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WEEDS IN CONSERVATION AGRICULTURE

Biology, emergence dynamics and modelling to improve their control

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Valentina Gasparini
20th January 2014

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Riassunto

La crescente attenzione da parte dell'opinione pubblica verso l'impatto che le attività produttive hanno sull'ambiente, ha reso improrogabile l'incentivazione a ridurre l'aggressività dei sistemi produttivi sull'ambiente. Anche il settore agrario, considerato una delle principali forze di trasformazione del territorio, è chiamato a predisporre programmi di produzione eco-compatibili. Le istituzioni e gli organismi nazionali e internazionali incoraggiano l'adozione di tecniche di agricoltura conservativa quale strumento per garantire la produzione agraria necessaria per far fronte alla domanda di cibo della popolazione in crescita e la difesa e il miglioramento della qualità delle risorse naturali. L'agricoltura conservativa nasce con l'intento di ridurre o eliminare le intense lavorazioni del suolo che hanno causato impoverimento, degradazione e perdita di terreno agrario a favore di una gestione più sinergica delle componenti dell'agroecosistema. Tuttavia uno dei problemi principali legati a questo tipo di sistema agronomico è rappresentato dalla gestione delle infestanti, la cui complessità è tale da costituire da costituire spesso un deterrente per gli agricoltori. La presenza delle piante infestanti è imputata essere la principale causa di danno economico per l'agricoltura a livello mondiale, sia in termini di calo di resa delle colture sia come costi sostenuti per il loro controllo. In un sistema agrario convenzionale il controllo delle malerbe è effettuato per mezzo di erbicidi e lavorazioni meccaniche del terreno che in modo sinergico riescono a mantenere il livello delle piante infestanti sotto la soglia di danno economico. In un sistema conservativo, per mantenere lo stesso livello di difesa delle colture è necessario aumentare il controllo chimico con conseguente aumento dei costi per l'azienda, rischi per la salute e danni ambientali. In questo scenario la gestione integrata delle malerbe gioca un ruolo cruciale per il raggiungimento di una maggiore sostenibilità ambientale, sociale ed economica delle produzioni agricole. In particolare, il ricorso a strumenti informatici quali i modelli previsionali della dinamica di emergenza delle malerbe in campo possono fornire utili indicazioni sui tempi, sui modi e sulla convenienza economica di un eventuale intervento di controllo.

La presente ricerca nasce con lo scopo di fornire un quadro di conoscenze più ampio e approfondito su ciò che comporta l'applicazione di protocolli di agricoltura conservativa per il settore malerbologico. L'obiettivo principale che guida tutti gli studi svolti in questo lavoro di tesi è la calibrazione di un modello di previsione delle emergenze per ottimizzare il momento

di intervento per il controllo delle infestanti in terreno non lavorato. Il modello oggetto di studio è AlertInf, un modello creato per i terreni lavorati che si basa sul concetto di Tempo Idrotermico. Secondo tale approccio la dinamica di emergenza è guidata da due principali fattori, che sono temperatura e potenziale idrico del suolo. I semi nel suolo accumulano tempo idrotermico per la germinazione secondo dei valori soglia di temperatura e potenziale idrico caratteristici per ogni specie. Il primo capitolo della tesi (**Capitolo I**) descrive gli esperimenti per la stima di queste soglie per le tipiche specie da sodo, *Taraxacum officinale*, *Sonchus oleraceus*, *Senecio vulgaris*, *Conyza canadensis* e *Conyza sumatrensis*, mettendo anche a confronto diversi metodi per la stima di tale parametro. Il secondo capitolo (**Capitolo II**) sottolinea l'importanza dell'acquisizione delle informazioni microclimatiche del suolo (temperatura e potenziale idrico) nella zona di germinazione dei semi. A tale fine, un esperimento di campo è stato predisposto per valutare l'entità dei cambiamenti di temperatura e umidità del suolo derivanti dalla non lavorazione del terreno. In particolare si è testato un sistema di sensori che permettesse la misurazione di temperatura e potenziale idrico negli strati più superficiali di suolo, essendo la superficie il luogo interessato dai processi di germinazione e crescita delle piante infestanti in un sistema conservativo. Ai fini della modellizzazione si è ritenuto fondamentale studiare la dinamica di emergenza di queste specie e allo stesso tempo, verificare se e come varia la dinamica di specie tipiche dell'ambiente arativo a seguito di un cambio di gestione agronomica. Uno studio è stato quindi condotto in ambiente controllato per testare l'effetto della profondità d'interramento dei semi e della lavorazione sulla quantità di piante emerse e sulla dinamica di emergenza (**Capitolo III**). Rilievi malerbologici stagionali sono stai eseguiti in tre aziende sperimentali del Veneto dal 2011 al 2013 in appezzamenti coltivati in modo convenzionale e conservativo per verificare le specie presenti nei due sistemi di gestione e le dinamiche di emergenza in campo (**Capitolo IV**) L'ultimo capitolo (**Capitolo V**) mostra la trasferibilità del modello AlertInf da mais a soia in gestione convenzionale. Un risultato che fa avanzare l'ipotesi di trasferibilità da un sistema agronomico convenzionale a conservativo. Con questo lavoro di tesi sono state poste le basi per la realizzazione di un modello di previsione delle emergenze delle infestanti in agricoltura conservativa, ma la realizzazione di un modello richiede approfondita conoscenza dei fattori coinvolti nella determinazione del fenomeno e accuratezza degli input, ed è stato evidenziato che molti sono ancora i problemi da risolvere e che ulteriore ricerca è necessaria.

