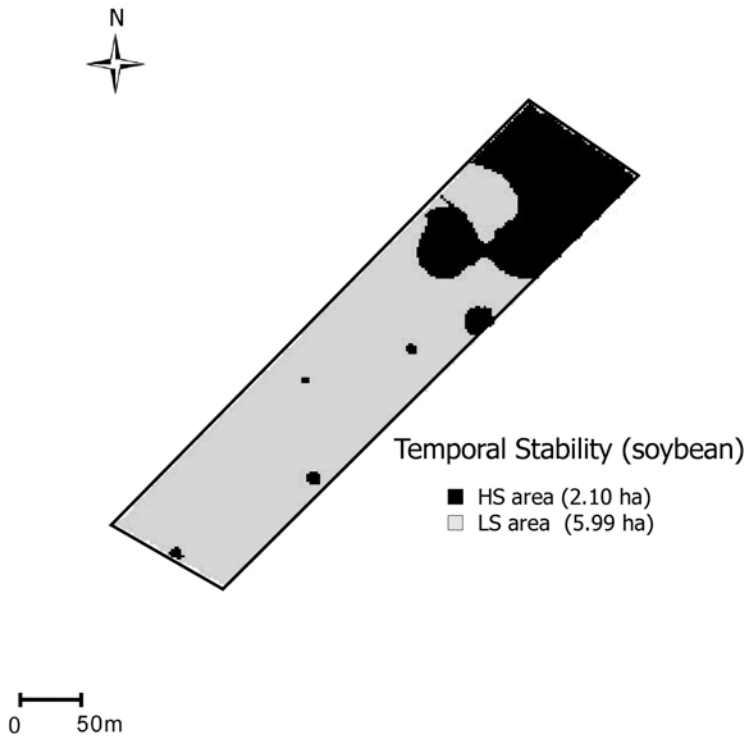


Figure 37.- Predicted long-term temporal stability of spatial variability in soybean.

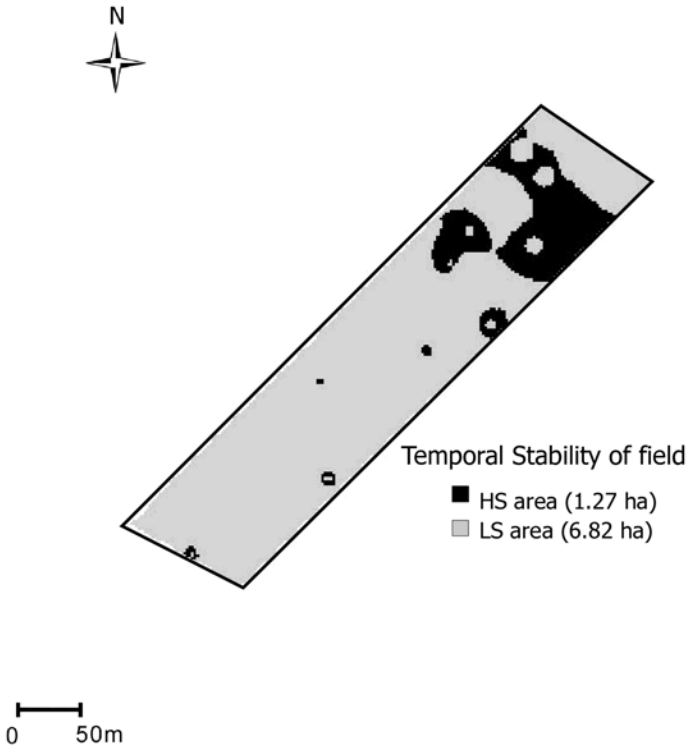


Figure 38.- Long-term temporal stability of spatial variability of yield obtained by overlying maps referring to the temporal stability of yield of single crop. *HS* and *LS* area indicate the stable area having high or low yield level respectively.

2.4.- Conclusions

In this study a method to determine the long-term temporal stability of spatial variability of yield was considered, and the combination of GIS tools and crop growth simulation model resulted useful to identify the homogenous and stable area within field, according to the stability criteria. In particular, the predicted long-term temporal stability of yield resulted variable by changing the considered crop, even if resulting homogenous area were roughly comparable, the *HS* and *LS* area corresponding to the upper and the bottom part for the analysed field respectively. Furthermore, the *HS* area identified within field resulted appreciably smaller than that obtained by considering only the yield maps monitored during the 5-year crop rotation, whilst *LS* area resulted greater, confirming that the accuracy of the temporal stability increase by increasing the years considered. At this regard, simulation model resulted a useful tool to identify homogeneous area accounting the temporal variability due to the influence of climatic conditions, supporting farmer to variably manage the variability existing within field according to site-specific practices.

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– Sezione 3 –

Simulazione degli effetti della lavorazione del terreno ad intensità variabile sulle proprietà del suolo e sulla resa in mais

Riassunto

La possibilità di eseguire gli interventi colturali ad intensità variabile all'interno dell'appezzamento può rappresentare un'interessante opportunità per l'azienda agricola, ma richiede inevitabilmente che vengano approfondite le conoscenze sugli effetti che possono derivare nel lungo periodo da tale strategia colturale. A tal proposito, il lavoro presentato in questo capitolo si propone di esaminare l'influenza esercitata da due diverse strategie di lavorazione conservativa del terreno (*MT* = Minimum Tillage, consistente in discatura del terreno e preparazione del letto di semina con erpice rotante; *NT* = No-Tillage, consistente nell'adozione della semina su sodo) rispetto al sistema di lavorazione conservativo tradizionalmente adottato in azienda per il mais (*Zea mays*, L.) (*CT* = Conventional Tillage, consistente nell'esecuzione di un intervento di ripuntatura, seguito dalla discatura, e nella preparazione del letto di semina con erpice rotante), sulle proprietà del suolo (contenuto d'acqua e densità volumica) e sulla resa. Le prove in campo sono state condotte nel corso del 2003 presso un'azienda privata situata in Ariano nel Polesine, Rovigo, Italia, su un appezzamento di 8.09 ha per il quale sono state inizialmente individuate le zone omogenee e stabili in base alla stabilità temporale della variabilità spaziale della resa simulata nel lungo periodo. I risultati ottenuti hanno evidenziato come il contenuto di umidità misurato lungo il profilo del suolo abbia risentito in maniera non significativa dell'effetto delle lavorazioni, essendo invece maggiormente apprezzabile la differenza tra le aree omogenee individuate all'interno dell'appezzamento. Per quanto riguarda la densità volumica del terreno è stata evidenziata una maggiore influenza su tale parametro da parte del sistema *CT*, sia in termini di riduzione dei valori iniziali di densità lungo il profilo del suolo che di durata dell'effetto nel corso del ciclo colturale. In termini di resa, nel corso del 2003 i sistemi di lavorazione del terreno esaminati non hanno dimostrato alcuna differenza statisticamente significativa, a causa dell'andamento climatico poco

favorevole rispetto alle condizioni medie del periodo quindicennale di riferimento, mentre nel caso della simulazione di lungo periodo (1989-2002) il sistema di lavorazione *CT* è risultato avere la maggiore probabilità di consentire il raggiungimento di una resa elevata nell'area *HS,* mentre nell'area *LS*, a parità di probabilità considerata (*P* = 50%), è risultato più conveniente in termini di resa il sistema *MT*, probabilmente a causa delle differenze esistenti a carico del terreno nelle due zone e della loro interazione con le condizioni climatiche. Sulla base dei risultati della simulazione di lungo periodo, i trattamenti *CT* ed *MT* sono risultati i più adatti per le due aree stabili individuate all'interno dell'appezzamento, sia in termini di resa conseguibile che di effetti sulle proprietà del suolo, mentre *NT* è risultato relativamente più conveniente soprattutto in concomitanza delle annate poco favorevoli.

Parole chiave: densità volumica; intensità variabile; lavorazioni del terreno; mais; stabilità temporale; simulazione; umidità del suolo; variabilità spaziale.

Abbreviazioni*: CT* – sistema di lavorazione convenzionale; *HS* – area con resa alta e stabile nel tempo; *LS* – area con resa bassa e stabile nel tempo; *MT* – sistema di minima lavorazione; *NT* – sistema di non lavorazione.

– Section 3 –

Long-term simulation of the effects of variable tillage intensity on soil properties and yield in maize

Abstract

Soil tillage practices exert different effects on soil properties and the adoption of tillage at variable intensity causes a variable influence on soil attributes along soil profile. This study has considered the variability of bulk density and soil water content after adopting two different conservative tillage systems (*MT* – Minimum Tillage; *NT* – No-Tillage) in comparison with the conventionally conservative tillage system – named *CT* – adopted in maize (*Zea Mays*, L.). After identifying homogenous stable area within field according to the temporal stability of yield criteria, field trials were carried out in 2003 at a private farm situated in Rovigo, NE Italy, and yield was simulated for a long period in order to consider also the influence exerted by climatic conditions. As regards soil water content, the effect of tillage along soil profile was almost neglible, whilst the different interactions between soil properties (e.g., soil organic carbon and clay content) and water resulted more significant, being differences between stable area more appreciable. Contrarily, tillage effect resulted statistically significant on influencing bulk density values along soil profile, with a greater effect in *CT* plot, decreasing bulk density values more appreciably and with a more durable effect respect to *MT* treatment. As regard the effects on yield, during trials results were influenced by climatic conditions, with lower differences among treatments, whilst simulation data revealed that in *HS* area *CT* system could allow a greater yield than *MT* or *NT* plots, whilst in *LS* area *MT* system resulted better than control and no-tillage, at the same level of probability (P = 50%). In conclusion, *CT* system seemed more convenient in *HS* area, whilst in *LS* area *MT* resulted the better tillage system, probably because of the different soil properties pattern between the two stable area of the field, whilst *NT* system seemed to be more convenient in not favourable growing season.

Keywords: bulk density; crop growth simulation; soil tillage; maize; soil water content; spatial variability; temporal stability.

Abbreviations: *CT* –Conventional Tillage system; *HS* area – area with high and stable yield; *LS* – area with low and stable yield; *MT* – Minimum Tillage system; *NT* – No-Tillage system.

3.1.- Introduction

In the last decades several studies have demonstrated the presence of variability within field, both in large and in small fields (Jaynes and Colvin, 1997; Yamagagishi et al., 2003; Ping et al., 2004). In particular, dynamic soil properties (e.g. soil water content) and crop yield may be affected by spatial and temporal variability (McBratney and Pringle, 1999; Blackmore et al., 2003), and different studies have proposed methods and solutions to variably manage them, in order to obtain economic and environmental benefits, being highly dependent on both the intensity and the magnitude of spatial variability of limiting factor affecting yield and on the accuracy of the understanding of its spatial structure within field (Pierce and Novak, 1999).
Despite to the within-field variability, agronomic practices were usually based on the average yield level obtained with the precedents crops (Stafford et al., 1996) and uniformly performed, consequently being inefficient both for the environmental impacts and for the productive costs (Stafford, 1993).

As regards soil tillage, the main objective is the porosity re-establishment in the cultivated soil layer in order to create a stable structure with an equilibrated liquid, solid and gaseous components ratio to improve soil conditions for crops (Giardini, 1992). But the uniform adoption of tillage practices within field may be correct in some areas and inappropriate in others, because of the spatial variability of soil properties (e.g. soil texture or organic matter content), attributes (e.g. field slope) and their long-term interactions (e.g. relationship between soil texture and electrical conductivity). In regard to the negative aspects of soil tillage, several studies have demonstrated that runoff and sediment loss can be significantly reduced by adopting minimal soil disturbance systems compared with traditional tillage (Hall et al., 1991; Packer et al., 1993), because of the benefits deriving from the presence of crop residue at soil surface. In fact, erosion effects decrease exponentially with an increase of residue at soil surface (Laflen et al., 1978), with greater decreasing in sediment-associated P pollutant losses by assuring a coverage of 48% at soil surface in comparison with a mouldboard plough based system (Ginting et al., 1998a; Ginting et al., 1998b), whilst a presence of 20% covered soil surface is sufficient to reduce at 50% soil erosion (Dickey et al., 1985), with important implications for crop productivity by varying field slop (Schumacher et al., 1999). The principal aspect to consider for tillage is consequently the intensity at which agronomic aspects are performed. Tillage intensity in fact may be correlated to some

negative aspects, as for example the presence of plough pan (Soane and van Oewerkerk, 1994; Fattah and Upadhyaya, 1996) or mineralisation of soil organic carbon. At this regard, the tillage systems not inverting soil layers could provide an appreciable increase in organic carbon content along soil profile (Franzluebbers et al., 1994), with an influence on the correlated aspects, as for example soil structural stability and bulk density (Hamblin and Davies, 1977; Carter, 1992), water infiltration and storage (Hamblin and Davies, 1977) and water availability for crop (Wagger et al., 1993), or nitrogen losses (Chan et al., 1992), with losses in total nitrogen that were in direct proportion to those of organic carbon until the C:N ratio of soil – i.e., C:N = 12:1 – was not modified. But intensive soil tillage has negative consequence also on economic aspects, principally due to the influence on technical factors consumptions (e.g., fuel and lubricants) and the costs of production. A this regard, a lot of studies revealed the economic convenience on reducing the tillage intensity, and in particular, a shallower tillage is demonstrated to cause a reduction of the draft and energy requirement (Raper et al., 2000), with a consequent amelioration of energy power and fuel consumption utilization (Godwin and Miller, 2003), reducing energy waste and costs of production due to tillage system (Basso et al., 2003).

The possibility of maintaining, or in same cases, improving the soil's fertility by decreasing soil tillage intensity, particularly on soils where high soil and organic matter losses are documented, and of improving economical sustainability of farm justify a further promotion of conservation tillage systems. However some disadvantages have also been recorded for reducing tillage, and results reported in literature regarding for example nitrogen losses are in some cases conflicting, because of the different water infiltration and organic carbon content in the upper soil layer deriving from the adoption of minimum tillage respect to conventional systems with a different pattern over different growing season, due to the influence of climate conditions and crop rotation (Granovsky et al., 1993; Meek et al., 1993; Drinkwater et al., 2000; Shipitalo et al., 2000; Catt et al., 2000).

Consequently, soil tillage has to be re-considered taking into account that a reduction of intensity is justified at least by both the maintenance or the improvement of the soil fertility and the evaluation of alternative combinations of agronomic practices which are environmentally benign, whilst farmers need reliable information about the likely long-term impact of any new system on farm income, in order to adopt the best management strategies.

In fact, a uniform tillage operation does not consider the existing within-field spatial variability of soil properties, but the same negative aspects correlated to tillage intensity (e.g. plough pan) (Soane

and van Oewerkerk, 1994; Fattah and Upadhyaya, 1996) may spatially vary within field, with higher susceptibility for area having greater clay loam soil (Kooistra et al., 1994), being soil strength variable within field and correlated to the soil properties (Hanquet et al., 2004), whilst the same soil water content pattern resulted variable within and between different growing season (da Silva et al., 2001) and nitrogen losses spatially varied within field (Ersahin, 2001), according to the spatial variability of soil properties. Furthermore the tillage impact may vary in time, the long-term degree to which the spatial patterns in soil dynamic physical properties are influenced by interaction between tillage and soil characteristics being not so clearly defined, as reported for example by Campbell and collaborators for a clay soil (Campbell et al., 1998).

In this framework, the adoption of process-oriented crop growth model could be useful to simulate the long-term effects of management practices performed, as for example soil tillage, on soil properties, by considering the temporal interactions on daily plant growth and yield processes (Basso et al., 2001). Crop model in fact are an interesting tool for both understanding the within-field variability (Jones et al., 2003), in order to identify homogeneous management zones and consequently for variably managing field operations, according to the possibility to perform site-specific practices created by advances in technology, and taking into account the environmental conditions and the effects of tillage (Basso et al., 2003), leading to a better control on production cost and to a more sustainable environment (Cora et al., 1999).

The main objectives of this paper are (***i***) to investigate during the growing season the effects on soil properties (bulk density and soil water content) of soil tillage performed at variable intensity, consisting on minimum tillage and no-tillage systems in comparison with the conservative practices normally adopted by the studied farm, in different homogeneous area identified within field, and (***ii***) to simulate the long-term temporal pattern of yield for the different tillage systems, taking into account the variable influence of climatic conditions, in maize (*Zea mays*, L.).

3.2.- Materials and methods

3.2.1.- Site description and climatic data

The field trials were carried out in 2003 in maize (Zea Mays, L.), in a 8-ha flat field, situated near Rovigo (44° 4’ 12” N, 11° 47’ 22” E, 6 m a.s.l.), NE Italy. The soil was clay, according to the USDA particles-size distribution limits.

The climate of the area (data relating to the 1989-2003 period) is characterised by an annual average rainfall of 700 mm, distributed mostly in autumn and spring. The annual average temperature is 13.3 °C, with a monthly maximum of 23.5 °C in July and a minimum of 3.2 °C in January (Figure 1).

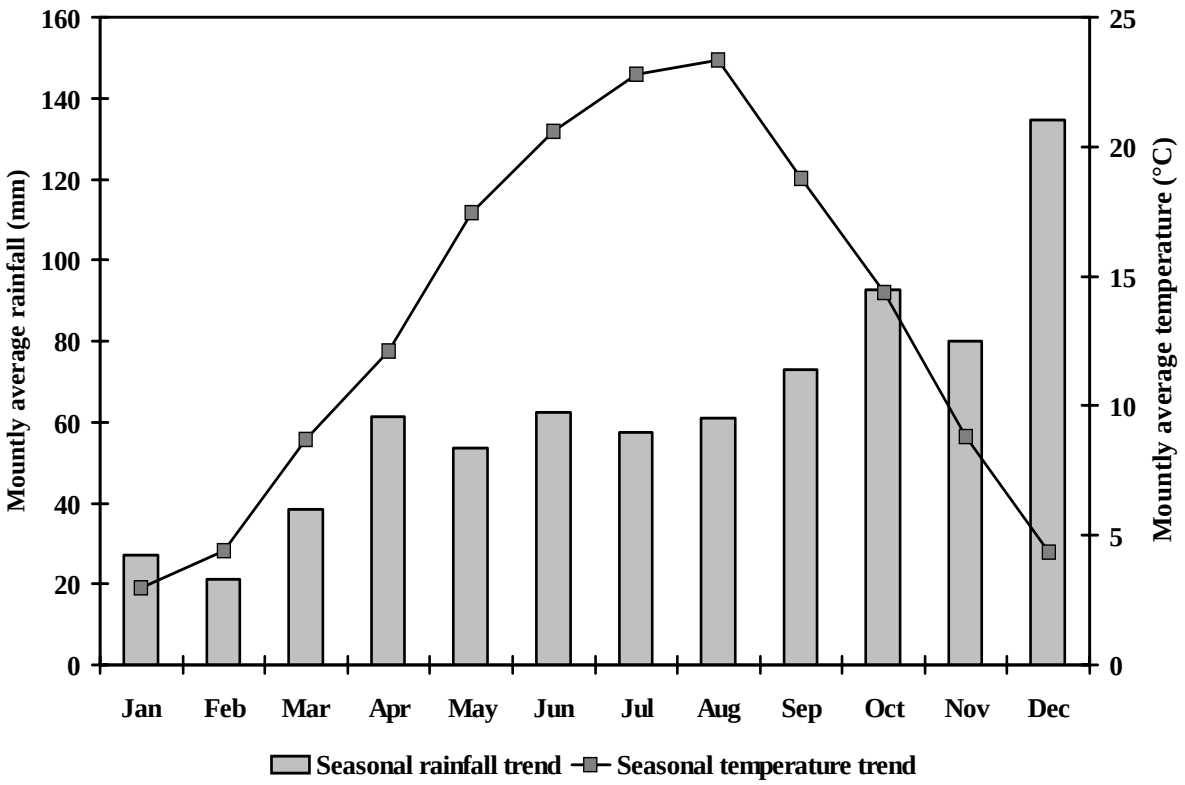

Figure 1.- Monthly total rainfall (mm) and average temperature (°C) long-term trend (1989-2002) in the site where the study was carried out.

3.2.2.- Crop growth model

The long-term pattern of yield grain was simulated over the 1989-2003 period in order to reduce the variability of yield over years due to climatic conditions and increase the accuracy of the definition of within-field homogeneous management area, according to that suggested by literature (Boydell and McBratney, 2002; Joernsgaard and Halmoe, 2003). Simulation was performed by using *CERES-Maize* model (Jones and Kiniry, 1986), being part of the *Decision Support System for Agrotechnology Transfer* (*DSSAT 3.5*, Hoogenboom et al., 1994), that provides several tools for model application, using a minimum database relating to the factors required to run the crop models and validate the outputs, as reported below.

Weather dataset

It includes the daily values of incoming solar radiation (MJ m^{-2} day^{-1}), maximum and minimum air temperature (ºC) and rainfall (mm), measured during the period used for the prediction at the Rosolina weather station (Arpav – Centro Meteorologico di Teolo, Padova, Italy), situated in Rovigo, Italy.

Soil dataset

It includes soil classification, surface slope, permeability, drainage and soil properties measured along the soil profile, as percentage sand, silt, and clay content, bulk density, organic carbon and water limits. In particular, soil properties – i.e., soil texture, organic matter – were determined after collecting soil samples at 35 locations randomly displaced within field with an undisturbed soil core sampler (Eijkelkamp, Glesbeek, NL). The hydrometer method was used to determine the textural characteristics of the soil. The organic matter content was calculated by using the Walkley-Black method (Walkley and Black, 1934). Undisturbed soil cores 8-cm in diameter ware collected and the bulk density was determined after oven-drying at 105°C to constant weight. Soil water limits were calculated using the procedure suggested by Ritchie et al. (1999). All the measurements were made along soil profile at different soil depth layers (0-15 cm, 15-30 cm, 30-45 cm) and sampling locations displaced within field were grouped according to the temporal stability criteria. Field measurements were periodically repeated during growing season, and in particular soil bulk density

and water content were measured in October 28, March 25, May 6 and June 10. During sampling a portable Trimble 132 receiver was used to localise each point within field.

Genetic coefficients dataset

It includes the genetic parameters required to simulate the crop growth in the experimental area according to the peculiar genotype of the crop considered. During field trials, the cultivar Costanza was used and the coefficient of were given by the genetic constitutor (Pioneer Hi-Bred International Inc., Des Moines, Iowa, USA).