Summary

The increasing attention of public opinion towards the environmental impact of production activities has made it imperative to reduce the aggressiveness of productive systems on the environment. Also the agricultural sector, considered one of the principal strengths of transformation of the territory, is asked to predispose eco-compatible programmes of production. The institutions and national and international organisms encourage the adoption of techniques of conservative agriculture as a tool for guaranteeing, on the one hand the necessary crop production to face the demand for food of the growing population and, on the other the safeguarding and improvement of the quality of natural resources. Conservative agriculture is born with the intent to reduce or eliminate the intense tillage of cultivated lands that has caused impoverishment, degradation and loss of soil in favour of a more eco-friendly management of different agroecosystem components. Nevertheless weed management, the complexity of which is a deterrent for the adoption of this type of agronomic system, represents one of the main problems. Weeds are the main cause of economic losses in agriculture worldwide, both as crop yield reduction and control costs. In a conventional farming system weeds are controlled by herbicides and mechanical operations that together are able to maintain the infestation level beneath the threshold of economic damage. In a conservative system, to obtain the same level of crop defence, it is necessary to increase the chemical control with the consequent increased costs for farmers, health risks and environmental impacts. In this scenario, Integrated Weed Management plays a key role in order to achieve environmental, social and economic sustainability of crop production. Particularly, weed emergence and weed-crop competition models can provide useful indications about timing, type and cost-effectiveness of control measures.

This research has the goal of providing wider and deeper knowledge of what is involved for the weed science sector in the implementation of conservation agriculture protocols. The main objective, common to all the studies presented in this thesis, is the calibration of a prediction model to optimize the timing for the weed control in a no-tillage soil. The model under study is AlertInf, a model created for tilled soils that is based on the concept of hydrothermal time. According to this approach the emergence dynamics is determined by two main factors: temperature and water potential of the soil. Seeds in the soil accumulate hydrothermal time for their germination according to temperature threshold values and a water potential typical

for each species. **Chapter 1** describes the experiments for the estimation of temperature thresholds for four no-tillage soil weed species: *Taraxacum officinale*, *Sonchus oleraceus*, *Senecio vulgaris*, *Conyza spp*, comparing different methods for the estimation of this parameter. **Chapter 2** highlights the importance of soil microclimate information acquisition (such as temperature and water potential) in the seed germination area. A field experiment was designed to assess the extent of changes in temperature and soil moisture resulting from no-tillage. In particular, a system of sensors, which allows the measurement of temperature and water potential in the upper soil layers, was tested as the soil surface is involved in the germination processes and weed growth in a conservative system. For modelling purposes, the emergence dynamics of the some weed species were studied and whether and how the dynamics of these species change in a different agronomic management was verified. A study was therefore conducted in a controlled environment to test the effect of the seed burial depth and tillage on the amount of emerging plants and the emergence dynamics (**Chapter 3**). Seasonal weed surveys were done on three experimental farms in Veneto region from 2011 to 2013 in conventional and conservative management fields to verify the species present in the two different systems and the emergence dynamics (**Chapter 4**). The last chapter (**Chapter 5**) shows the transferability of AlertInf model from maize to soybean in conventional management. A result that advances the hypothesis of the transferability also in a conservative environment.

With this thesis the bases have been established for the construction of a predictive model of weed emergences in conservation agriculture, but model construction necessitates in-depth knowledge of all the factors involved in the phenomenon determination and accurate inputs, therefore it has been underlined that many problems still have to be solved and further researches are needed.

General Introduction

Agriculture was born as a human activity aimed at producing food and raw materials by cultivation and breeding. With the gradual population growth worldwide and the consequent increase in demand for food, the primary sector had to increase production and this led to a strong push in the search for tools and technologies designed to counter all that could limit the yields, such as disease and stress factors. When the powerful insecticide DDT was discovered in the 1940s, it led to a massive rise in production and use of chemicals and this marked the starting point of modern agriculture. Modern agriculture is an approach to farming in which the goal is to obtain as high as possible a yield and this meant increasing the number of growing cycles per year, intensifying tillage operations, without considering the sustainability of the overall production process. The use of large amounts of chemical compounds and intensification of the production process certainly permitted the satisfactory level of crop production necessary to meet the population needs in terms of both quantity and quality. However, for some years there has been an awareness of the high environmental costs that this type of agriculture has in terms of reduction of biodiversity, water pollution and more in general the consumption of non-renewable resources (Howden et al., 2007; Lal, 2013). Modern agriculture is for these reasons considered one of the most important transformation forces of the territory and environment and is often accused of being one of the main sources of landscape simplification and pollution of natural ecosystems (Almagro et al., 2013; Quinton et al., 2010; Blanco-Canqui and Lal, 2008). In recent years the best known Institutions worldwide have been looking for crop production systems that can maintain satisfactory yields and at the same time protect the environment, with particular emphasis on preserving its capability to support crops. Consequently an intense debate has arisen in political and scientific communities about how to combine the two aims and which strategies should be adopted in order to combine economic issues and environmental sustainability. A first effort to reduce soil erosion and reverse the loss of soil organic matter due to intensive tillage is attributable to a movement borne in the USA after a long period known as the Dust Bowl (Hobbs et al., 2008), an epoch well described in the novel “The Grapes of Wrath” by John Steinbeck, who was awarded the Nobel prize for Literature in 1962. When severe drought struck the Great Plains region in the 1930s, it exposed the increased risk for soil erosion that was created by the intensive and deep tillage farming practices as a consequence of crop production intensification and the rapid mechanisation of farm implements. The drought dried the topsoil and over time it became friable, in some places reduced to a powdery consistency. Without the indigenous deep-rooted grasses that normally trapped soil in place, the high winds that are common on the plains created the massive dust storms that marked the Dust Bowl period (Warrick, 1980) degrading almost 90 Mha of land (Utz et al., 1938). After the damage to agricultural soils caused by continuous ploughing, the main aim of local Governments was to detect a sustainable cropping system that could guarantee high yield levels while concurrently protecting land resources on which production depends. The importance of conserving soil quality and structure was considered for the first time and the combination of practices and techniques aiming to preserve soil from degradation and erosion was named conservation agriculture (Baker et al., 2002). Conservation agriculture systems, according to the FAO definition, are based on three key points: 1) minimizing soil disturbance, 2) maximizing soil surface cover by organic residues, and 3) stimulating biological activity through crop rotation, cover crops and integrated pest management (FAO, 2013). However, there are no universal protocols vouchsafing satisfactory results in terms of environmental protection and high crop yields. Although the practice of conservation agriculture on a large scale originated in Brazil and Argentina, countries interested in reducing negative impacts from conventional land management needed to develop their own conservation agriculture systems according to local environmental features as well as due to differences in soil composition (texture and native organic matter content) and specific site conditions (Dumansky et al., 2006). As reported by Derpsch et al. (2014), to guarantee higher performances than with convention tillage systems in order to encourage the adoption of conservative practices by farmers, a multitude of different methodologies, technologies and also definitions were set up worldwide but this has led to misunderstandings and confusing research. In this sense, there is undoubtedly a need in the scientific community for a standardized research approach including definitions and descriptions of procedures. Conservation agriculture is the generic title indicating a large set of farming practices to enhance the sustainability of crop production while conserving and protecting natural resources (Hubbard et al., 1994) by keeping external inputs to a minimum (Garcia-Torres et al., 2003). Conservation tillage refers to a restricted set of practices adopted to enhance water infiltration and reduce soil erosion risk. Because this term is strictly linked to the type and intensity of soil disturbance, it is more appropriate to consider conservation tillage as a transition step towards the broader conservation agriculture system rather than as a synonym