Management and experimental data

It includes all the information referring to the farming system suited by the farmer during the crop cycle (e.g., planting date, planting density, row spacing, planting depth, crop variety, irrigation, fertilizer practices and rates, etc.). At this regard, specific farming practices and timeframe used as input for model simulation, adopted by farm for the crop considered in this study are reported below.

3.2.3.- Identification of management zones

Based on long-term (1989-2003) predicted yield data, the temporal stability of spatial variability of yield for maize was determined in order to increase the accuracy for identifying homogeneous management area within field, according to the methods for spatial and temporal variability identification suggested by Blackmore (Blackmore, 2000; Blackmore et al. 2003).
The analysis was performed in *ArcView version 3.2*^{TM} (*ESRI*, 1999), by querying the overlaid layers referring to spatial pattern and temporal variance of yield respectively.
In particular, the long-term spatial variability of predicted yield values showed the presence of an area, having a yield greater than 11 t ha^{-1} and oriented according to the principal axle of the field, that covered almost the 50% of the complete field (Figure 2). A similar area covering the remnant part of the field showed a lower long-term production. The temporal variance pattern resulted more irregular within field, being divided into a lot of small area having different values of temporal variance of yield (Figure 3).
Based on both the spatial pattern and the temporal variance of yield, the long-term temporal stability of spatial variability of yield showed the presence of two clearly distinct manageable area,

characterised by temporal stability and having a different level of production, identified as *HS* and *LS* area. *HS* area covered the 32.6% of the field, corresponding to 2.64 ha, the remnant part being identified with the *LS* area (5.45 ha) (Figure 4).

In both cases, the dimensions of the homogeneous and stable area identified within field resulted technically manageable by adopting practices at variable intensity, such as soil tillage, being the two area clearly identified within field. At this regards, the upper part of the field was practically considered as an homogeneous area, without separately managing the final part of the field, following down into the *LS* area during the analysis, because of the presence of greatest temporal variance of yield, in order to practically manage the variability detected within field. Consequently the field resulted practically divided into two independent area, *HS* and *LS* having a surface area of 3.40 ha and 4.69 ha respectively.

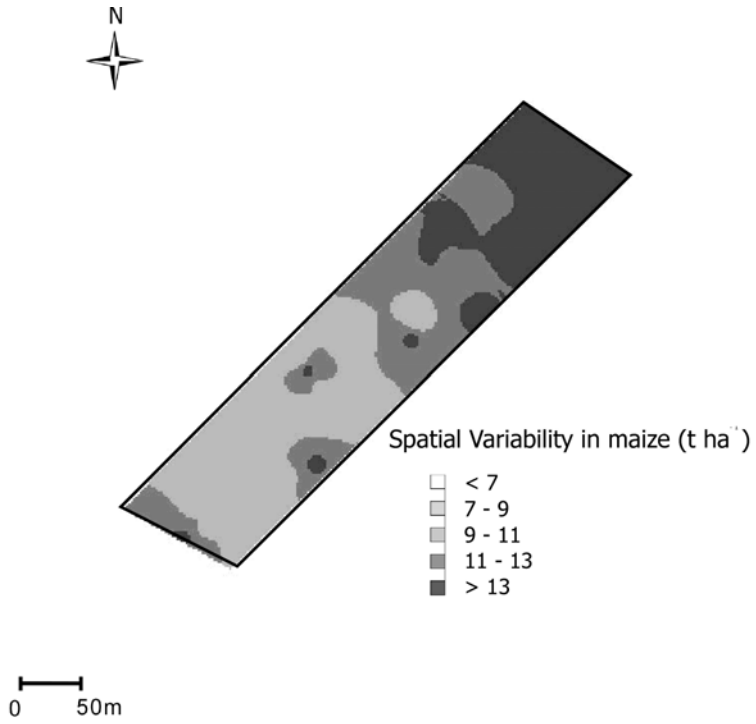

Figure 2.- Predicted long-term spatial variability of yield within field in maize.

3.2.4.- Field trials and agronomic management

Based on the temporal stability map, three 652-m long × 42-m wide plots was delimited within field, and named *CT* (*CT* – Conventional Tillage system), *MT* (*MT* – Minimum Tillage system) and *NT* (*NT* – No-Tillage system) respectively, according to the conservative tillage practices performed (Figure 5), in order to compare the two tillage systems with the practice conventionally adopted by the farm in maize (*Zea mays*, L.). Analysis was carried out in the two different area identified within field, practically delimited according to the temporal stability criteria (Figure 6).

During field trials the equipments available at farm – *i.e.*, subsoiler, disk harrowing and rotary hoe – were used to perform tillage operations, coupled to a *New Holland* 176 kW 4 WD tractor. In particular a V-frame subsoiler and a rear mounted hitch disk harrow were used for soil tillage at 35 cm and 15 cm respectively. Seedbed preparation was performed with the rotary harrow.

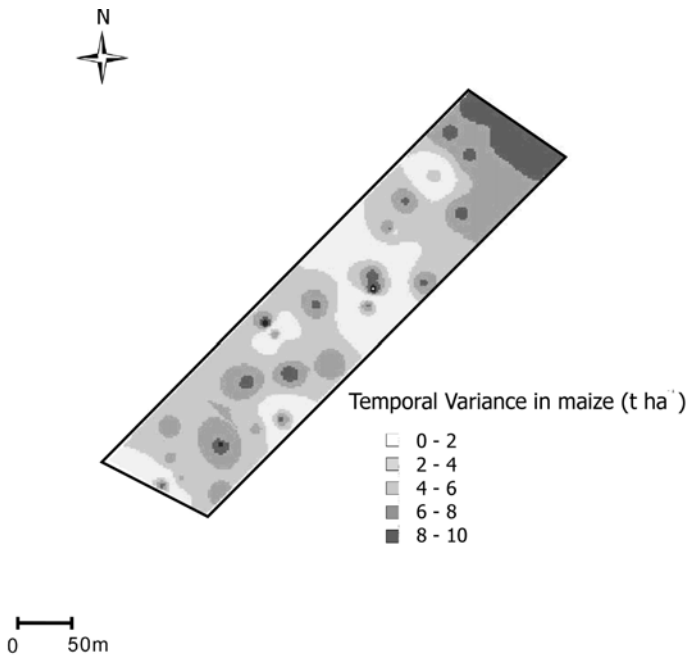

Figure 3.- Predicted long-term temporal variance of yield within field in maize.

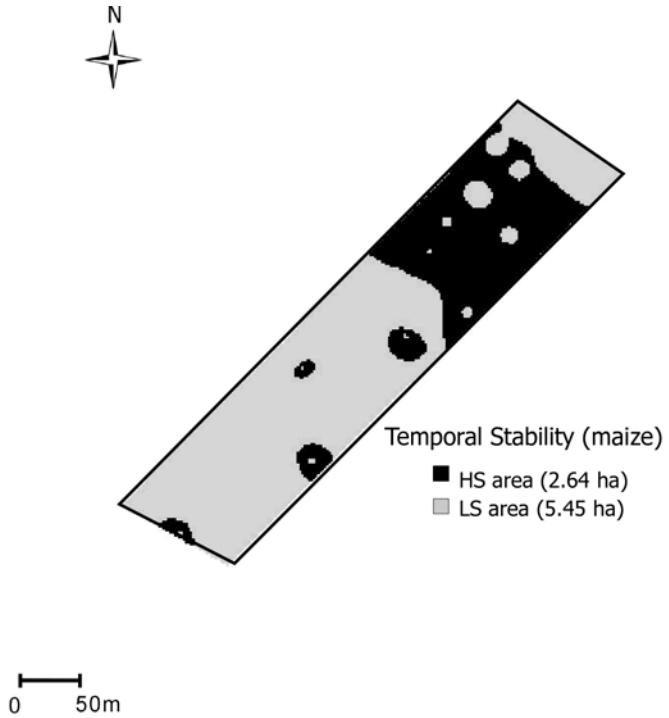

Figure 4.-Temporal stability of spatial variability of the long-term predicted yield within field in maize.

According to that, primary tillage was performed in the *CT* plot with the subsoiler on February 21, whilst the disk harrow was employed in both the *CT* and the *MT* plots on March 3. For seedbed preparing, rotary harrowing was carried out on March 19 on both plots, whilst on March 27 this agronomic practice was carried out only in the *CT* plot, in order to achieve a greater reduction of soil clods.

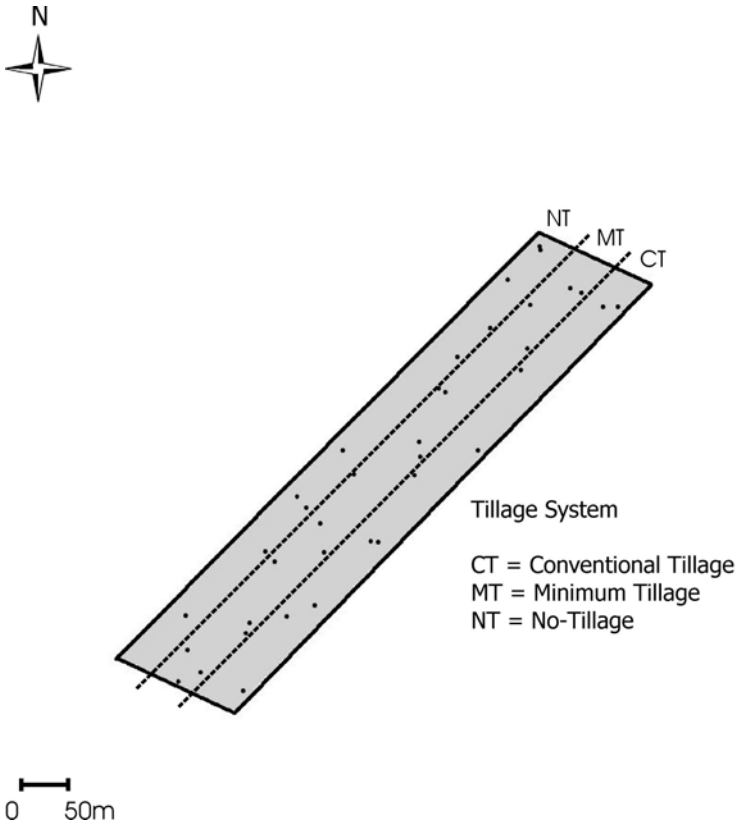

Figure 5.- Experimental scheme reporting tillage systems performed during field trials. Markers indicate sampling points at which soil properties were measured.

Fertilizers, herbicides and seeding rates and timeframe were the same for all plots. In particular, chemical fertilizers (47 P kg ha^{-1} and 37 K kg ha^{-1}) were applied before seedbed preparation on November 9 2002 and on January 16, respectively, with a double spinner disk, whilst 185 N kg ha^{-1} was applied on May 19 with a pneumatic distributor. The *Costanza* cultivar was sown on March 28, with a seeding rate of 3.34 kg ha^{-1} (0.75 m row spacing, 7.8 plants m^{-2}), by using a planter, whilst in the *NT* plot a no-till planter was used. In *CT* and *MT* plots weed control was achieved through the combination of herbicide application, carried out with a field sprayer on April 07, April 12 and April 19 respectively, and row crop cultivation, performed on May 30 by using a weeder. Only in the *NT* plot weed control was realised by coupling pre- and post-emergence herbicide applications. Harvest was carried out on August 29 for all plots, according to the maturity status of the crop.

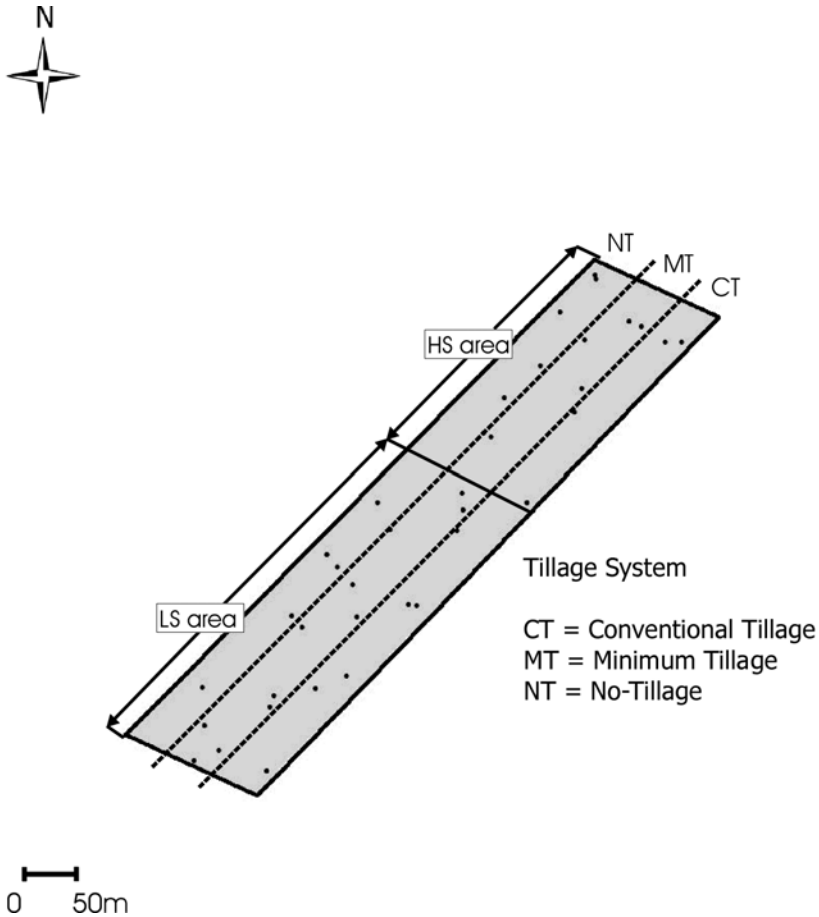

Figure 6.- Final experimental scheme reporting tillage systems performed during field trials in the homogeneous area practically identified within field according to the temporal stability criteria. Markers indicate sampling points at which soil properties were measured.

3.2.5.- Yield data

The yield data were manually collected at harvesting maturity, within 27 sub-plots centred on each sampling point, for a total of 30 plants x sub-plot (10 plant row^{-1} x 3 rows sub-plot^{-1}), and the intra-row spacing between adjacent plants was measured, to calculate the real number of plants m^{-2}. The weigh of the grain was measured and referred to dry matter (0% of moisture content), in order to generate in ArcView version 3.2^{TM} the yield map of differently tilled plots.

3.2.6.- Long-term simulation of yield and soil attributes

The effects of variable tillage intensity on soil properties – bulk density and soil water content – spatial patterns during the growing season and on the long-term (1989-2003) variability of grain yield were simulated by using the SALUS (System Approach to Land Use Sustainability) model, which was designed to simulate continuous crop, soil, water and nutrient conditions under different management strategies, as for example crop rotations, planting dates, plant populations, irrigation and fertilizer applications, and tillage practices, for multiple years (Basso, 2000). In particular, the model can simulate every day of the growing season and for each management strategy being run, the major components of the crop-soil-water system (e.g., management practices; water balance, considering surface runoff, infiltration, surface evaporation, saturated and unsaturated soil water flow, drainage, root water uptake, soil evaporation and transpiration; soil organic matter, nitrogen and phosphorous dynamics; plant growth and development).

The SALUS biophysical model is composed of the following main structural components (Figure 7), linked each one to the other:

- ***a set of crop growth modules***, including maize and wheat modules, derived from the *CERES* and *IBSNAT* family of crop production models that were originally developed for single year, monoculture simulations, and legumes and alfalfa modules. In general, the development and growth of plants use temperature and light to calculate the potential rates of growth for the plant, which is then reduced based on water and nitrogen limitations. Phases development is controlled by environmental variables (e.g., degree days, photoperiod) governed by variety-specific genetic coefficients. Carbon assimilation and dry matter production are a function of potential rates (controlled by light interception and parameters defining the variety-specific growth potential) which are then reduced according to water and/or N limitations. The main external inputs required for the crop growth routines are the genetic (variety-specie) coefficients and daily solar radiation as a driving variable;

- ***a soil organic matter and nutrient cycling module***: the soil organic matter and nutrient model simulates organic matter decomposition, N mineralization and formation of ammonium and nitrate, N immobilization, gaseous N losses and labile, active and stable pools of inorganic phosphorous. The soil organic matter and nitrogen module is derived from the Century model with a number of modifications incorporated. The model simulates organic matter and N

mineralization/immobilization from three organic matter pools (active, slow and passive) which vary in their turnover rates and characteristic C:N ratios. There are two crop residue/fresh organic matter pools (structural and metabolic), for representing recalcitrant and easily decomposable residues, based on residue lignin and N content, whilst a surface active SOM pool associated with the surface residue pools is considered to best represent conservation tillage systems and perennial crops;

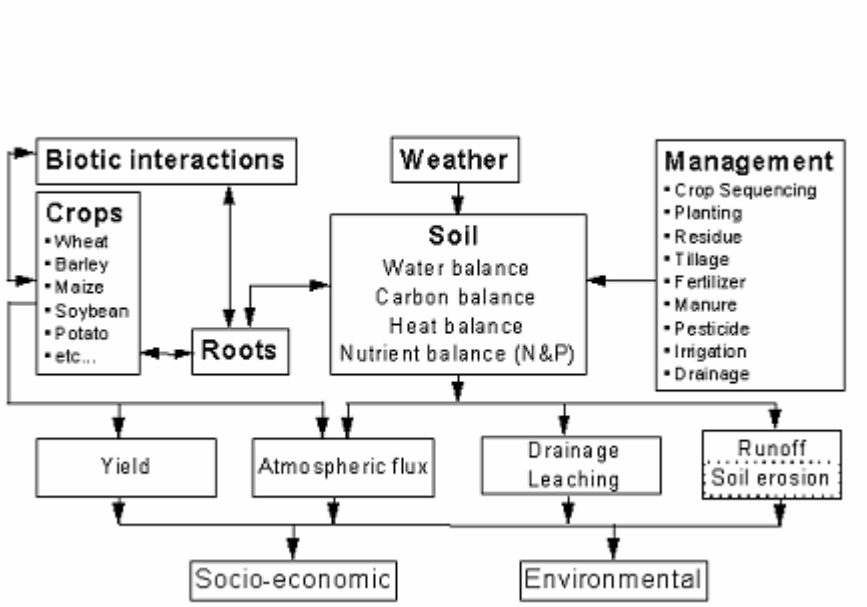

Figure 7.- Diagram of the components of *SALUS* model

- ***a soil water balance and temperature module***: the soil water balance module is based on that used in the *CERES* model but incorporates a major revision in calculating infiltration, drainage, evaporation and runoff. In *SALUS*, a time-to-ponding (TP) concept is used to replace the previous runoff and infiltration calculations which were based on SCS runoff curve numbers.

The entire program has been written in Visual Basic programming language to allow efficient computation and easy portability of the program to different computer platforms, and at now an application for a web-based system and a linkage to a GIS platform is under development by the GIS Research Center of Feng Chia University in Taiwan.

Statistical analysis and *ANOVA* multivariate were developed in *SAS version 8.0* (*SAS Institute Inc*., 1999).

3.3.- Results and discussion

3.3.1.- Yield monitoring

Yield obtained in 2003 was appreciably lower respect to the data monitored in the precedent growing seasons (Table 1), with a statistically significant reduction of almost 42% and 32% respect to that monitored in the 1998 and 2000 respectively (Figure 8).

Table 1.- Descriptive statistics for yield data measured in 2003 within the complete field, compared to that monitored in the precedent growing seasons. Different letters indicate significant differences between different years (*LSD* test, P≤0.05).

Statistics	**Grain yield (t ha^{-1})**		
	1998	2000	2003
mean	9.69 a	8.25 b	5.63c
mode	10.84	6.99	6.61
median	10.16	8.28	5.73
standard deviation	± 2.24	± 1.73	± 1.38
kurtosis	1.10	1.53	0.30
skewness	-0.51	0.73	-0.60
minimum	0.67	0.72	0.71
first quartile (Q_1)	8.95	7.26	4.71
third quartile (Q_3)	11.10	9.56	6.57
maximum	21.00	18.41	10.24
coefficient of variation (*CV*; %)	23.11	20.95	24.52

The standard deviation value measured within field resulted relatively lower, whilst the coefficient of variation was greater than other years, with yield values slightly more concentrated around the classes having greater values, as revealed by the negative skewness index (- 0.60) and the small separation distance between mode and mean values (Figure 9). A intra-year variability was detected within field, particularly as regard the stable area identified within field, with a greater production registered in the northern part of the field, respect to the remnant part of the field, characterised by lower yield data. Despite the adoption of different soil tillage systems along the major transect of the field, no appreciably differences were detected accord to the experimental scheme, different plots having comparable values of yield within the same homogenous zone (Figure 10), which resulted statistically different (Figure 11). In particular, tillage system and area showed a statistically significant effect on explaining the yield variability, the model explaining a moderate percentage of the total variability of yield, as revealed by the value of the coefficient of determination (R^2 = 0.38) (Table 2).

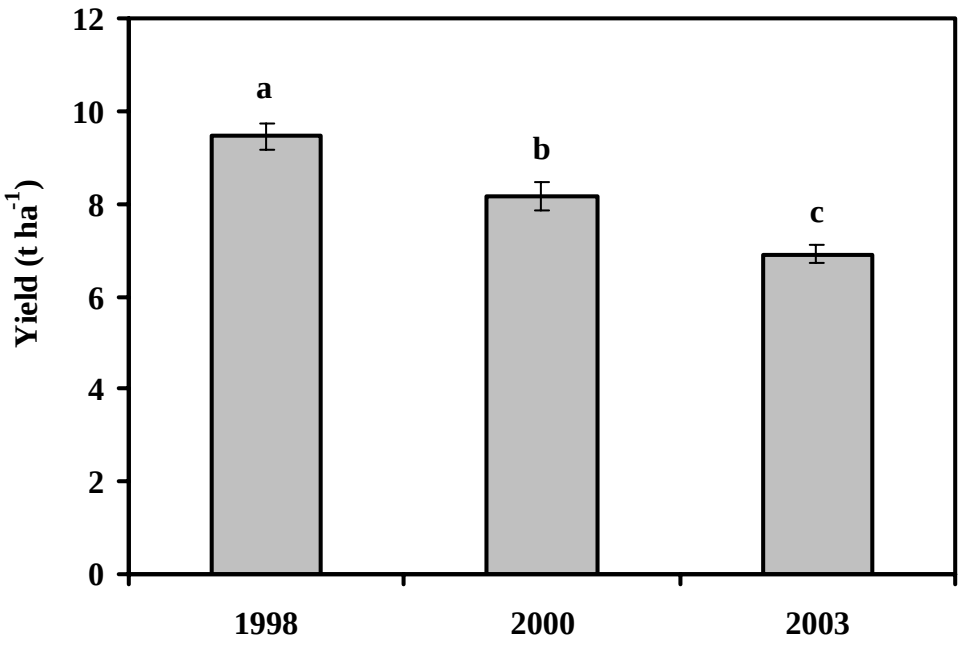

Figure 8.- Average yield obtained in the complete field in 2003 respect to the precedent growing seasons. Vertical bars refer to standard error of the yield data. Different letters indicate statistically significant differences on yield level between years (LSD test, P≤0.05).

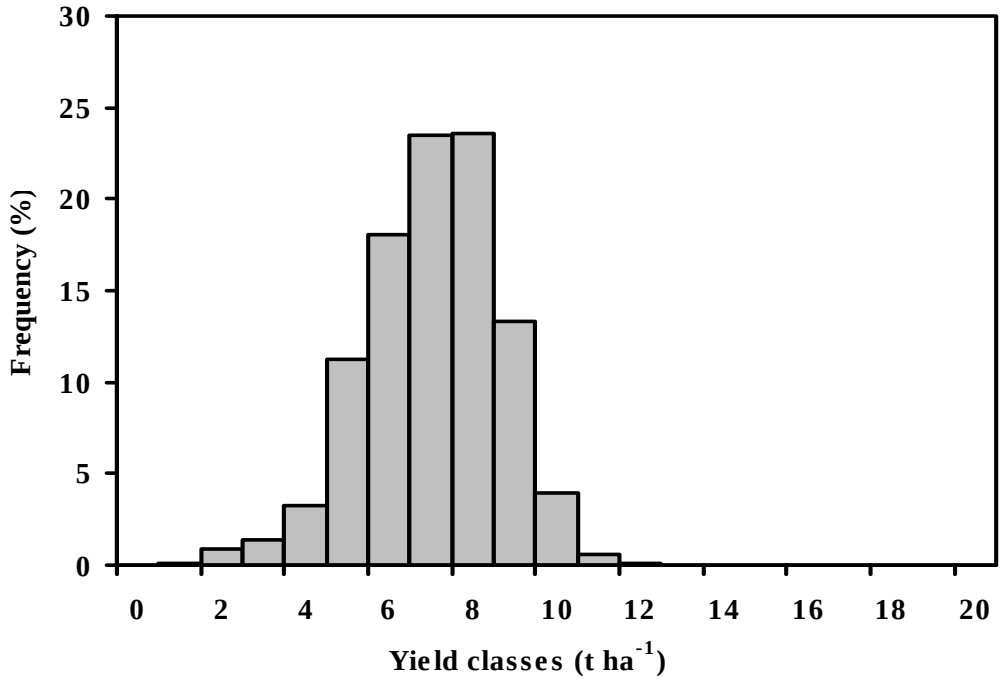

Figure 9.- Frequency distribution (expressed in %) of yield measured in 2003 in maize.

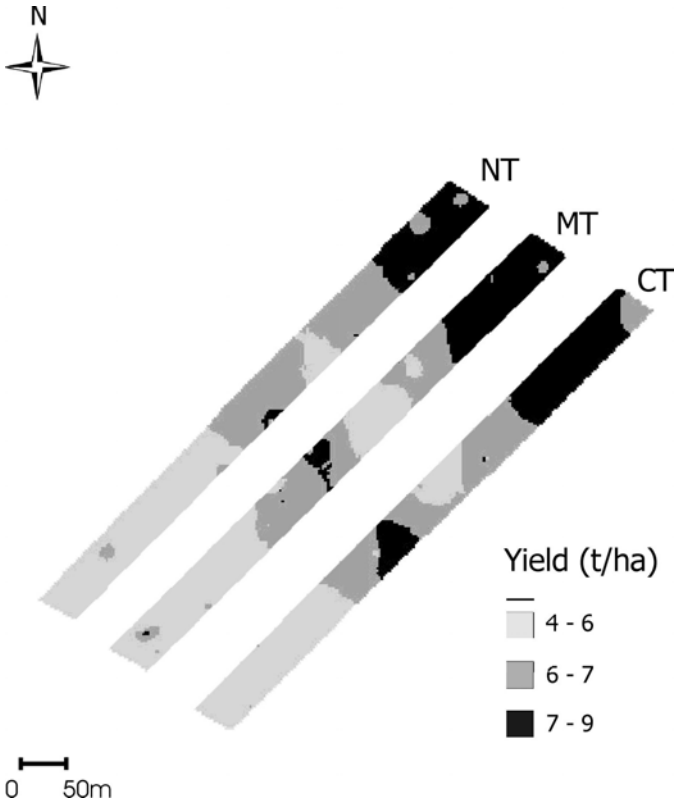

Figure 10.- Yield data obtained in 2003 within the different tilled plot defined within field, according to the experimental scheme.

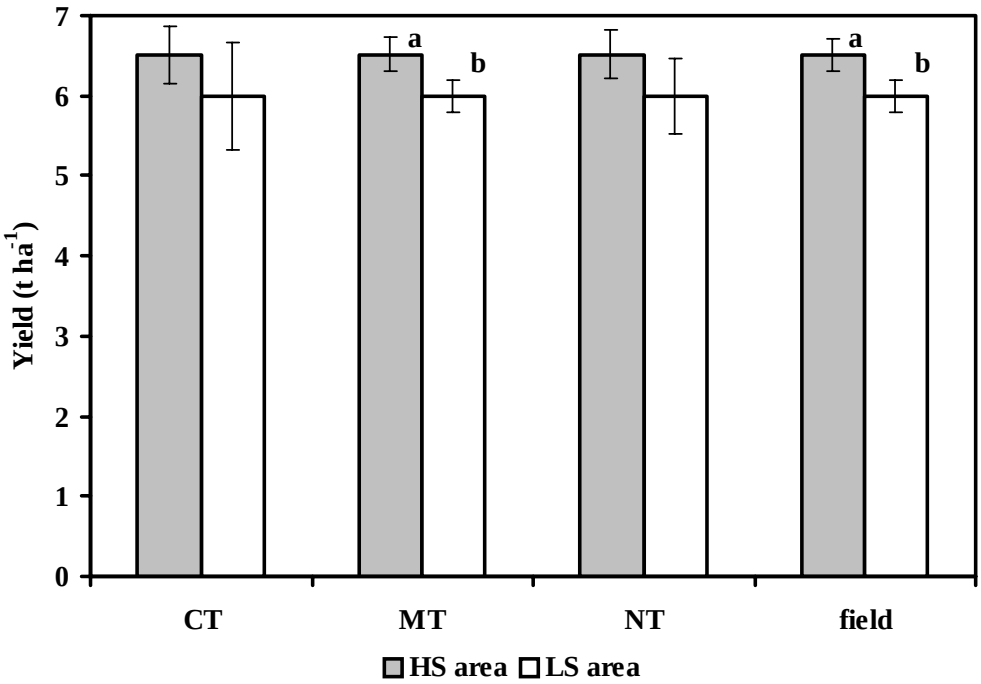

Figure 11.- Yield data obtained in 2003 within the stable area identified according to the temporal stability criteria. Vertical bars refer to standard error of the yield data. Different letters indicate statistically significant differences on yield level for the same tillage system (LSD test, $P \leq 0.05$).

Table 2.- Analysis of variance for the yield obtained in 2003 (*** = significant at P< 0.001 level of significance).

Source of variation	d.f.	Mean square
Area	1	0.112 ***
Tillage	2	8.623
Area × Tillage	2	0.696
Error	30	0.640
R^2		0.38

3.3.2.- Soil physical properties

Soil texture components resulted not different along soil profile within the complete field (Table 3), with higher values of standard deviation, revealing the presence of area having different percentage content of particles size, as shown by the statistically significant differences between the two stable area identified within field (Figure 12).

Table 3.- Average soil properties measured for the different area identified within field and entered into the simulation model

Investigated layers	Clay (%)	Sand (%)	Loam (%)	OM (%)	LL (cm^3 cm^{-3})	DUL (cm^3 cm^{-3})
0÷15 cm	41 ± 3.6	20 ± 8.3	39 ± 6.5	2.80 ± 1.1	0.254 ± 0.04	0.108 ± 0.04
15÷30 cm	40 ± 4.1	20 ± 8.1	40 ± 6.1	2.60 ± 1.3	0.260 ± 0.04	0.115 ± 0.04
30÷45 cm	42 ± 5.1	18 ± 8.6	40 ± 6.5	2.46 ± 1.3	0.247 ± 0.05	0.103 ± 0.05

As regards soil organic matter, the percentage content was comparable along soil profile, with a gradient involving the different layers, the upper layer having a content of organic matter greater than 7.7% and 13.8% in comparison with the second and the deeper layers. By considering the differences measured between the stable area – *i.e.*, *HS* and *LS* area – the organic matter content measured in *HS* area resulted greater almost than 1% in comparison with the *LS* area, revealing that the two stable area had appreciable differences along soil profile in terms of soil static physical properties directly influencing dynamic soil attributes, as for example hydraulic water limits.

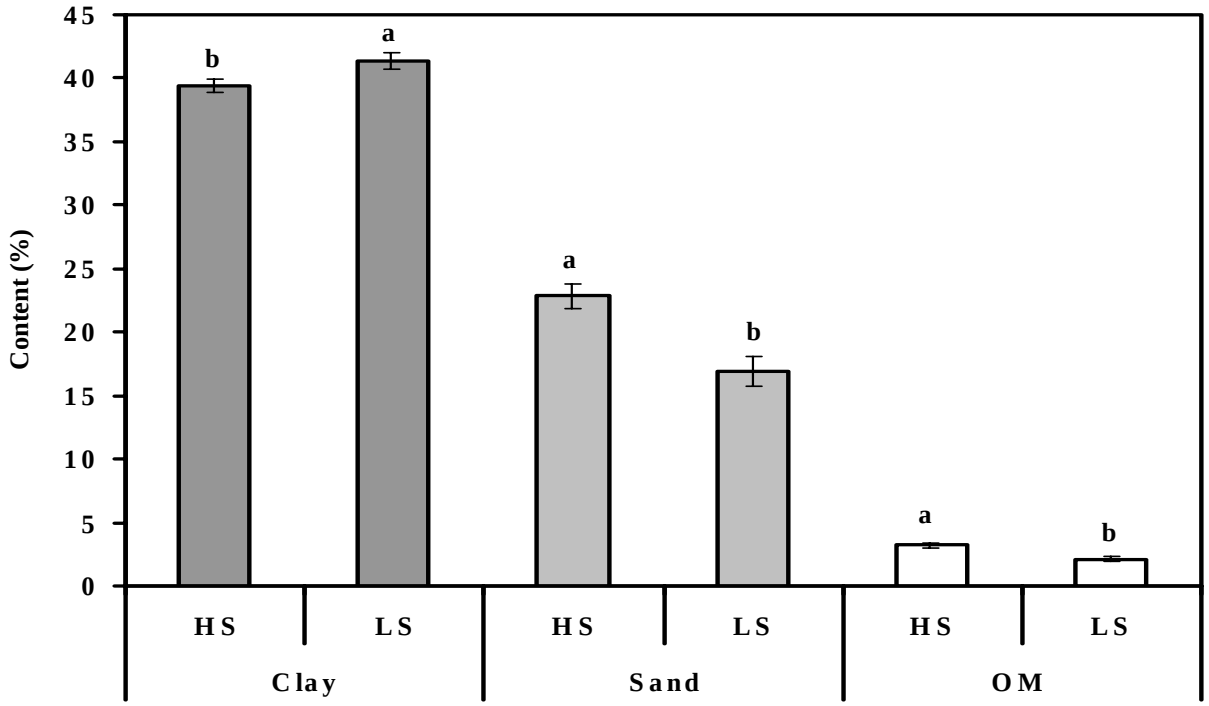

Figure 12.- Average soil properties measured along soil profile (0÷45 cm) within stable area. Vertical bars refer to the standard error of data. Different letters indicate statistically significant differences between the two area for the same soil attribute (*LSD* test, P≤0.05).

3.3.3.- Climatic data

Results obtained in 2003 were probably appreciably influenced by the climatic conditions. The average temperature attained greater values during the summer, with an annual average temperature of 14 °C, respect to that registered during the 1989-2002 period (annual average temperature of 13°C) (Figure 13). In particular, monthly temperature resulted greater in the last part of the Spring and in Summer, probably being a cause of stress for the crop growth, especially because of the lack of rainfall during this part of the growing season, as shown in Figure 14. As regards rainfall in fact, the total annual rainfall (677 mm) resulted lower than that measured in the 1989-2002 period, and in particular only 224.4 mm of rain occurred during the growing season (March-September interval

period), corresponding to a rainfall 15.4% lower than that of the long-term considered period, with a statistically appreciable lack of rainfall during the flowering stage of growth. Because of the particular not favourable climatic conditions registered during the field trials, results were simulated in a long-term period, in order to take into account these variables and their influence on yield and soil properties pattern.

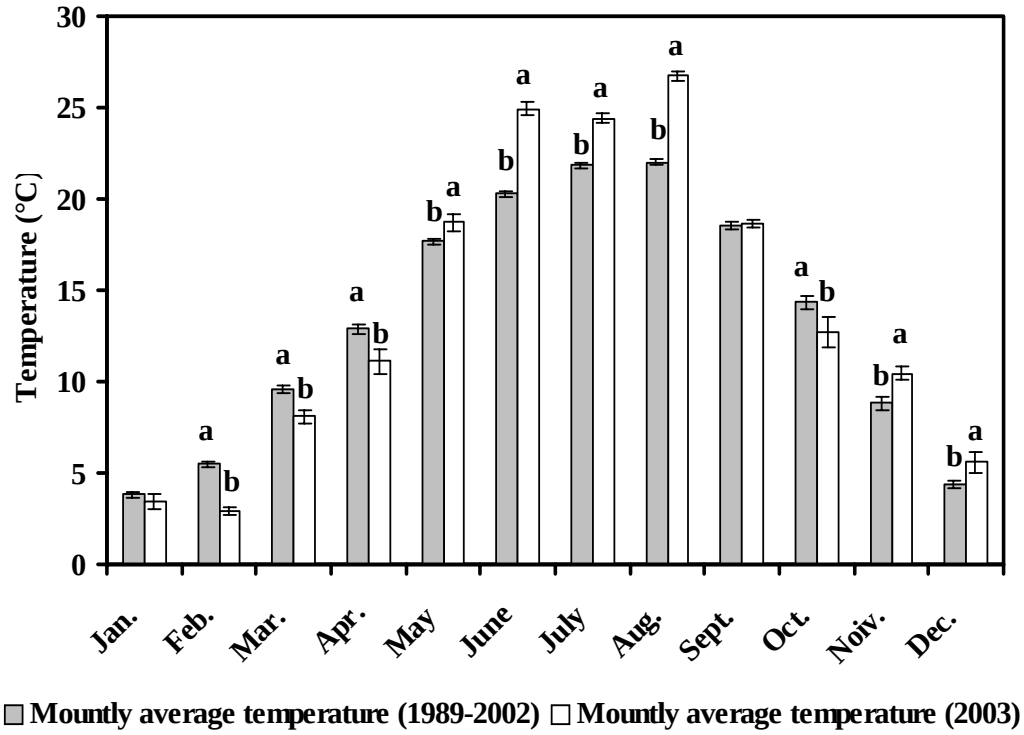

Figure 13.- Monthly average temperature (°C) registered in 2003 respect the values of the long-term trend (1989-2002). Vertical bars refer to the standard error of the measured data. Different letters indicate statistically significant differences for the same month (LSD test, P≤0.05).

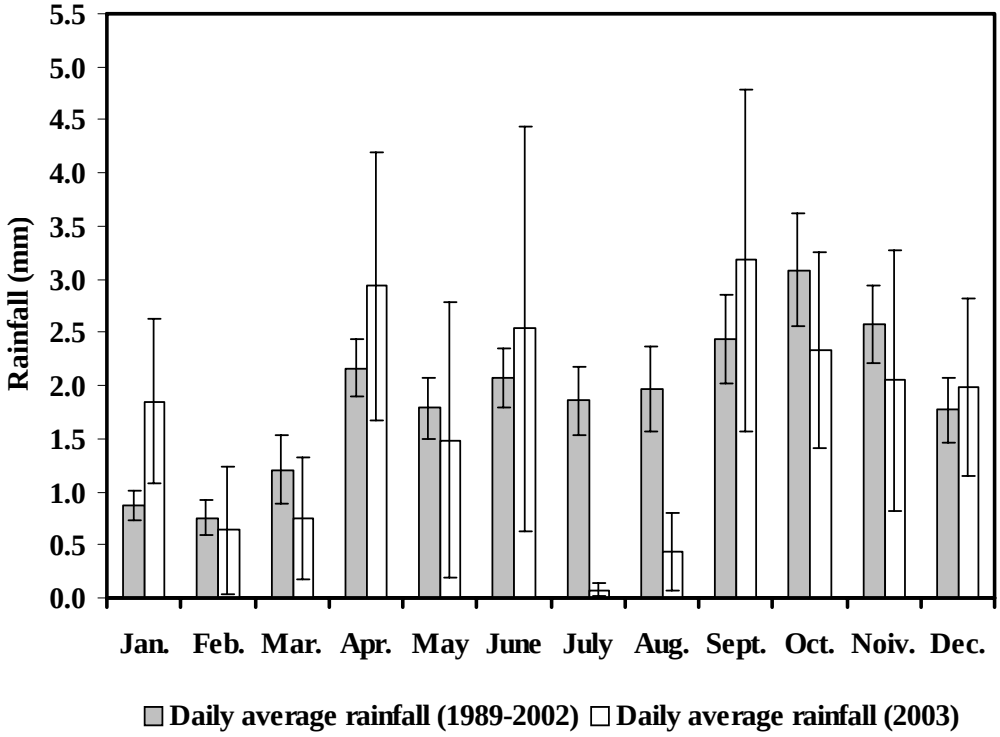

Figure 14.- Monthly total rainfall (mm) registered in 2003 respect the values of the long-term trend (1989-2002). Vertical bars refer to the standard error of the measured data.

3.3.4.- Annual simulation of yield

Predicted yield data resulted comparable with the measured data for all the tilled plots, being the percentage difference between predicted and measured values lower than the threshold limit (15%) accounted to consider the performance of the simulation model. In particular the model generally underestimated the measured yield, with an average percentage error that seemed not influenced by the tillage system adopted, resulting greater for *HS* area (average error = 9.6%) than *LS* area (average error = 3%), except for the predicted values for *NT* plot in *HS* area, for which the model overestimated the measured data (Figure 15).

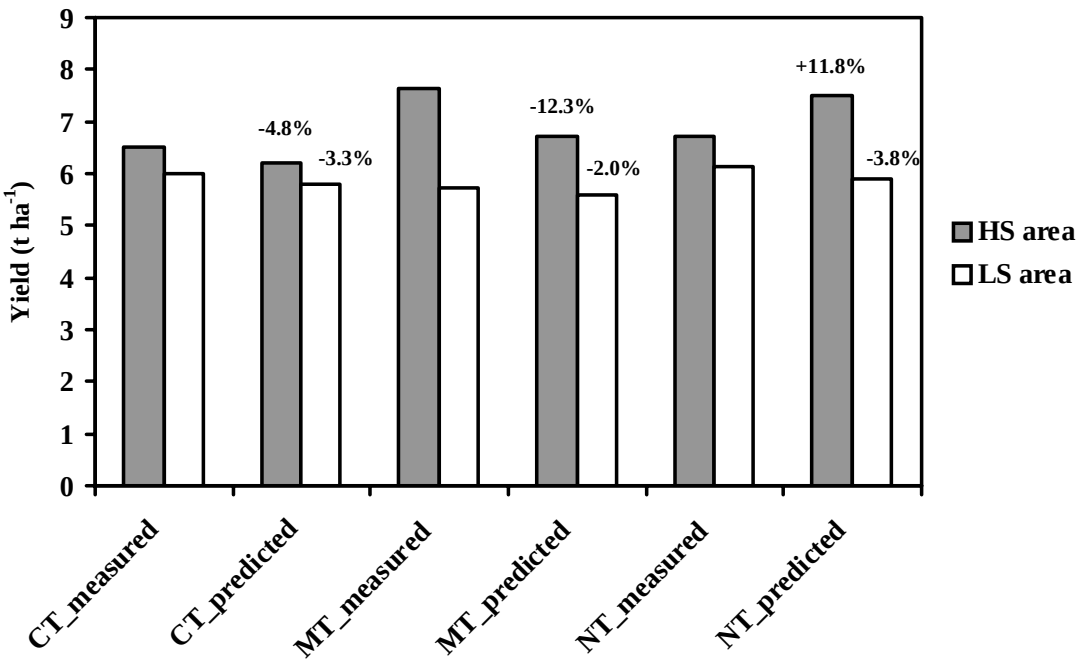

Figure 15.- Average predicted values compared to the measured yield data for the different tillage systems within stable area. Percentages refer to the differences of predicted values respect to that measured.

3.3.5.- Soil water content and bulk density

Results relating to soil water content and bulk density showed the presence of spatial and temporal variability within field, according to the influence of single sources of variation entered into the model used to explain the variability of the predicted soil properties along soil profile (Table 4). In particular, for both water content and bulk density the stable area was statistically significant for the all layers, indicating the presence of a different pattern within field, whilst the "*time effect*" resulted statistically significant within field, revealing values changed during the growing season. The

"*tillage effect*" resulted almost negligible for explaining water variability, except for the upper layer, because of the more intensive evaporation process occurred after tilling, whilst for bulk density the influence of tillage resulted statistically appreciable along the soil profile, because of the effect of tillage operation on soil structure. The accuracy of the model on explaining the variability of soil properties predicted over the growing season along the soil profile resulted very high, as confirmed by the values of the coefficient of determination, being for the entire profile the average $R^2 = 0.98$ and $R^2 = 0.99$ for water content and bulk density respectively. Based on that, for water only the interaction "*area × time*" resulted significant in the second soil layer, whilst for bulk density it was appreciable also in the remnant part of the profile. In particular, for bulk density all the interactions resulted statistically significant along the soil profile, confirming the importance of the influence exerted by tillage effect and the spatial and temporal components of variability, soil bulk density assuming different values over the growing season, with a variable intensity according to the considered area within field. The analysis of soil water variability for the stable area identified within field indicated an appreciable difference in the upper layer, by considering the average values of water content for the complete area, tillage effect not being significant (Figure 16).

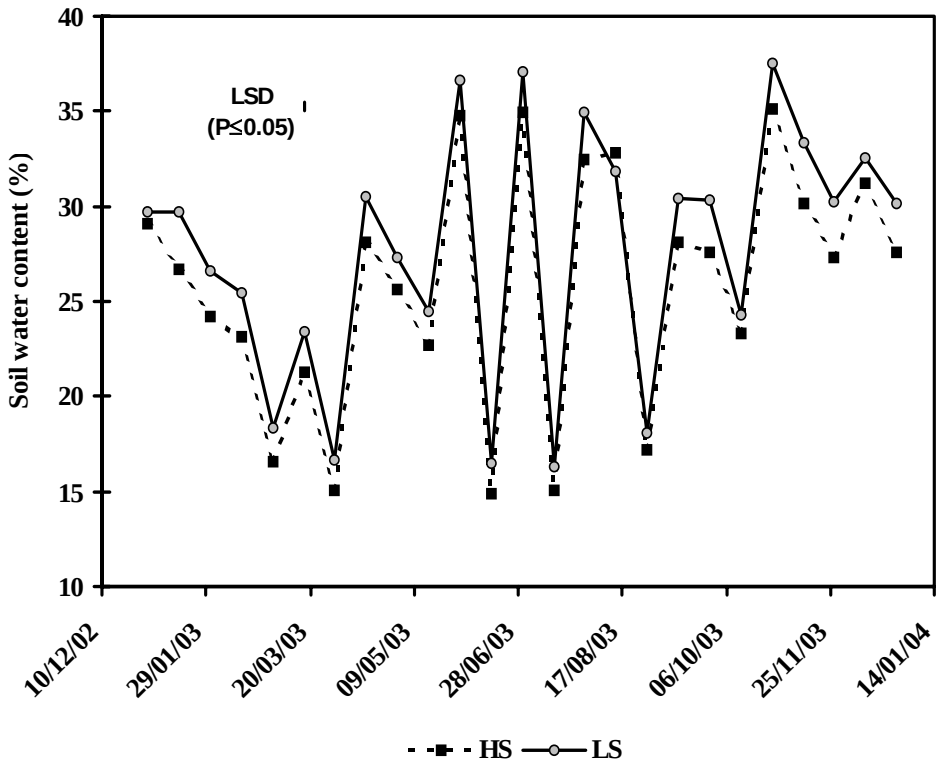

Figure 16.- Predicted soil water trend during the growing season in the upper layer (2÷7 cm) within the *HS* and *LS* area. *LSD* value for "*area × time*" interaction at P≤0.05: 0.50.

Table 4.- Analysis of variance for the annual predicted soil water content (expressed in %) and bulk density (expressed in Mg t^{-1}) along the soil profile (* = significant at P< 0.05 level of significance; ** = significant level of significance; *** = significant at P< 0.001 level of significance).

Source of variation	**d.f.**	**Means square within different layers along soil profile**					
		2-7 cm		**7-14 cm**		**14-26 cm**	
		water content	**bulk density**	**water content**	**bulk density**	**water content**	**bulk density**
Time	23	156.9531 ***	0.0032 ***	121.5873 ***	0.0011 ***	170.3057 ***	0.0003 ***
Area	1	90.0639 ***	0.1137 ***	66.2683 ***	0.1203 ***	293.6405 ***	0.1986 ***
Tillage system	1	5.6605 *	0.0000 **	0.8459	0.0000	1.2801	0.0005 **
Area × Time	24	0.7998	0.0006 ***	1.2724	0.0014 ***	37.1385 ***	0.0000
Time × Tillage system	1	5.7909 *	0.0000 ***	10.6262 *	0.0000	0.6943	0.0005 ***
Area × Tillage system	1	0.1081	0.0001 ***	0.0036	0.0005 ***	1.8479	0.0006 ***
Error	47	1.014	0.000	1.956	0.000	1.432	0.000
R^2		0.988	0.998	0.970	0.994	0.987	0.991

In particular, *HS* area had a lower water content during the growing season than *LS* area, with an average difference of –7.36% (average water content of 25.79% and 27.69% in *HS* and *LS*, respectively).

In the intermediate layer results were similar, with a more appreciable difference on water content for the two area within field, *HS* area having an average value of soil water (26.8%) lower than *LS* area (28.5%) over the growing season (Figure 17).

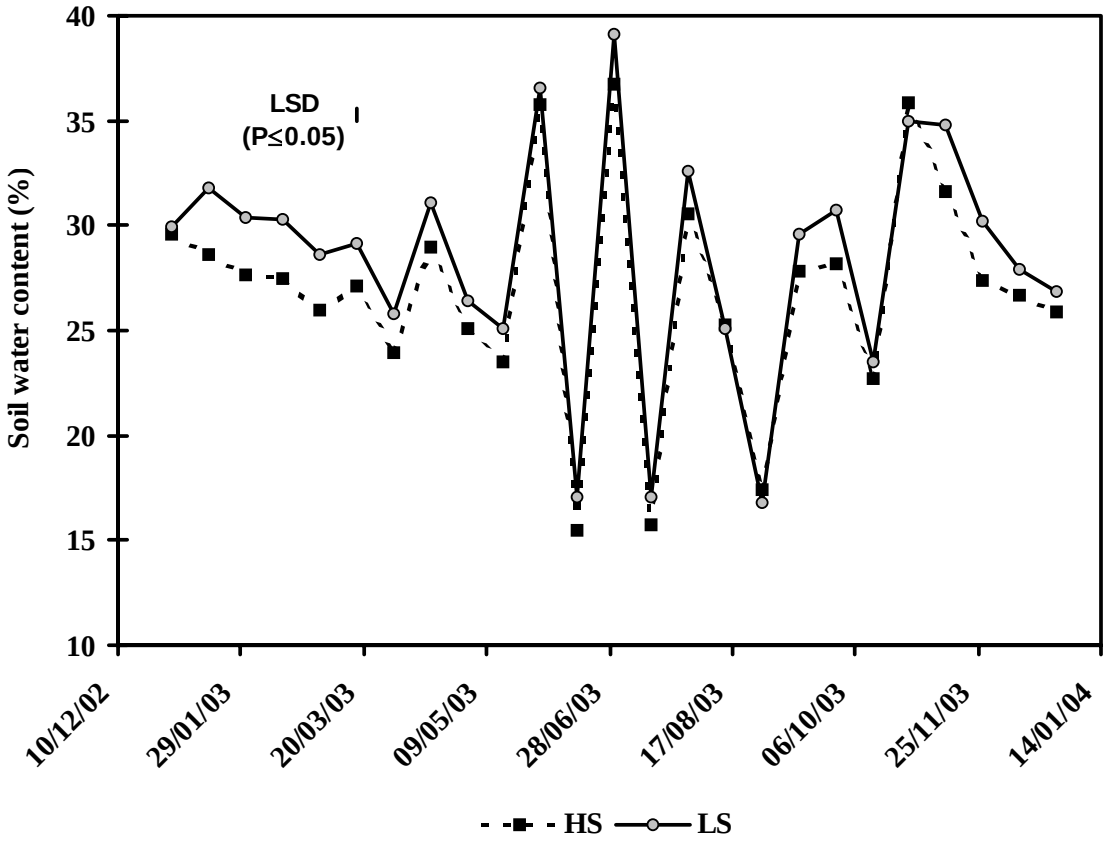

Figure 17.- Predicted soil water trend during the growing season in the intermediate layer (7÷14 cm) within the *HS* and *LS* area. *LSD* value for "*area × time*" interaction at P≤0.05: 0.56.

In the deeper layer *HS* area showed a generally greater soil water content than *LS* area, particularly during the relative driest period of the growing season, relating to the lack of rainfall measured from June to August, with a seasonal average water content greater of 13.66% in *HS* area than in *LS* area (Figure 18).

These results were probably due to the different characteristics measured along the soil profile, with *LS* area having a lower volume of soil available for root exploration, because of the greater soil penetration resistance measured in the deeper layer, which represented an obstacle for water movements. Consequently, the upper portion of soil in *LS* area resulted wetter than *HS* because of

the slower infiltration, whilst with lack of rainfall the capillary ascendance involved more appreciably *HS* area.

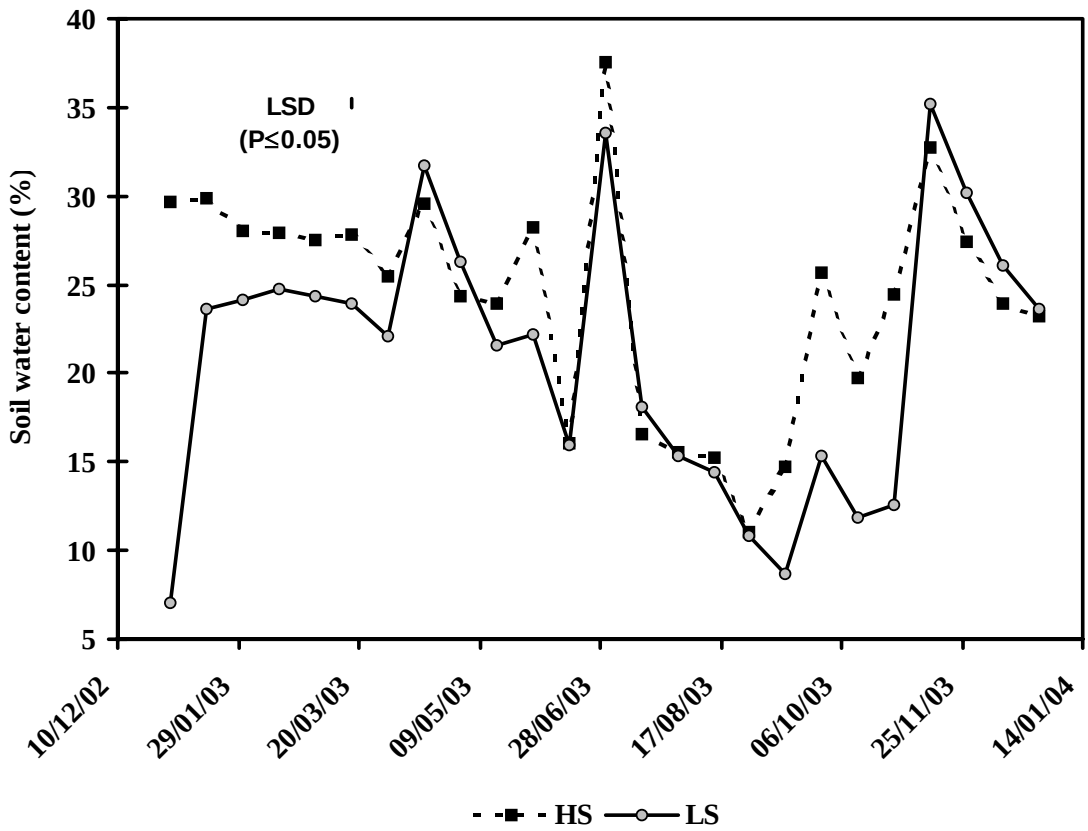

Figure 18.- Predicted soil water trend during the growing season in the deeper layer (14÷26 cm) within the *HS* and *LS* area. *LSD* value for "*area × time*" interaction at P≤0.05: 0.48.

For the bulk density pattern the stable area – i.e., *HS* and *LS* area – had different initial conditions, LS having a lower bulk density than HS, an aspect that accentuated the influence of "*area effect*". As regards "tillage effect" it was particularly appreciable in *HS* area, causing a greater decreasing of bulk density along the soil profile. Furthermore, the more evident effect of tillage was due to the shorter effect of tillage on soil porosity in both area after the decreasing of bulk density values due to soil tillage, with a lower slope for the predicted trend of the *HS* area. In particular, in the upper layer (2÷7 cm)the tillage effect was negligible in the both area (Figure 19), whilst in the second layer (7÷14 cm) analysed along soil profile the difference between *CT* and *MT* system was statistically appreciable only in *HS* area, for which bulk density attained the initial values in a longer period than *LS* area (Figure 20). Finally, in the deeper layer the trend was comparable with the precedent layers, being *CT* effects more appreciable in *HS* area than in *LS*, respect to the initial conditions, probably because the greater organic matter content (Figure 21). The latter aspect in fact may be connected to the differences between the two area, with the consequence that in *LS* area the

effect of tillage was less evident both in space and in time, whilst in *HS* the effect of tillage was more evident, especially for *CT*, characterised by a longer effect on porosity.

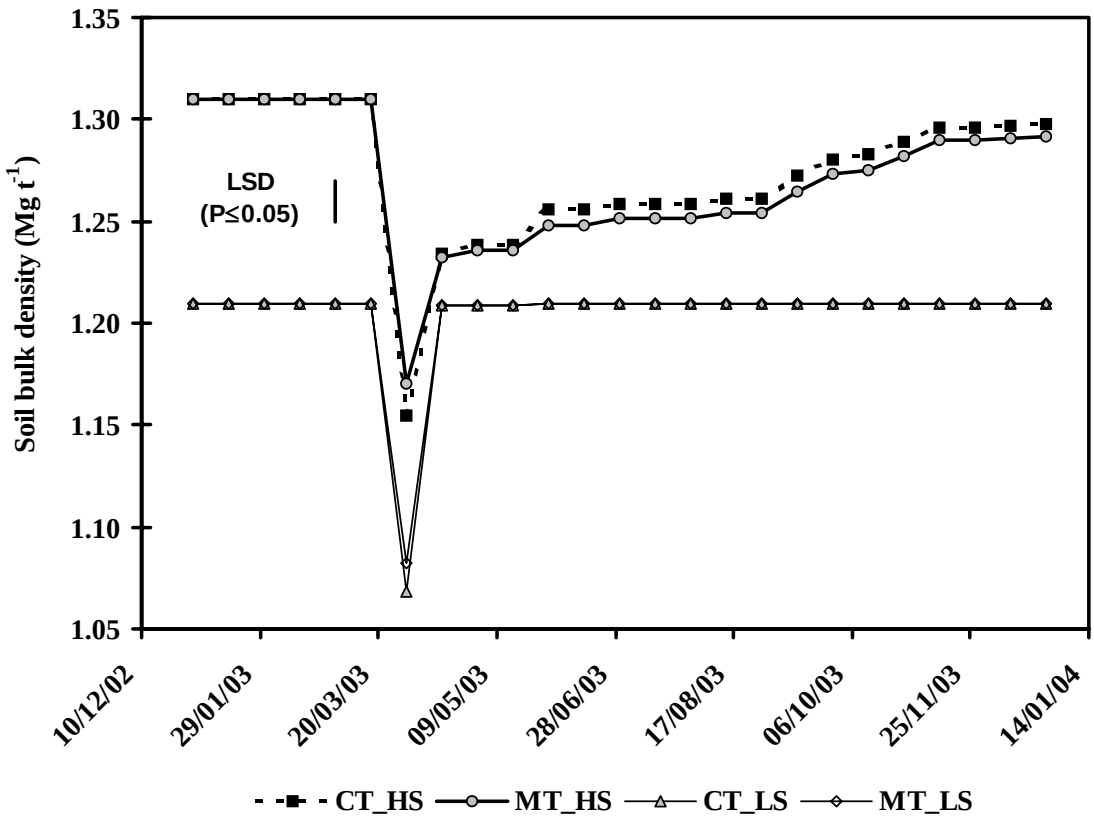

Figure 19.- Predicted soil bulk density trend during the growing season in the upper layer (2÷7 cm) within the *HS* and *LS* area for the different tillage system adopted. *LSD* value for "*area × tillage*" interaction at P≤0.05: 0.02.

In conclusion, as regards the effects of tillage on soil properties, there was a not appreciable effect on soil water content, and particularly HS area had greater values than LS, especially during the driest period of the growing season, probably because the different soil properties measured along the soil profile, sol organic matter content being greater in HS area and influencing positively the water balance of soil. For bulk density, the effect of tillage was appreciable in the second layer, particular in the HS area, whilst in general CT system more appreciably decreased the bulk density values than MT system, with a longer effect on HS area, probably because the more important influence of soil organic matter content on tillage/soil properties interactions. Consequently, tillage seemed not to be efficient in the LS area, whilst in HS area CT system resulted more positively influencing on spatial and temporal variability of soil properties.

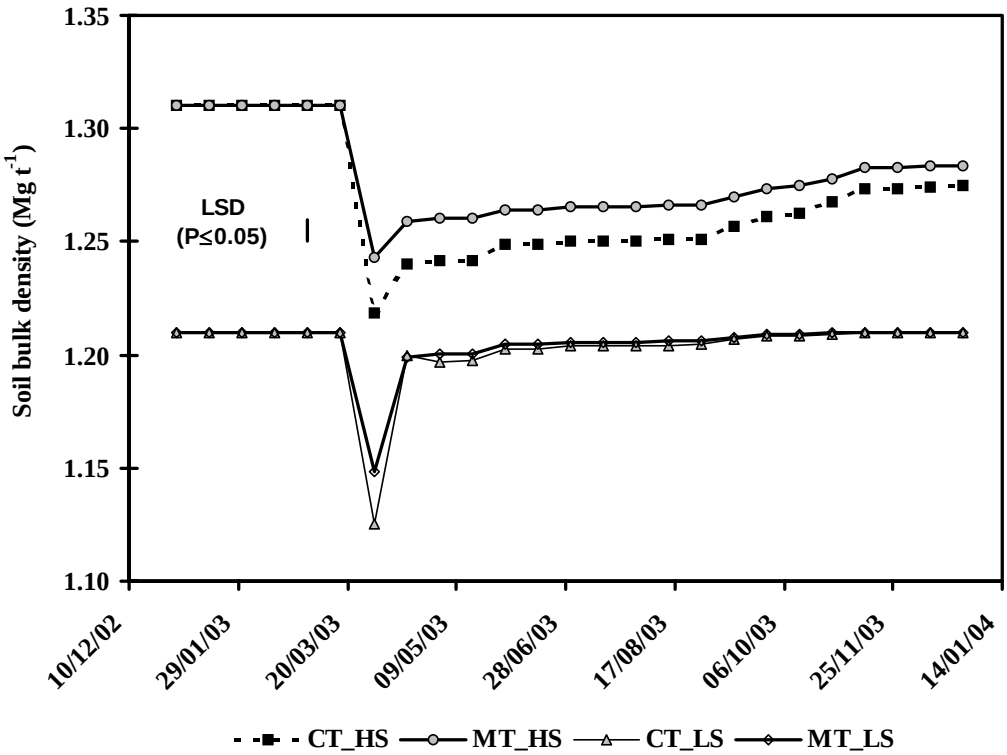

Figure 20.- Predicted soil bulk density trend during the growing season in the intermediate layer (7÷14 cm) within the *HS* and *LS* area for the different tillage system adopted. *LSD* value for "*area × tillage*" interaction at P≤0.05: 0.01.

3.3.6.- Long-term yield pattern

For the predicted yield the different area resulted statistically significant in explaining the variability of yield, confirming the differences detected in 2003 between the *HS* and *LS* area identified within field, whilst also tillage and year effects were statistically significant in the model used to explain the yield variability detected for the long-term predicted values, as confirmed by the relatively high value of the coefficient of determination (R^2 = 0.96) (Table 5). These results indicate that yield had intra-year (Figure 22) and inter-years variability over the considered period, with tillage variable that was significant on explaining the variability of yield, being significant the interaction "*area × tillage*" and "*year × tillage*" at P< 0.01 and at P< 0.001 level of significant respectively.

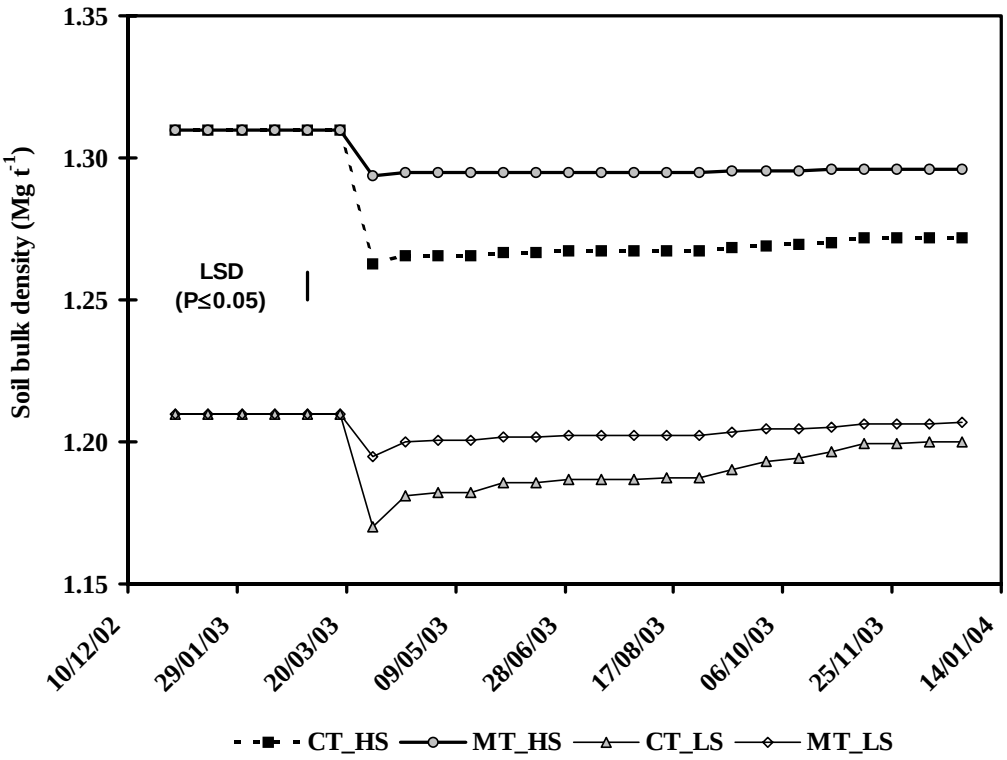

Figure 21.- Predicted soil bulk density trend during the growing season in the upper layer (14÷26 cm) within the *HS* and *LS* area for the different tillage system adopted. *LSD* value for "*area × tillage*" interaction at P≤0.05: 0.01.

Table 5.- Analysis of variance for the long-term predicted yield values within field (** = significant level of significance; *** = significant at P< 0.001 level of significance).

Source of variation	d.f.	Mean square
Area	1	48.154 ***
Tillage	2	4.931 ***
Year	13	11.196 ***
Area × Year	13	0.374
Year × Tillage system	26	1.394 **
Area × Tillage system	2	35.718 ***
Error	26	0.436
R^2		0.96

Being significant the presence of two different homogeneous area within field, the effect of tillage was analysed within each stable area separately (Figure 23). For the *HS* area the predicted yield for the *MT* and *NT* tilled plots was appreciably lower than that relating to the control plot – i.e., *CT* tilled plot. In particular, yield was not different for the *MT* and *NT* plots respectively, except for the

growing seasons having lowest rainfall (Figure 24), for which the *NT* plot in *HS* area has the worse performance, whilst when abundant rainfall occurred the difference between the two systems was generally negligible, and data were comparable with the yield measured for the *CT* plot, as detected for example in 1989 or in 2002. According to the predicted yield data, in general *CT* plot had the greater production, with an average long-term yield slightly greater than 12 t ha^{-1}, which was statistically higher than yield obtained in *MT* and *NT* plot, having comparable average yield data (test *LSD*, P≤0.05).

Furthermore, in *MT* plot yield resulted greater only in correspondence of not favourable climatic conditions, being similar to that obtained in *NT* plot in other cases, with an average long-term productions of 9.57 t ha^{-1} and 8.98 t ha^{-1} respectively.

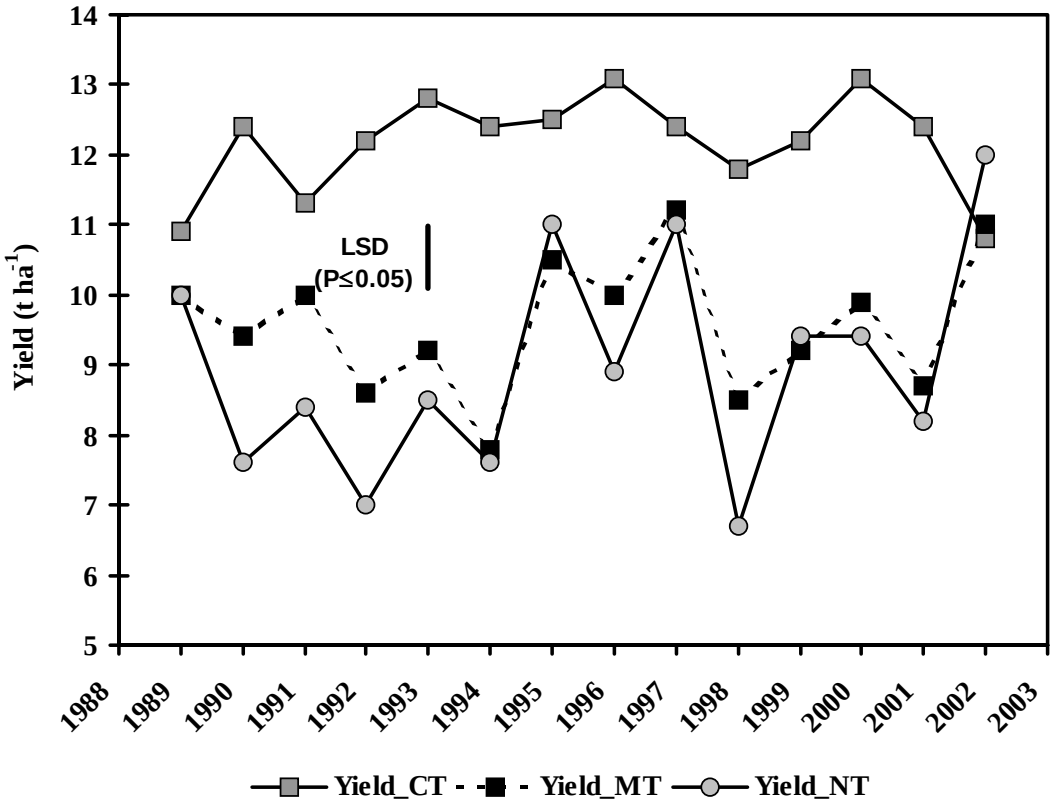

Figure 22.- Average predicted yield for the different tilled plots within the *HS* area identified within field. *LSD* value for "*tillage system × year*" interaction at P≤0.05: 0.88.

In the *LS* area results were more variable over years, and *CT* plot resulted the worst scenario, having a long-term average yield of 8.04 t ha^{-1}, with lowest production data in correspondence of the more appreciable lack of rainfall respect to the *MT* and *NT* plots. In particular, *MT* plot resulted the more productive over years, with an average long-term yield of 9.43 t ha^{-1}, statistically different respect to

that of the *NT* plot (8.70 t ha^{-1}) and particularly of the *CT* plot (*LSD* test, P≤0.05) Furthermore, the difference between the two plots and the control plot increased with the lower rainfall. In conclusion, *MT* system was the best performed within *LS* area, having the greater long-term predicted yield. These results were probably due to the different soil properties measured along the soil profile, the *HS* area having a greater amount of organic matter respect to the *LS* area, being benign for the interaction of soil and water.

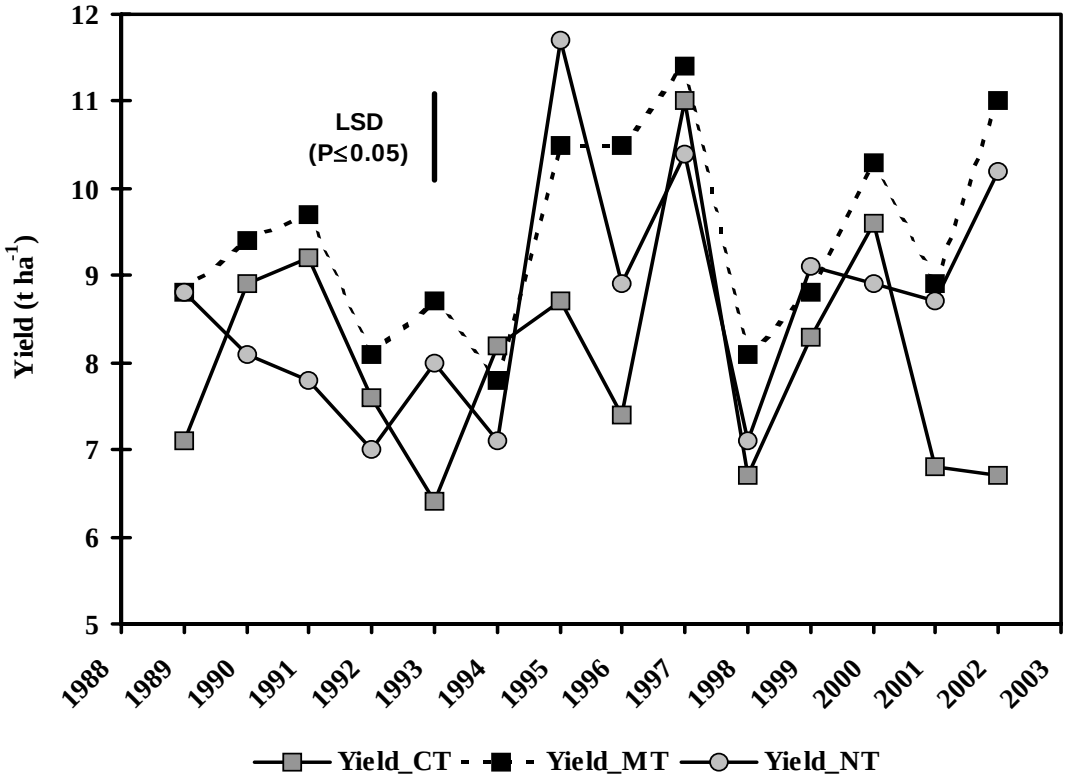

Figure 23.- Average predicted yield for the different tilled plots within the *LS* area identified within field. *LSD* value for "*tillage system × year*" interaction at P≤0.05: 0.98.

As regards the function of cumulative probability (*P*) *CT* plot within *HS* area showed the greatest yield in comparison with all treatments performed in the field, having for this area a probability of almost 10% and 80% to have a yield lower than 11 t ha^{-1} and higher than 13 t ha^{-1} respectively, with a probability of 50% to obtain a yield slightly lower than 12.5 t ha^{-1} (Figure 25). The *NT* and *MT* plots had a lower probability to obtained comparable yield in *HS* area, with a yield of 8.5 t ha^{-1} and 9.4 t ha^{-1} at 50% of probability respectively, and a probability greater than 70% to obtain a greater yield in *NT* plot respect to *MT* plot.

In *LS* area *CT* system had the lower production, whilst *MT* resulted the best productive plot, with a probability of 50% to have a yield slightly lower than 9 t ha^{-1}, respect to a yield of 8.6 t ha^{-1} and 7.6 t ha^{-1} obtainable in *NT* and *CT* plots respectively at the same probability level. In particular, for *LS*

area the interval of variation for yield in the long-term was greater than in *LS* area, but the functions was more close around the average probability of the area than in *HS* area, whilst there was a probability greater than 75% to obtain a yield of 8.7 t ha^{-1} and 8.9 t ha^{-1} in *CT* and *NT* plots, that were similar, respect to the significantly higher production obtainable with *MT* system (10.3 t ha^{-1}).

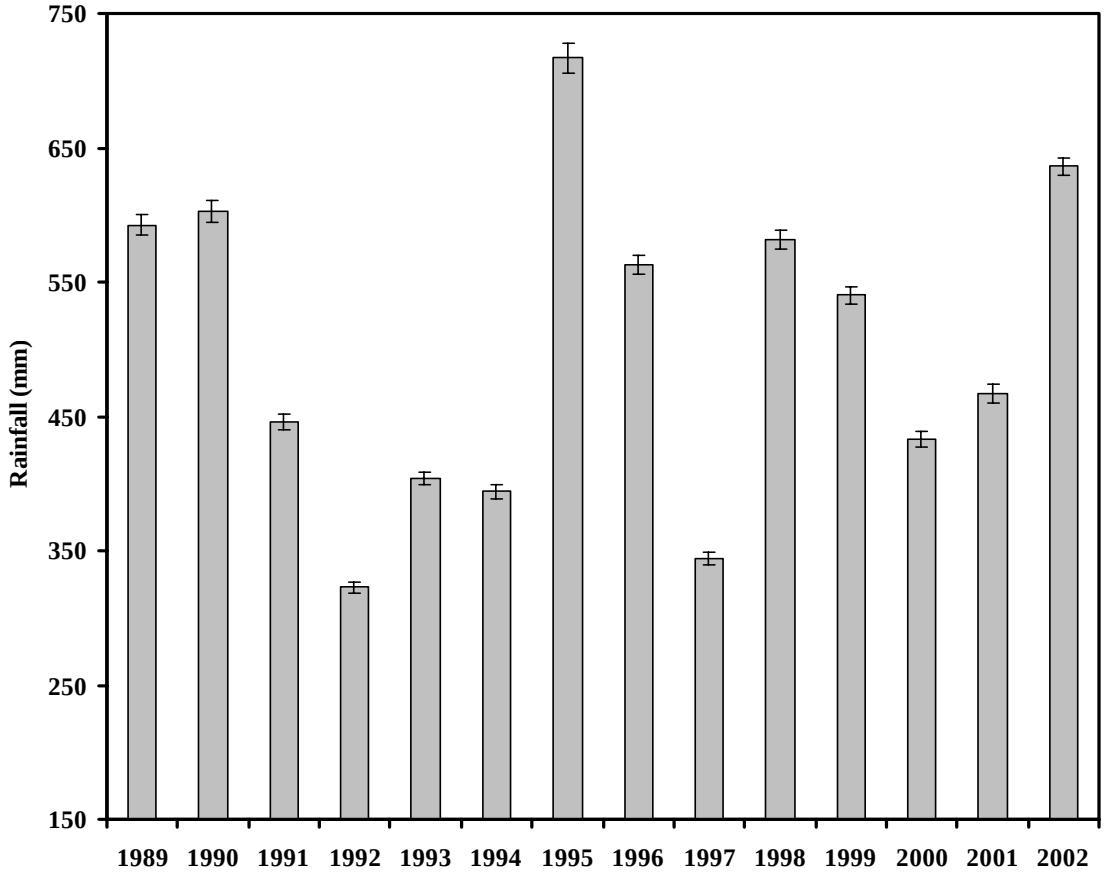

Figure 24.- Lon-term trend of the total rainfall occurred during the annual growing season (March-October). Vertical bars refer to the standard error of measured data.

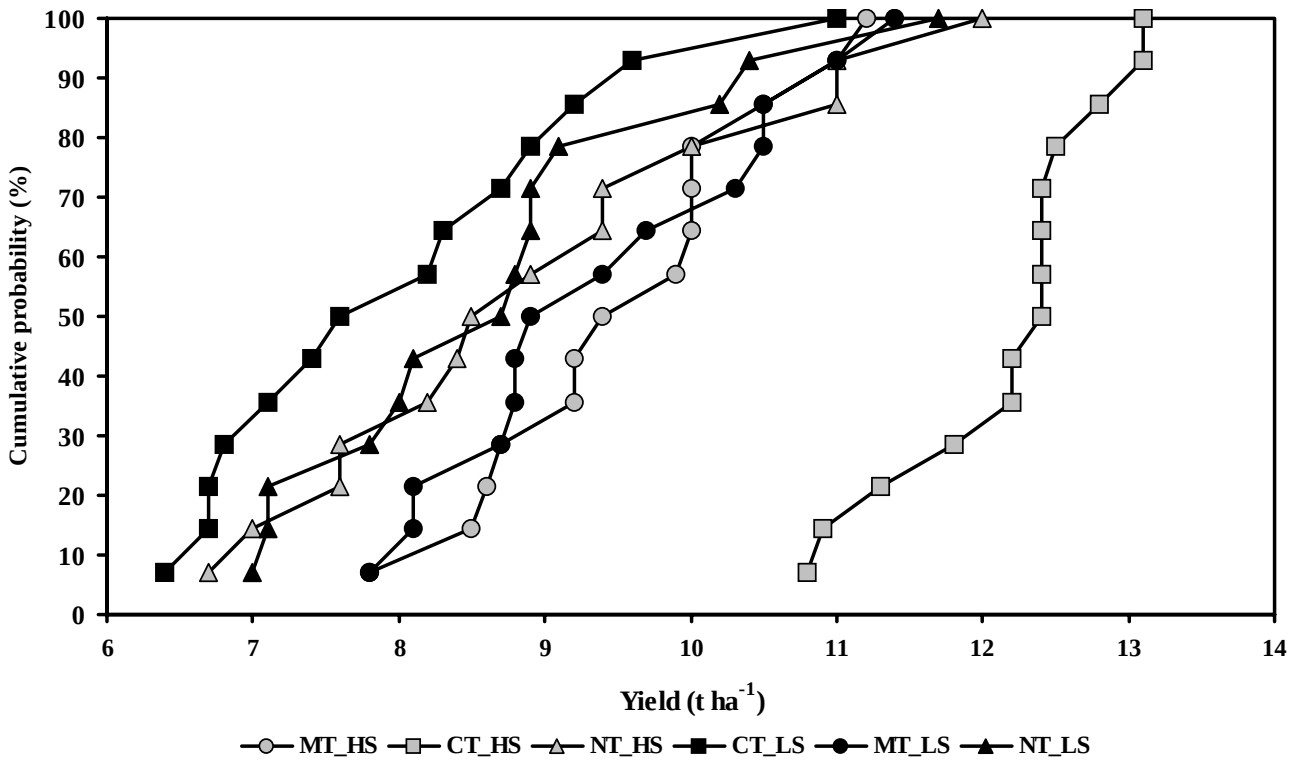

Figure 25.- Cumulative probability function for predicted yield for maize in different tilled plot within *HS* and *LS* area identified within field.

3.4.- Conclusions

This study has considered the effects of tillage performed at variable intensity within homogeneous stable area, consisting in a comparison of minimum and no-tillage systems – named *MT* and *NT* systems respectively – with conservative tillage practices (*CT* system) normally adopted by farmer, on soil properties and long-term predicted yield of maize. As regards soil water content, the effect of tillage along soil profile was not appreciable, whilst the differences on soil water content within the stable area identified were more significant, probably due to the interactions between soil properties (e.g., soil organic carbon and clay content) and water. Contrarily, tillage effect resulted statistically significant on influencing bulk density values along soil profile, with a greater effect on *CT* plot, decreasing bulk density values more appreciably and with a more durable effect respect to *MT* treatment in *HS* area, probably because the more important influence of soil organic matter content on tillage/soil properties interactions. As regards the effects on yield, during trials results were influenced by climatic conditions, with lower differences among treatments, whilst predicted data revealed that in *HS* area *CT* system could allow a greater yield than *MT* or *NT* plots, whilst in *LS* area *MT* system resulted better than control and no-tillage, at the same level of probability (P = 50%), NT system being more convenient for the not favourable growing season.
In conclusion, *CT* system seemed more convenient in *HS* area, whilst in *LS* area *MT* resulted the better tillage system, in terms of effects of tillage both on soil properties pattern along profile during growing season and on yield level, the differences between area being statistically appreciable.

At this regard, further studies are needed to understand the temporal effects of different tillage systems on soil properties and yield, by considering also the economic aspects and the convenience on adopting tillage at variable intensity within homogeneous stable area of field.

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– Sezione 4 –

Analisi e simulazione della convenienza economica nel lungo periodo all'adozione di un sistema di lavorazione del terreno sito-specifica in mais

Riassunto

La possibilità di adottare in azienda strategie per l'esecuzione di interventi ad intensità variabile è interpretato come un'interessante prospettiva per l'azienda ai fini della riduzione dei costi di produzione e dell'impatto esercitato dalle tecniche colturali messe in atto sulle risorse naturali. A tal proposito, pur essendo stati condotti importanti studi sugli effetti economici derivanti dall'adozione di tali tecnologie sul reddito aziendale e sulla propensione dell'imprenditore agricolo ad avvicinarsi ad esse, nel caso specifico delle lavorazioni del terreno, si hanno relativamente poche testimonianze in bibliografia della convenienza economica all'adozione di sistemi di lavorazione ad intensità variabile rispetto ad una lavorazione uniforme all'interno dell'appezzamento.

Il lavoro presentato in questo capitolo si propone di esaminare, in termini di reddito aziendale, la convenienza economica all'adozione di diverse strategie conservative di lavorazione del terreno (*MT* – Minimum Tillage, data dalla discatura del terreno e dalla preparazione del letto di semina con erpice rotante; *NT* – No-Tillage, consistente nell'adozione della semina su sodo) rispetto al sistema di lavorazione conservativo normalmente adottato in azienda (*CT* – Conventional Tillage, consistente nella lavorazione del terreno attraverso un intervento di ripuntatura, seguito dalla discatura e dalla preparazione del letto di semina con erpice rotante). Le prove sono state condotte nel corso del 2003 in mais (*Zea mays*, L.), su un appezzamento avente terreno argilloso situato ad Ariano nel Polesine, in provincia di Rovigo, Italia. In particolare, il lavoro è stato mirato all'analisi dell'influenza esercitata dalle diverse tecniche di lavorazione del terreno sulla resa e quindi sul reddito aziendale nel corso dell'annata di sperimentazione, valutando poi tali aspetti nel lungo periodo mediante l'adozione di un apposito modello di simulazione. Dai risultati è emerso come nel corso del 2003 il reddito sia risultato statisticamente differente all'interno delle due zone stabili individuate nell'appezzamento e, all'interno di queste stesse, come la tipologia di lavorazione eseguita abbia esercitato un'influenza significativa. In particolare, date le condizioni climatiche particolarmente sfavorevoli registrate nel 2003, il sistema che prevedeva la non lavorazione e la semina su sodo ha garantito il reddito più elevato all'interno delle aree stabili *HS* e *LS* definite

all'interno dell'appezzamento, a seguito dell'influenza dei costi di produzione più che del valore economico della resa conseguita.
I risultati di lungo periodo ottenuti dalla simulazione hanno invece evidenziato come i sistemi di lavorazione del terreno *CT* e *MT* siano in grado di assicurare il conseguimento di un reddito maggiore rispettivamente all'interno delle aree omogenee *HS* e *LS*, ad uno stesso livello di probabilità (P = 50%). La diversificazione della tecnica di lavorazione del terreno, nelle condizioni sperimentali considerate, è risultata quindi giustificata dal punto di vista economico, sia intermini di costi fissi derivanti dall'investimento iniziale che in termini di vantaggio economico ritraibile.

Parole chiave: analisi economica; costi di produzione; lavorazioni sito-specifiche; mais; reddito lordo aziendale; simulazione

Abbreviazioni: *CT* – sistema di lavorazione convenzionale; *HS* – area con resa alta e stabile; *LS* – area con resa bassa e stabile; *MT* – sistema di minima lavorazione; *NT* – sistema di non lavorazione

– Section 4 –

A preliminary economic approach to the opportunity of site-specific tillage management and simulation of long-term convenience in maize

Abstract

Soil tillage practices exert different effects on soil properties and the adoption of tillage at variable intensity may cause a variable influence on grain yield, with a consequent variability on farm gross margin. This study has considered the influence on yield and economic aspects due to the adoption of two conservative tillage systems (*MT* – Minimum Tillage and *NT* – No-Tillage) in comparison with the conservative tillage practices (*CT* system) normally adopted by farm. Field trials were carried out in 2003 in a clay soil situated in Rovigo, NE Italy, and different tillage strategies were performed within homogenous stable area, identified according to the temporal stability of yield criteria. Yield data were simulated with *DSSAT 3.5* – module *CERES-Maize* – for a long period (1989-2002), in order to consider also the influence exerted by climatic conditions. In 2003, yield resulted influenced by climatic conditions and resulted not appreciably statistically significant for different area of the field, NT system assuring a greater farm gross margin due to the more evident influence of cost of production than the economic value of yield. In particular, the cost for tillage resulted lower in *NT* plot, whilst for disk harrowing the value of cost was greater in *MT* plot than *CT* plot, being used as primary or secondary tillage respectively. As regards the long-term analysis yield was more appreciably different between stable area identified within field than for the complete field, and consequently *HS* and *LS* area were separately considered: the effects due to the tillage system resulted statistically significant on yield within each stable area, and consequently the farm gross margin appreciably varied for different tillage systems. In particular, *CT* resulted the best system for *HS* area, assuring the greatest farm gross margin, whilst in *LS* area the greater value was assured by *MT* system, at the same level of probability (P = 50%).

Keywords: economic analysis; maize; production cost; profitability; simulation; site-specific tillage.

Abbreviations: *CT* – Conventional Tillage system; *HS* – stable area with high yield; *LS* – stable area with low yield; *MT* – Minimum Tillage system; *NT* – No-Tillage system.

4.1.- Introduction

In the last decades several studies have demonstrated the presence of variability within field, both in large and in small fields (Jaynes and Colvin, 1997; Yamagagishi et al., 2003; Ping et al., 2004). In particular, dynamic soil properties (e.g. soil water content) and crop yield may be affected by spatial and temporal variability (Eghball and Varvel, 1997; McBratney and Pringle, 1999; Blackmore et al., 2003), and different studies have proposed methods and solutions to variably manage them, in order to obtain economic and environmental benefits, being highly dependent on both the intensity and the magnitude of spatial variability of limiting factor affecting yield and on the accuracy of the understanding of its spatial structure within field (Pierce and Novak, 1999).

Despite to that, agronomic practices were usually based on the average yield level obtained with the precedents crops (Stafford et al., 1996) and uniformly performed within-field, consequently being inefficient both for the environmental impacts and for the productive costs (Stafford, 1993). As regards soil tillage, practices uniformly performed within field may be correct in some areas and inappropriate in others, because of the spatial variability of soil properties (e.g. soil texture or organic matter content), attributes (e.g. field slope) and their long-term interactions (e.g. relationship between soil texture and electrical conductivity). In particular, several studies have demonstrated that runoff and sediment loss can be significantly reduced by adopting minimal soil disturbance systems compared with traditional tillage (Hall et al., 1991; Packer et al., 1993), because of the benefits deriving from the presence of crop residue at soil surface. In particular, the erosion effects decrease exponentially with an increase of residue at soil surface (Laflen et al., 1978), with greater decreasing in sediment-associated phosphorus pollutant losses by assuring a coverage of 48% at soil surface in comparison with a mouldboard plough based system (Ginting et al., 1998a; Ginting et al., 1998b), whilst a presence of 20% covered soil surface is sufficient to reduce at 50% soil erosion (Dickey et al., 1985), with important implications for crop productivity by varying field slop (Schumacher et al., 1999).

The possibility of maintaining or improving soil fertility by decreasing soil tillage intensity by adopting conservation tillage systems is recognised and documented in literature. Tillage intensity in fact may be correlated to some negative aspects regarding soil fertility, as for example the presence of plough pan (Soane and van Oewerkerk, 1994; Fattah and Upadhyaya, 1996) or the rate of decreasing on soil organic carbon. At this regard, the tillage systems not inverting soil layers

could provide an appreciable increase in soil organic carbon (Franzluebbers et al., 1994), with an influence on the correlated aspects, as for example water infiltration and availability for crop (da Silva et al., 2001), soil structural stability and bulk density (Hamblin and Davies, 1977; Carter, 1992) or nitrogen losses (Chan et al., 1992). About the latter subject, results reported in literature are in some cases conflicting, because the different water infiltration and organic carbon content in the upper soil layer deriving from the adoption of minimum tillage respect to conventional systems with a different pattern over different growing season because of the influence of climate conditions and crop rotation (Granovsky et al., 1993; Meek et al., 1993; Drinkwater et al., 2000; Shipitalo et al., 2000).

In this framework, the adoption of precision agriculture techniques is considered as an opportunity for farmers to obtain various benefits, mainly considering the possibility to increase the efficiency of the agricultural production process and to control and decrease the environmental impacts on natural resources. However, despite advancements in technology and learning that make possible the variable rate application of inputs, the economic benefits, intended as greater net return than uniform-field management, are not generally appreciable or demonstrable, having spatially and temporally different scale of variation (Lowenberg-DeBoer and Swinton, 1997), and varying for different factors or crops considered (Watkins et al., 1998; Bongiovanni and Lowenberg-DeBoer, 2004). As regards economic benefits deriving from the adoption of tillage systems at variable intensity, this strategy may increase the net return for farm by reducing the costs of production due to mechanisation without altering the yield level obtained, but results reported in literature are contrasting for a few years of trials. In particular, a shallower tillage causes a reduction of the draught and energy requirement (Raper et al., 2000), with a consequent amelioration of energy power and fuel consumption utilization (Godwin and Miller, 2003), reducing costs of production due to tillage system (Basso et al., 2003). But the economic benefit deriving from the adoption of tillage systems at variable intensity may be variable by considering different growing season or soil initial conditions. At this regard, in same cases a greater yield characterised plots tilled at compacted depth layer, respect to that no-tilled or conventionally tilled having comparable values of soil strength in the shallower depth along soil profile (Wells et al., 2003), whilst Ginting et al. showed that in dry season crop yield may be greater for maize and soybean in plots managed with simplified tillage than that conventionally tilled, whilst in wet years the opposite situation was found, due to the influence of climatic conditions on soil tillage effects (Ginting et al., 2003).
Furthermore, despite to the demonstrated profitability for variable rate application of inputs, some authors pointed out the possibility to obtain an increase of the net return by increasing the efficiency

of the production system and varying the rate distributed within field rather then generally reducing the rate of input applied (Bullock and Bullock, 2000), with a variable function of productivity within field in the short period, according to the level of input distributed (Giau, 1999).

As regards soil tillage, in Mediterranean area the adoption of an appropriate tillage system is a crucial aspect in order to maintain or improve the soil's fertility and to reduce costs of production (Basso et al., 2003), but the diffusion of that strategies has to be supported by appreciable economic benefits, by considering economically and technically convenient solutions. The economic convenience to the adoption of innovation may depend on the equipments availability at farm or on the adoption of commercial solutions (Ginting et al., 2003). In the last years in fact some solutions were proposed by considering a unique soil parameter, as for example soil compaction, intended as limiting factor for root growth and crop yield (Gorucu et al., 2001; Wells et al., 2001; Adamchuk et al. 2003), or various physical and chemical soil properties (e.g. texture, organic matter content, etc.) (Voβhenrich and Sommer, 2003) for acquiring information about soil status in order to vary soil tillage intensity within field. Despite to the demonstrated advantages, at present in Italy their application remains a prospective, due to both technical problems and farmer's attitude. The adoption of innovation in agriculture in fact generally depends on various aspects, as reported in literature, as regarding the learning which improves farmer ability to implement the new technology or methodology in the production system, the expectation of farmer about the possible future improvement of net return by adopting the innovation and their risk attitude. Furthermore, for precision agriculture these aspects have to be summed to the difficult to consider the economic profitability for farmers, because of the influence exerted by the within-field spatial and temporal variability on aspects resulting from the adoption of new systems and technologies (Marra et al., 2003).

In this framework, the adoption of simulation models could be useful for taking into account the long-term influence exerted by the within-field spatial and temporal variability on strategies adopted by farmer, as for example the adoption of variable rate technologies. In particular, crop models could be an interesting tool for understanding the within-field variability (Jones et al., 2003), and considering the temporal interactions on daily plant growth and yield processes (Basso et al., 2001). As regards soil tillage, simulation model may help farmers to better understand the long-term effects of different tillage system on soil properties (Basso et al., 2003) and their interactions with environmental conditions on influencing crop growth, allowing to the adoption of sustainable and convenient tillage systems.

The main objectives of this paper are (***i***) to investigate the economic aspects of the adoption of soil tillage performed at variable intensity within homogeneous practically manageable zones, identified according to the long-term predicted temporal stability of spatial variability of yield, throughout the comparison of two conservative tillage systems – *i.e.*, minimum tillage and no-tillage – with the conservative practices normally adopted by the studied farm, and (***ii***) to analyse the economic convenience over a 15-year period, in order to take into account the variable influence of climatic conditions on temporal variability of risk and identify the more convenient system for each stable area, in maize (*Zea mays*, L.).

4.2.- Material and methods

4.2.1.- Site description and climatic data

The field trials were carried out in 2003 in a 8-ha flat field, situated near Rovigo (44° 4’ 12” N, 11° 47’ 22” E, 6 m a.s.l.), NE Italy. The soil was clay, according to the USDA particles-size distribution limits.

The climate of the area (data relating to the 1989-2003 period) is characterised by an annual average rainfall of 700 mm, distributed mostly in autumn and spring. The annual average temperature is 13.3 °C, with a monthly maximum of 23.5 °C in July and a minimum of 3.2 °C in January (Figure1).

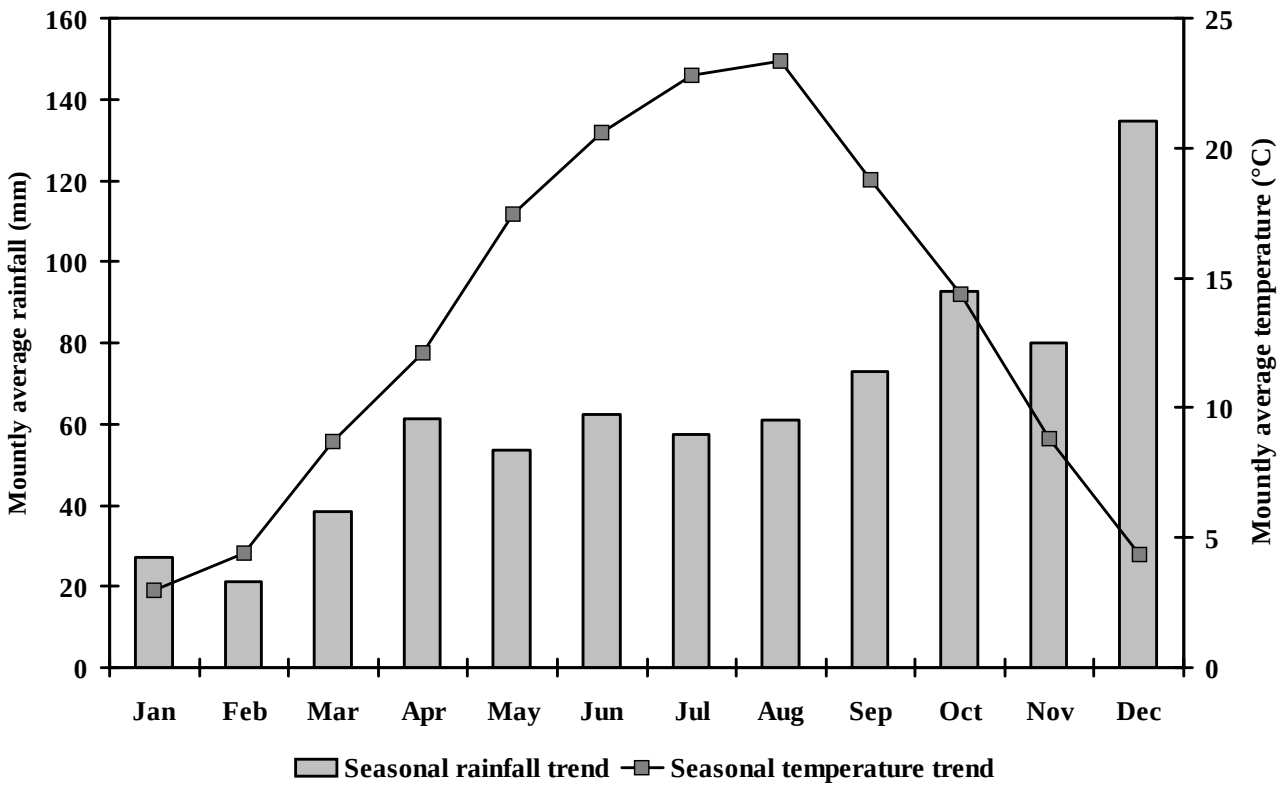

Figure 1.- Monthly total rainfall (mm) and average temperature (°C) long-term trend (1989-2002) in the site where the study was carried out.

4.2.2.- Crop growth model

The long-term pattern of yield grain was simulated over the 1989-2003 period in order to reduce the variability of yield over years due to climatic conditions and increase the accuracy of the definition of within-field homogeneous management area, according to that suggested by literature (Boydell and McBratney, 2002; Joernsgaard and Halmoe, 2003). Simulation was performed by using *CERES-Maize* model (Jones and Kiniry, 1986), being part of the *Decision Support System for Agrotechnology Transfer* (*DSSAT 3.5*, Hoogenboom et al., 1994), that provides several tools for model application, using a minimum database relating to the factors required to run the crop models and validate the outputs, as reported below.

Weather dataset

It includes the daily values of incoming solar radiation (MJ m^{-2} day^{-1}), maximum and minimum air temperature (ºC), and rainfall (mm), measured during the period used for the prediction at the Rosolina weather station (*Arpav* – Centro Meteorologico di Teolo, Padova, Italy), situated in Rovigo, Italy.

Soil dataset

It includes soil classification, surface slope, permeability, drainage and soil properties measured along the soil profile, as percentage sand, silt, and clay content, bulk density, organic carbon and water limits. In particular, soil properties – *i.e.*, soil texture, organic matter – were determined after collecting soil samples at 35 locations randomly displaced within field with an undisturbed soil core sampler (*Eijkelkamp*, Glesbeek, NL). A portable *Trimble 132* receiver, having differential correction, was used to localise each point within field. The hydrometer method was used to determine the textural characteristics of the soil. The organic matter content was calculated by using the Walkley-Black method (Walkley and Black, 1934). Undisturbed soil cores 8-cm in diameter ware collected and the bulk density was determined after oven-drying at 105°C to constant weight. All the measurements were made at three soil depth layers (0-15 cm, 15-30 cm and 30-45 cm) (Table 1), and sampling locations displaced within field were grouped according to the temporal stability criteria. Soil water limits were calculated using the procedure suggested by Ritchie et al. (1999), by considering the measured soil properties.

Genetic coefficients dataset

It includes the genetic parameters required to simulate the crop growth in the experimental area according to the peculiar genotype of the crop considered. During field trials, the cultivar *Costanza* was used and the coefficient of were given by the genetic constitutor (*Pioneer Hi-Bred International Inc., Des Moines, Iowa, USA*).

Table 1.- Average soil properties measured along soil profile for homogeneous area identified within field and entered into the crop growth simulation model.

Area	**Soil properties (%) for different layers**											
	0÷15 cm				**15÷30 cm**				**30÷45 cm**			
	Clay	Sand	Loam	OM	Clay	Sand	Loam	OM	Clay	Sand	Loam	OM
HS	39	25	35	3.73	38	24	38	3.71	40	21	39	3.61
LS	41	14	45	2.39	41	14	45	1.81	44	15	41	1.89

Management and experimental data

It includes all the information referring to the farming system suited by the farmer during the crop cycle (e.g., planting date, planting density, row spacing, planting depth, crop variety, irrigation, fertilizer practices and rates, etc.). At this regard, specific farming practices and timeframe used as input for model simulation, adopted by farm for the crop considered in this study are reported below.

4.2.3.- Identification of management zones

Based on long-term (1989-2003) predicted yield data, the temporal stability of spatial variability of yield for maize was determined in order to increase the accuracy for identifying homogeneous management area within field, according to the method proposed by Blakmore (Blackmore, 2000; Blackmore et al., 2003). The identification of stable area was performed in ArcView version 3.2^{TM} (ESRI, 1999), by considering the combination of the spatial variability, intended as intra-year variability and calculated as relative percentage difference of yield from the average at each point

mapped, and the temporal variance, intended as the magnitude of inter-years variability of yield, in order to identify homogeneous management zones, according to the temporal stability criteria.

4.2.4.- Field trials and agronomic management

Based on the stability pattern of grain yield, three 652-m long × 42-m wide plots was delimited within field, and named *CT* (*CT* = Conventional Tillage system), *MT* (*MT* = Minimum Tillage system) and *NT* (*NT* = No-Tillage system) respectively, according to the tillage practices adopted (Figure 2), in order to compare the two tillage system with the practice conventionally adopted by the farm in maize (*Zea* m*ays*, L.).

During field trials the equipments available at farm – *i.e.*, subsoiler, disk and rotary harrows – were used to perform tillage operations, coupled to a *New Holland* 176 kW 4 WD tractor, and particularly a V-frame subsoiler and a rear mounted hitch disk harrow were used for soil tillage at 35 cm and 15 cm respectively. Seedbed preparation was performed at a 10-cm depth with a rotary harrow. According to that, primary tillage was performed in the *CT* plot with the subsoiler on February 21, whilst the disk harrow was employed in both the *CT* and the *MT* plots on March 3. For seedbed preparing, rotary harrowing was carried out on March 19 on both plots, whilst on March 27 this agronomic practice was carried out only in the *CT* plot, in order to achieve a greater reduction of soil clods.

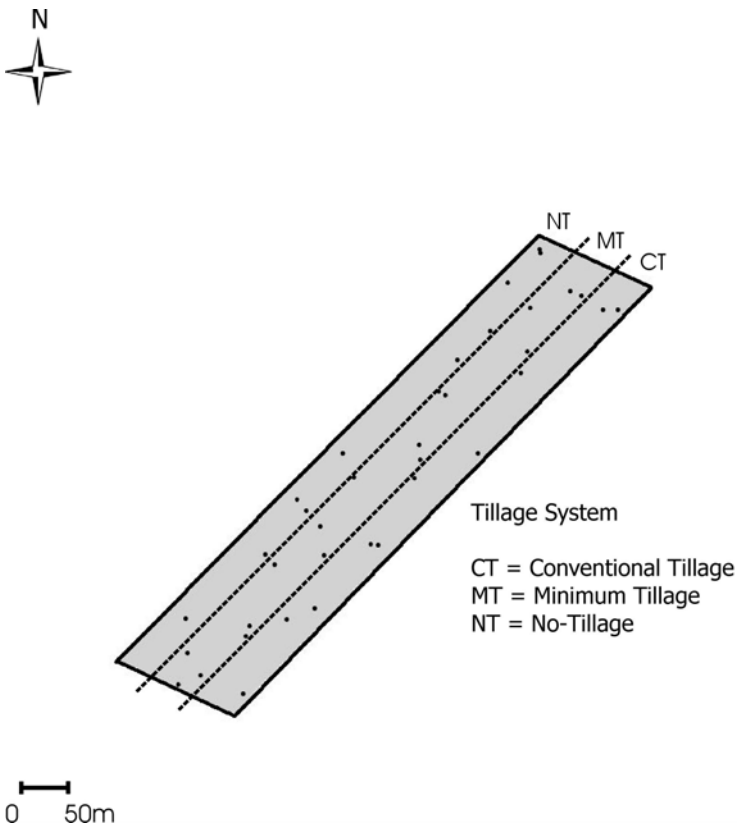

Figure 2.- Experimental scheme used reporting tillage systems performed during field trials.

Fertilizers, herbicides and seeding rates and timeframe were the same for all plots. In particular, chemical fertilizers (47 P kg ha^{-1} and 37 K kg ha^{-1}) were applied before seedbed preparation on November 9 2002 and on January 16, respectively, with a double spinner disk, whilst 185 N kg ha^{-1} was applied on May 19 with a pneumatic distributor. The cultivar *Costanza* was sown on March 28, with a seeding rate of 3.34 kg ha^{-1} (0.75 m row spacing, 7.8 plants m^{-2}), by using a planter, whilst in the *NT* plot a no-till planter was used. In *CT* and *MT* plots weed control was achieved through the combination of herbicide application, carried out with a field sprayer on April 07, April 12 and April 19 respectively, and row crop cultivation, performed on May 30 by using a weeder. Only in the *NT* plot weed control was realised by coupling pre- and post-emergence herbicide applications. Harvest was carried out on August 29 for all plots, according to the maturity status of the crop.

4.2.5.- Yield data

The yield data were manually collected at harvesting maturity, within 27 sub-plots centred on each sampling point, for a total of 30 plants x sub-plot (10 plant row^{-1} x 3 rows $sub\text{-}plot^{-1}$), and

the intra-row spacing between adjacent plants was measured, to calculate the real number of plants m^{-2}.

The weigh of the grain was measured and referred to dry matter (0% of moisture content), in order to generate in *ArcView version 3.2*™ the yield map of differently tilled plots.

4.2.6.- Long-term predicted yield for different tillage system

Based on the statistically appreciable influence exerted by climatic conditions on yield, yield data were predicted on long-term period (1989-2003), by using the SALUS (System Approach to Land Use Sustainability) model, which was designed to simulate continuous crop, soil, water and nutrient conditions under different management strategies (e.g., crop rotations, planting dates, plant populations, irrigation and fertilizer applications, and tillage practices) for multiple years (Basso, 2000). The long-term economic convenience for soil tillage at variable intensity was then considered.

4.2.7.- Economic analysis

The analysis of the cost due to the adoption of soil tillage at variable depth was carried out based on the following assumptions:

- differences regarding costs of production for single tilled plots are only due to the adoption of tillage strategy, the cost of other agronomic practices (*e.g.*, fertilisation, crop protection, etc.) and employed technical factors (*e.g.*, fertilisers, herbicides, seeds sown, etc.) being constant. In particular, this value was considered constant within the complete field, and it was not considered in the economic analysis;
- the cost due to the adoption of variable tillage resulted constituted by two components, relating to the costs of the precision farming system required to perform soil tillage at variable intensity and the soil tillage practices;
- the cost due to the adoption of the complete system for carrying out soil tillage was referred to the complete surface area of the farm (300 ha), in order to take into account only the amount of money relating to the experimental area;
- tillage at variable intensity was carried out by using the equipment available at farm, and the cost of single tillage operations was determined according to the normal cost values suggested by farm;

- only the cost for sowing was accounted in the economic analysis, being the others constant, because of the use of a pneumatic planter in *CT* and *MT* plots and a no-till planter in NT plot, with a different operative coefficient of efficiency.

Based on these assumptions, the total cost per unit area (€ ha^{-1}) for adopting tillage at variable intensity (*CTVI* – cost for adopting tillage at variable intensity) was calculated by summing the investment of capital for the components (hardware, software, sensors, etc.) purchased to upgrade the farming system (*e.g.*, yield mapping, etc.) for training and for acquiring and interpreting the information about field variability (Table 2), to the costs due to tractor and equipment use for soil tillage. For the investment required for adopting the precision agricultural system the same depreciation – based on straight-line depreciation– and maintenance methods and rates used for machinery were considered, whilst the cost of capital was determined by using an interest rate of 5%, because of the higher risk relating to the adoption of a precision farming system. The values of different parameters used for analysing costs of machinery (Table 3) was determined by considering the conditions of the experimental area.

Technological upgrading cost

The technological upgrading regarded the purchase of the electronic components of the yield monitor system and included also the human labour necessary to install the new components in the combine. In particular, it included the yield mapping system – i.e. grain moisture and mass flow sensors, yield monitor – and the relative software installed at the farm PC to download the row grain yield data, generate and manage maps. The cost of yield monitor included also the DGPS receiver installed in the combine, whilst the annual fee paid by farmer to receive the signal of correction of the positioning data was included in the annual costs.

Table 2.- Costs of the components considered in the economic analysis of the precision farming system implemented by farm to perform soil tillage at variable intensity.

Component of cost	**Objective**
Yield monitor (*e.g.*, sensors, receiver, etc.)	acquiring yield data within field
Fee for differential correction of receiver signal	increasing the accuracy of row data monitored
Software and hardware (*e.g.*, ram-card, etc.)	managing row yield data
Training	understanding methods for analysing variability
Data collection and analysis of yield maps	creating yield and prescription maps according to the

	spatial and temporal variability of yield
Qualified assistance	assuring the respect of the procedure and the technological upgrading

Data collection costs

The costs for the data collection was mainly due to the soil sampling and the yield mapping process, and were calculated by multiplying the time spent for samples collection or the download and the storage of the row yield data for the hour labour cost rate. For soil sampling the cost for the analysis of the static soil properties – *i.e.* soil texture and organic matter content – was also considered, by taking into account the market prices.

Costs for interpreting the variability

This cost was due to the analysis of both yield and soil data, in order to interpret the variability measured within field and identify the homogeneous management zones. The total cost was determined by multiplying the time spent for the labour cost (expressed in € h^{-1}), intended as hour rate for specialist technician.

Training cost

This was calculated as the money to cover the direct cost of trainer and the cost indirectly due to the frequency of the course by farmer, calculated by multiplying the hours of the course for the labour rate of farmer and of trainer respectively, and then by summing these components. In particular, 25 hours of training were considered reasonable for the farmer to understand the single steps of the precision farming system adopted, while a few hours of upgrading were taken into account for each single year.

Tractors and implements costs

The total operating cost (*TOC* – Total Operating Cost) was calculated for each tillage system by dividing the annual constant cost (*ACC* – Annual Constant Cost) for the annual use of implements, expressed in hours, and by summing the result to the hour variable cost (*HVC* – Hour Variable

Cost) (Table 4). The total operating cost per hectare was then calculated by dividing the resulting value for the work rate, determined by considering the width of implements and the speed of work.

Table 3.- Equipment and functional parameters considered in the economic analysis of the system implemented by farm to perform soil tillage at variable intensity.

Type of operation	**Tractor power (kW)**	**Equipments**	**Width (m)**	**Speed (km h^{-1})**	**Operative efficiency**	**Field capacity (ha h^{-1})**
soil tillage	161.76	subsoiler	2.80	4.00÷4.50	0.90	1.00÷1.13
	161.76	disk harrow	2.80	4.50÷5.50	0.90	1.13÷1.39
	161.76	rotary harrow	5.80	6.00÷6.50	0.90	3.13÷3.40
seeding	69.85	planter	6.00	6.50÷7.00	0.80	3.12÷3.36
	69.85	no-till planter	6.00	6.50÷7.00	0.75	2.93÷3.15

In particular, the *ACC* value (€ year^{-1}), being constant by varying the use of machinery, was determined by summing the cost of the capital used by farmer to purchase machinery to the amount of costs for replacing machinery at the end of the service life and for various factors, according to the following equation (eq. 1):

$$ACC = C_c + C_r + C_v \qquad \text{(eq. 1)}$$

in which:

C_c = cost to borrow the money needed to buy machinery;

C_r = cost for money that every year must be take a part to have the sum needed to replace the machine (e.g., lodging, insurance, taxes, etc.);

C_v = cost of various factors, calculated as constant percentage of the annual average value of farm machinery.

The *HVC* value (€ h^{-1}), having an increasing trend by increase the use of machinery, was determined by summing the costs for equipments repair and maintenance to that for human labour rate and fuel and lubricants use for tillage, according to the following equation (eq.2):

$$HVC = C_{rm} + C_{hl} + C_{fl} \qquad \text{(eq.2)}$$

in which:

C_{rm} = **costs for repair and maintenance, calculated as a constant annual percentage of the annual average value of the equipment, trough a repairing (α) and a maintenance (β) coefficients according to the following relationship:**

$$C_{rm} = \beta Cl + ({}_{n}V\alpha)/{}_{n}H_{\max} \qquad \textbf{(eq. 3)}$$

in which:

C_{hl} = **cost for human labour, intended as the amount of hour spent during tillage practices multiplied for the labour cost (10 € h^{-1} for experimental conditions);**

C_{fl} = cost for fuel and lubricants.

In particular, the cost for fuel was determined ad a function of the force required for traction (*Ft* – force required for traction, expressed in N), depending on constant and variable parameters (Glancey et al., 1996), as the characteristics of implement used (*e.g.*, width and constructive parameters, etc.) and the settled operating aspects (*e.g.*, angles of disks, tools spacing, etc.) (Serrano et al., 2003), the operative conditions (*e.g.*, speed of work, depth, etc.), and the within-field soil properties variability (*e.g.*, texture, force of cohesion, etc.), regarding in particular the tilled layer (Upadhyaya et al., 1987; Sànchez et al., 2003).

Drought force was derived from the following equation:

$$Ft = F_i \times [A + B(S) + C(S)^2] \times W \times T \qquad \text{(eq. 4)}$$

in which:

F_i = dimensionless soil texture adjustment parameter, depending on the incidence of the percentage granulometric component;

A, B and *C* = machine-specific parameters;

S = field speed (km h^{-1});

W = machine width (m);

T = tillage depth (cm).

During trials, after setting operative parameters for each equipment according to the indications of farmer and tractor driver, the draught force was considered as a function of soil properties and consequently determined for each sampled point within field according to the *Standard ASAE D497.4*. The fuel consumption was derived from drought force, because of the existence of a demonstrated closely relationship between draught force and fuel consumption in different soil initial conditions (Perfect et al., 1996; Arvidsson et al., 2004; Kheiralla et al., 2004).

Table 4.- Parameters used for the analysis of the annual constant and hour variable costs.

Parameter	*Definition*	**Value**
r	interest rate	0.05
n	service life in years	10 (tractors) 10÷15 (implements)
$_nH$	annual use in hours	700 (tractor) 100÷250 (implements)
α	repairing rate, calculated as ratio of the accumulated repair cost at the end of machine life to its purchase price	0.4 (tractors) 0.025÷0.1 (implements)
β	maintenance rate, calculated as a ratio between annual hours for maintenance and annual use of machine	0.1 (tractors) 0.025÷0.1 (implements)
η	tractor power load coefficient	0.60 (sub-soiling) 0.65 (dick harrowing) 0.70 (rotary harrowing)
F_p	fuel price	0.50 € kg^{-1}
L_p	lubricant price	5.00 € kg^{-1}
L_c	labour cost	10 € h^{-1} (worker) 25 € h^{-1} (farm technicians)

The Farm Gross Margin (*FGM*) was then calculated for each tilled plot by subtracting the *CTVI* to the economic value of grain yield (*EVY* – economic value of yield), which was obtained by multiplying the grain yield quantity for the market price (10 € t^{-1}in experimental area).

Based on the long-term predicted yield data, the economic analysis was carried out to consider the long-term economical convenience on adopting tillage at variable intensity, intended as predicted farm gross margin (*FGM'*).

The prices applied both for crop yield and technical factors in the simulated scenarios were those registered in 2003.

Statistical analyses and *ANOVA multivariate* were developed in *SAS version 8.0* (*SAS Institute Inc.*, 1999).

4.3.- Results and discussion

4.3.1.- Identification of long-term management area

The long-term spatial variability of predicted yield values for maize showed the presence of two area, having a yield greater and lower than 11 t ha^{-1} and oriented according to the principal axle of the field, that covered almost the 50% of the complete field (Figure 3). The temporal variance pattern resulted more irregular within field, being divided into a lot of small area having different temporal variance on yield level (Figure 4). Based on both the spatial pattern and the temporal variance of yield, the long-term temporal stability of spatial variability of yield showed the presence of two clearly distinct area, characterised by temporal stability but having a different level of production, identified as *HS* and *LS* area. In particular, *HS* area covered the 32.6% of the field, corresponding to 2.64 ha, the remnant part being identified with the *LS* area (5.45 ha) (Figure 5).

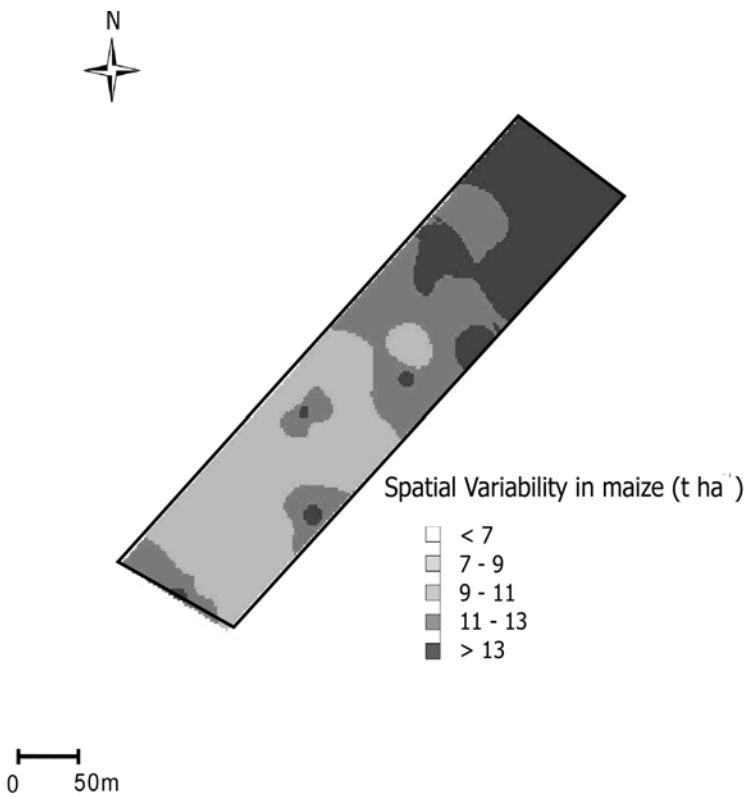

Figure 3.- Predicted long-term spatial variability of yield within field in maize.

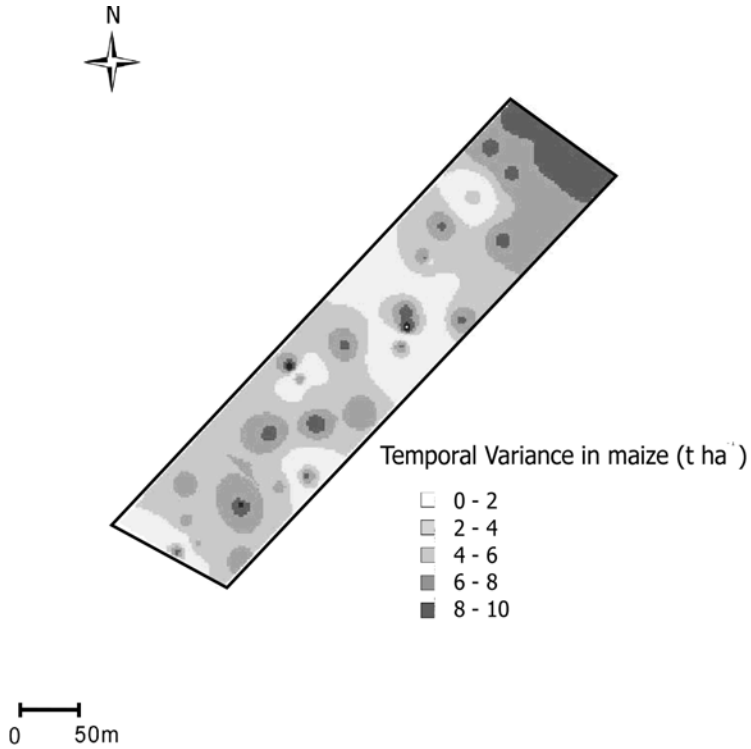

Figure 4.- Predicted long-term temporal variance of yield within field in maize.

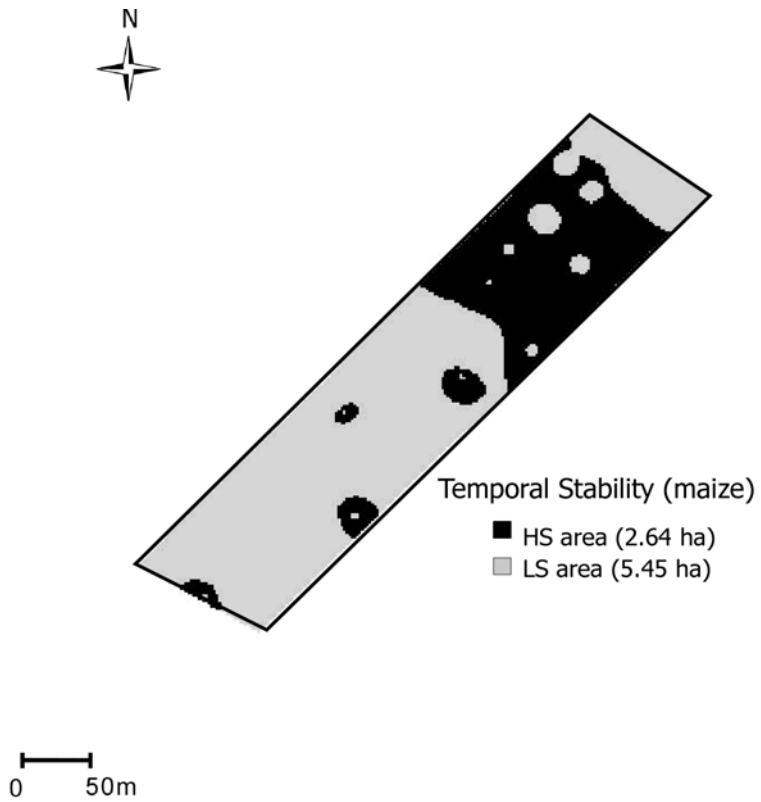

Figure 5.-Temporal stability of spatial variability of the long-term predicted yield within field in maize.

Based on the temporal stability of spatial variability of yield, field was divided into three plots having the principal axle parallel to the axel of the field, in order to practically adopt different soil tillage strategies according to the suggestions of the farm (Figure 5).

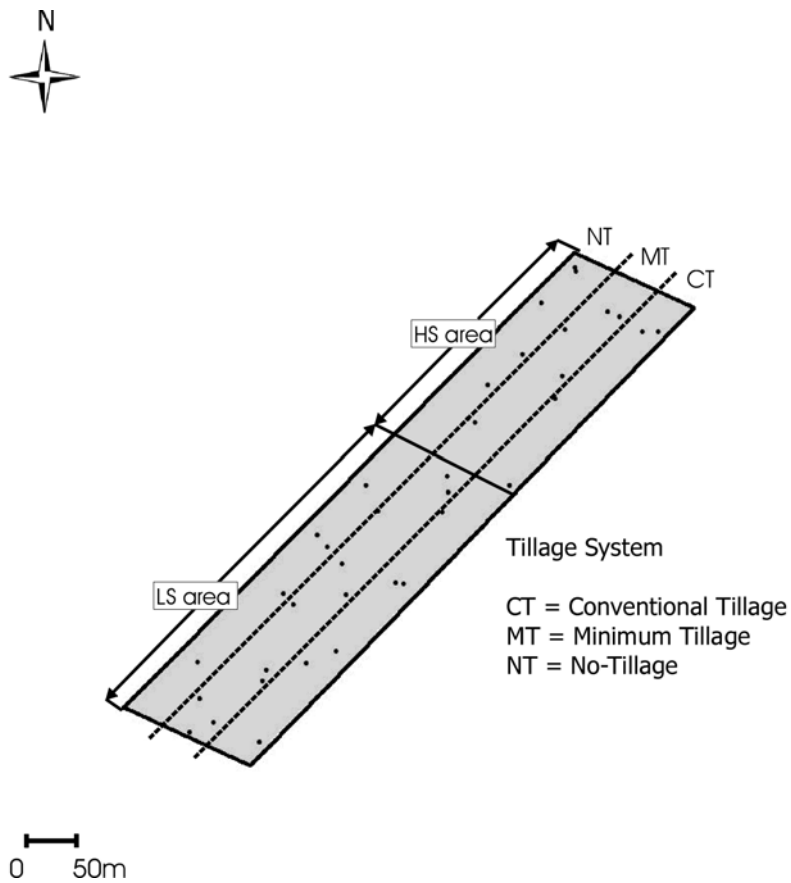

Figure 5.- Experimental scheme reporting tillage systems performed during trials in the homogeneous area practically identified within field according to the temporal stability criteria. Markers indicate sampling points at which soil properties were measured.

4.3.2.- Yield data

Yield obtained in 2003 was appreciably lower respect to the data monitored in the precedent growing seasons (Table 5), with a statistically significant reduction of almost 42% and 32% respect to that monitored in the 1998 and 2000 respectively (Figure 6).

The standard deviation value measured within field resulted relatively lower, whilst the coefficient of variation was greater than other years, with yield values slightly more concentrated around the classes having greater values, as revealed by the negative skewness index (- 0.60) and the small separation distance between mode and mean values (Figure 7).

Table 5.- Descriptive statistics for yield data measured in 2003 within field, compared to that monitored in the precedent growing seasons. Different letters indicate significant differences between different years (*LSD* test, P≤0.05).

Statistics	**Grain yield (t ha^{-1})**		
	1998	2000	2003
mean	9.69 a	8.25 b	5.63c
mode	10.84	6.99	6.61
median	10.16	8.28	5.73
standard deviation	± 2.24	± 1.73	± 1.38
kurtosis	1.10	1.53	0.30
skewness	-0.51	0.73	-0.60
minimum	0.67	0.72	0.71
first quartile (Q_1)	8.95	7.26	4.71
third quartile (Q_3)	11.10	9.56	6.57
maximum	21.00	18.41	10.24
coefficient of variation (*CV*; %)	23.11	20.95	24.52

A intra-year variability was detected within field, particularly as regard the stable area identified within field, with a greater production registered in the northern part of the field, respect to the remnant part of the field, characterised by lower yield data. Despite the adoption of different soil tillage systems along the major transect of the field, no appreciably differences were detected accord to the experimental scheme, different plots having comparable values of yield within the same homogenous zone (Figure 8). The model explained a moderate percentage of yield variability, as revealed by the value of the coefficient of determination (R^2 = 0.38) (Table 6), with an appreciable effect due to the presence of the two stable area identified within field (Figure 9), resulting different at a level of significance of P< 0.001. The "*tillage effect*" and the interaction "*area × tillage*" not resulted statistically significant on explaining the variability detected within field, probably because of the low influence exerted by tillage systems on soil properties and the particularly not favourable environmental conditions occurred in 2003.

Table 6.- Analysis of variance for the yield obtained in 2003 (*** = significant at P< 0.001 level of significance).

Source of variation	**d.f.**	**Mean square**
Area	1	0.112 ***
Tillage	2	8.623
Area × Tillage	2	0.696
Error	30	0.640
R^2		0.38

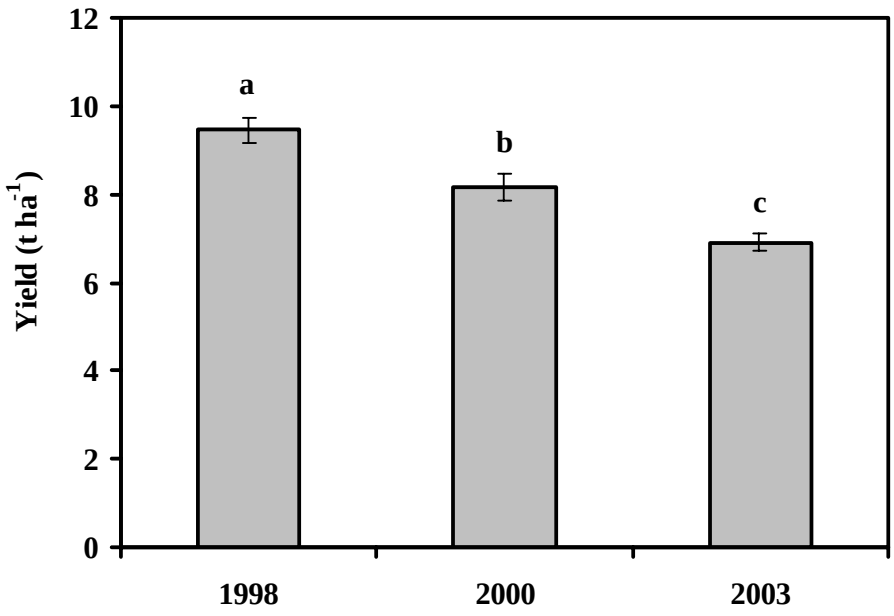

Figure 6.- Average yield obtained in the complete field in 2003 respect to the precedent growing seasons. Vertical bars refer to standard error of the yield data. Different letters indicate statistically significant differences on yield level between years (*LSD* test, P≤0.05).

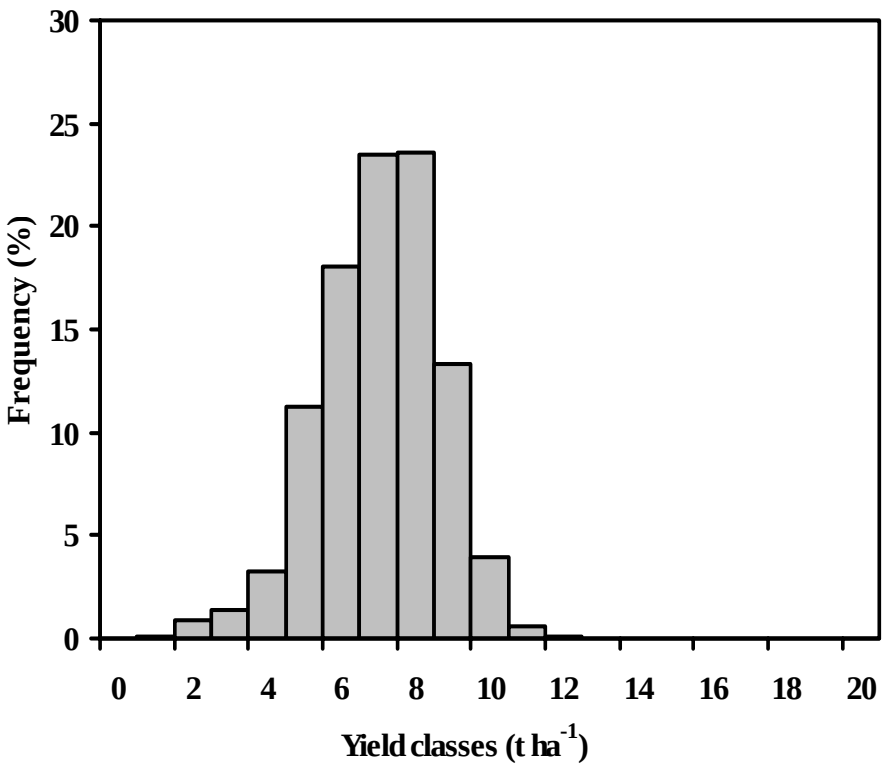

Figure 7.- Frequency distribution (expressed in %) of yield measured in 2003 in maize.

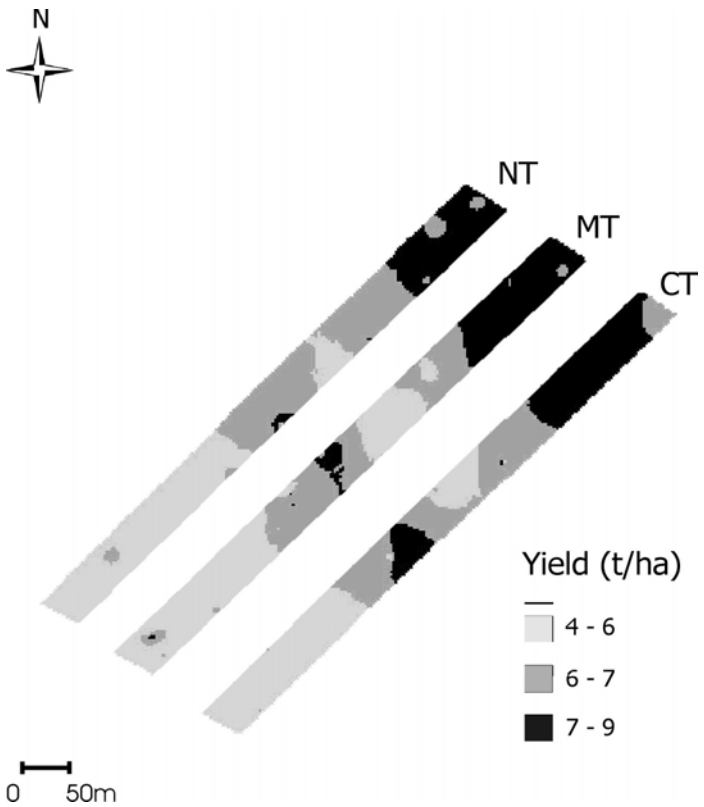

Figure 8.- Yield data obtained in 2003 within the different tilled plot defined within field, according to the experimental scheme.

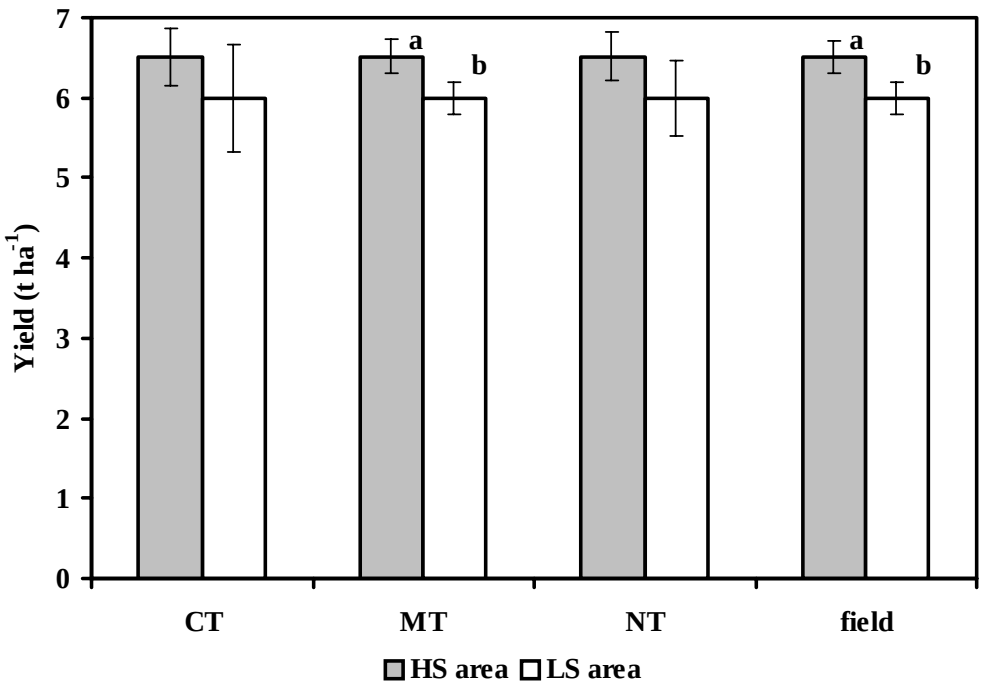

Figure 9.- Yield data obtained in 2003 within the stable area identified according to the temporal stability criteria. Vertical bars refer to standard error of the yield data. Different letters indicate statistically significant differences on yield level for the same tillage system (*LSD* test, P≤0.05).

Differences detected within field resulted influenced by the presence of stable area, different tillage systems being not appreciably different within the complete field, probably because of the not relatively favourable climatic conditions, that covered the "*tillage effect*".

4.3.3.- Climatic data

Climatic conditions registered for the experimental area resulted not favourable during the growing season in terms of both temperature and rainfall. In fact, the average temperature attained greater values during the summer respect to that registered during the long-term period (1989-2002), with an annual average temperature of 14 °C, almost 1°C greater than the long-term annual average temperature (13°C) (Figure 10). Monthly temperature resulted greater in the last part of the Spring and in Summer (Figure 11). The total annual rainfall (677 mm) resulted lower than that measured in the 1989-2002 period, and only 224.4 mm of rain occurred during the growing season (March-September interval period), corresponding to a rainfall 15.4% lower than that of the long-term considered period. In particular, a statistically appreciable lack of rainfall was registered during the flowering stage of growth, and this fact was probably a cause of stress for crop, especially because of the correspondence with higher values of temperature.

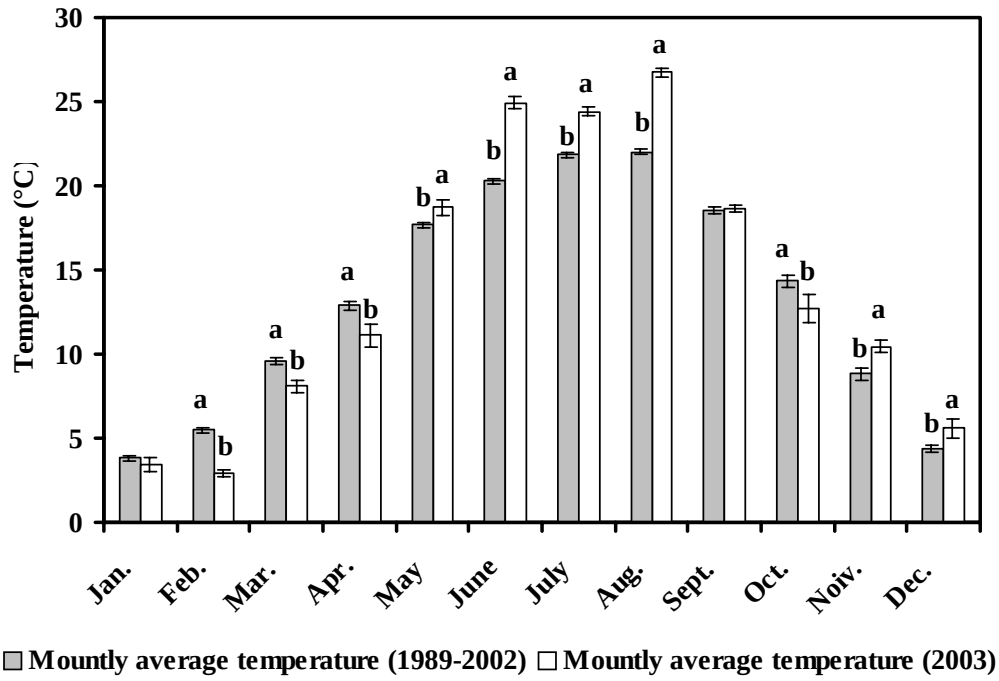

Figure 10.- Monthly average temperature (°C) registered in 2003 respect the values of the long-term trend (1989-2002). Vertical bars refer to the standard error of the measured data. Different letters indicate statistically significant differences for the same month (*LSD* test, P≤0.05).

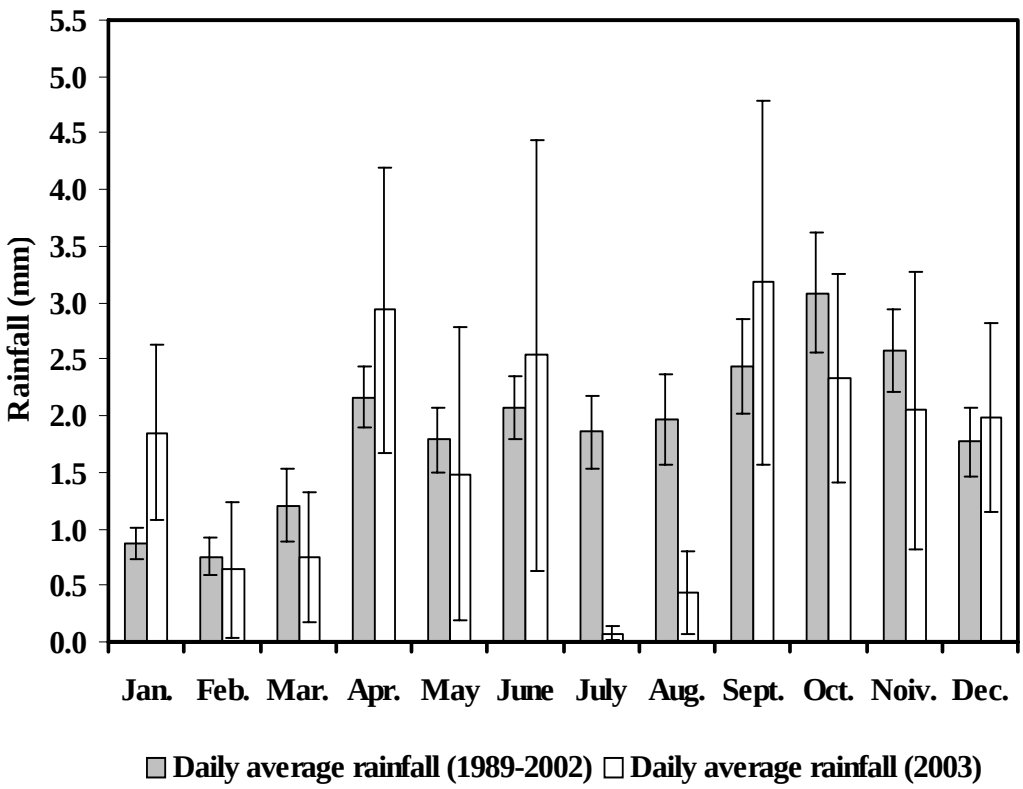

Figure 11.- Monthly total rainfall (mm) registered in 2003 respect the values of the long-term trend (1989-2002). Vertical bars refer to the standard error of the measured data.

4.3.4.- Economic aspects

Although the not appreciable differences in terms of yield measured for tillage system performed within field, the economic analysis showed statistical differences in terms of both cost of production and farm gross margin. In particular, the fixed cost due to the analysis and interpretation of data attained in the experimental conditions a value of around 16 € ha^{-1} (Table 7), according to the relationship existing between costs value and annual tilled surface (Figure 12), and the relative percentage influence on cost required for tillage operations resulted variable, being greater for the less expensive system – *i.e.*, *NT* system – ranging from a minimum of almost 12%, to a maximum of 61% for *CT* and *NT* systems respectively, with an intermediate value of 18% for *MT* system.

Table 7.- Components of annual cost for tillage and relative cost per hectare, relating to the farm where field trials were carried out.

Components of cost due to the system of tillage at variable intensity	**Cost (€)**	**Cost (€ ha^{-1})**
Installation of hardware and software components	17	0.05
Interest and depreciation	1,778	6.00
Repair and maintenance	140	0.46
Labour	216	0.71
Training	572	1.89
Soil sampling and analysis	2,000	6.65
Other (fee for DGPS signal correction, etc.)	250	0.83
Total costs	**4,988**	**16.00**

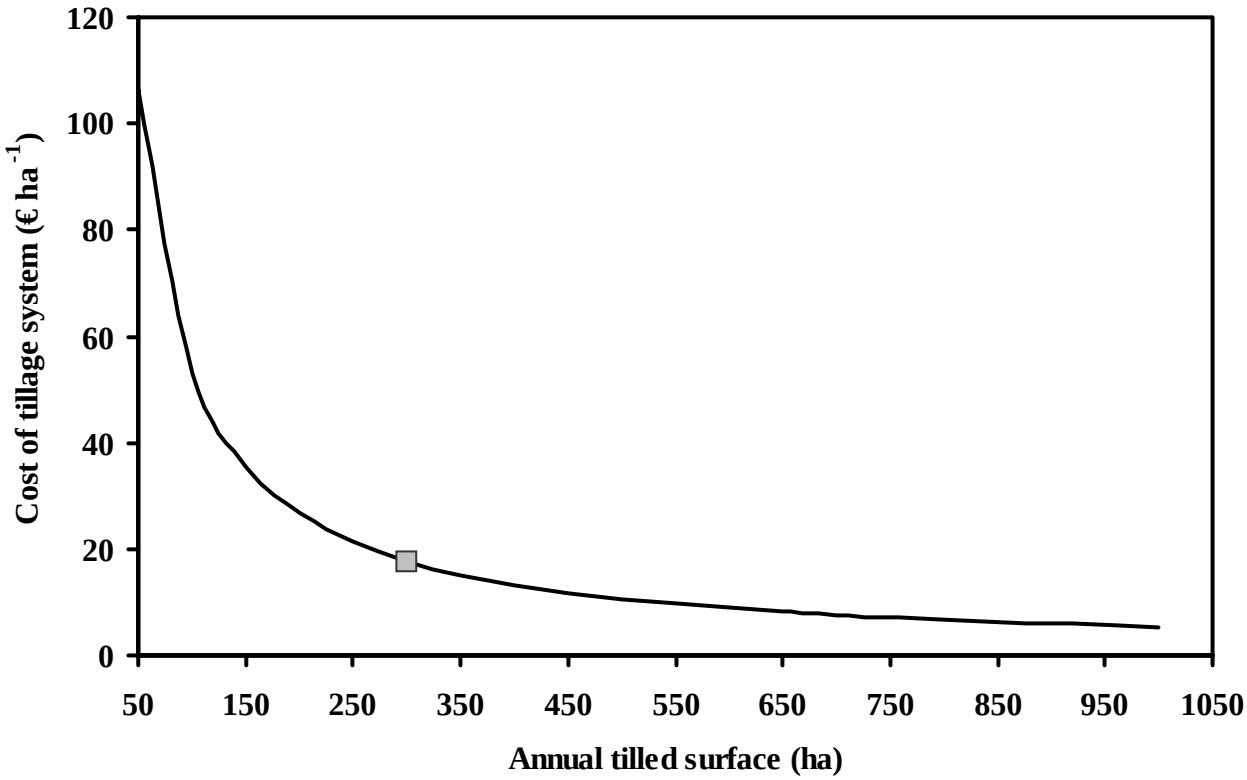

Figure 12.- Relationship between the fixed cost (€ ha^{-1}) and the annual tilled surface. Data refer to the experimental conditions, and marker indicate the cost determined for the farm in which field trials were carried out.

Costs for tillage at variable intensity

As expected, cost of production caused differences between different tillage systems because of the reduction of agronomic practices performed (Figure 13), but for the same practice cost value varied according to the type of system, as showed by values measured for disk harrowing.

In particular, the analysis of cost of production for soil tillage performed at variable intensity within field showed that sub-soiling was the more expensive practices adopted, with not appreciable differences between area, suited by rotary harrowing operation, the latter resulting not influenced by soil attributes. As regards this aspect, soil properties exerted a statistically significant effect only on cost measured for disk harrowing (Figure 14), being the cost greater in particular for disk harrowing performed as primary tillage than for the same operation performed after sub soiling.
In particular, disk harrowing influence on cost resulted slightly higher in *LS* area than *HS* area for the *MT* plot, whilst the difference between *CT* and *MT* plots was more appreciable, corresponding to a cost greater than almost 4 € ha^{-1} in *MT* system, due to the different drought force required and consequently to the fuel consumption and cost.

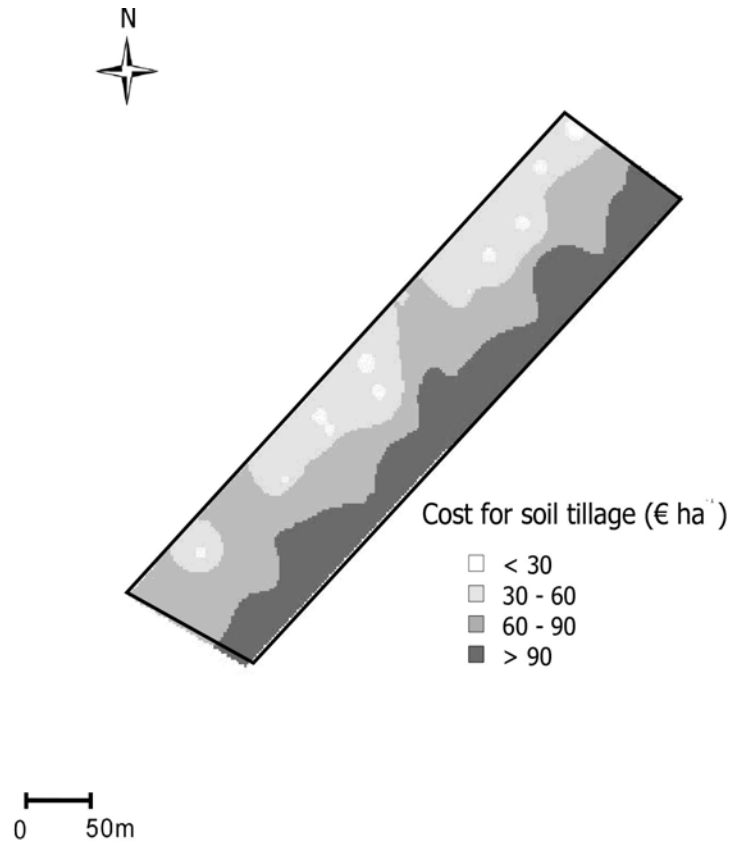

Figure 12.- Map of costs due to the adoption of different soil tillage systems within field.

Farm Gross Margin

Based on costs of production and fixed costs due to the adoption of different tillage strategies the farm gross margin resulted statistically different for the stable area, being greater in *HS* area than *LS* area (Table 8), whilst also differences between tillage systems were appreciable for the complete field.

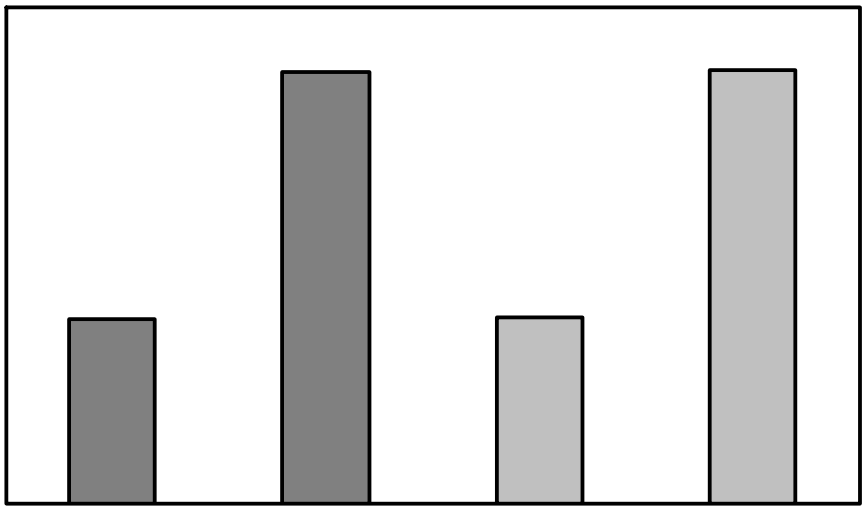

Figure 13.- Average costs for disk harrowing performed as primary or secondary soil tillage in CT and MT plots respectively. Different letters indicate statistically significant differences between tillage systems adopted within the same stable area (*LSD* test, P≤0.05).

The interaction "*tillage × area*" resulted not significant (Table 9), as confirmed by the absence of statistically significant differences between tillage systems within the same area, although the greater values of farm gross margin detected for the no-tilled plot (Figure 14 and Figure 15).

Table 8.- Costs of production and farm gross margin obtained in 2003 by adopting different tillage strategies within different stable area of the field.

Tillage system	**Stable area**	**Costs (€ ha^{-1})**	**Farm Gross Margin (€ ha^{-1})**
CT		129.56	589.00
MT	*HS*	87.16	691.00
NT		26.00	707.00
CT		129.67	527.00
MT	*LS*	87.20	517.00
NT		26.00	640.00