(Stagnari et al., 2010). Conservation tillage systems, also known as non-inversion tillage, include a series of techniques with different levels of soil disturbance, i.e. minimum tillage that involves fewer passes than conventionally made and is based on the use of tine and disc implements that do not invert the soil (Christian, 1994). In a minimum tillage system the entire field area is disturbed for seedbed preparation (Gajri et al., 2002), on the contrary, in no-tillage systems, or direct drilling, the crops are sown directly onto the previous crop with all crop residues left on soil surface. With this technique, the soil profile remains completely undisturbed and residues tend to accumulate on the soil surface influencing crop growth patterns (Sprague and Triplett, 1986; Triplett and Worsham, 1986). In conservation cropping systems, tillage is reduced or eliminated and this implies a change in environmental conditions with respect to conventionally tilled fields. Soil tillage plays several fundamental roles in cropping systems such as the preparation of a good seedbed by burying all surface residues giving the crop optimum germination conditions (Morris et al., 2007; Gajri et al., 2002). Traditionally, the primary reason for tillage was interrupting weed, pest and disease life cycles but with the increasing range of agrochemicals available, the chance of reducing tillage became more concrete (Cannel, 1985). On the contrary, recent reports demonstrate that weed control seems to be a major factor limiting adoption of conservation tillage systems (Dorado and López-Fando, 2006) because it is more difficult under reduced tillage (Moyer et al., 1994). Among different factors limiting crop production, weeds have always represented an important variable as indicated by Owen (1998), who observed that weed growth is perceived by farmers as being the greatest cause of yield loss in agricultural crops. Oerke (2006) estimated that, if not controlled, the potential yield loss due to weed competition in a conventional crop system would be approximately 23% for wheat, 37% for rice and soybean and 40% for maize. A multitude of studies have investigated which factor affects weed flora composition and most of them demonstrate that there is not just one or a few factors, but a complex of biotic and abiotic factors and their interactions acting in different ways on the build-up of weed communities (Fried et al., 2008; Hallgreen et al., 1999). According to Fried et al. (2008), the main factor differentiating weed species composition is agronomic management practices, crop type in particular having the most significant influence, crop rotations and tillage systems (Shrestha et al., 2002; Loudyi et al., 1995). Changes in cropping practices could reduce weed interference in crops by modifying soil microsite conditions and making them less or more favourable to weed seedling recruitment. Management practices such as tillage influence the vertical placement of weed seeds in microsites within the seedbank (Van Acker et al., 2004; Tørresen et al., 2003). Other management practices manipulate crop residue levels to amend the microsite environment (Fennimore and Jackson, 2003). In general, the combination of environment (soil properties and climate) and agronomic practices (tillage, crop rotations, cover crops) determines weed flora, which will reflect the interactions of these two main factors (Bullied et al., 2012). The switch from conventional tillage to conservation cropping systems generally results in a shift of weed species (Locke et al., 2002; Bilasis et al., 2001; Froud-Williams et al., 1983) because differences in soil tillage depth modify the vertical distribution of the seeds in the soil profile and this places seeds in different environmental conditions with respect to those allowing them to germinate first, and emerge later (Colbach et al., 2005; El Titi, 2003; Vleeshouwers et al., 1995). Hence, the likelihood of a certain weed species surviving will depend on the degree of soil disturbance during tillage operations, which are considered the main cause of burial and vertical movement of weed seeds into favourable or unfavourable microsites within the recruitment zone (Cousens and Moss, 1990). The depth at which seeds are found influences environmental properties within a microsite: in particular light (Ballaré et al., 1992), temperature (Benvenuti and Macchia, 1993), soil water content (Roberts and Potter, 1985) and level of soil compaction (Pareja and Staniforth, 1985) are considered to be the main ecological factors in germination, emergence and early seedling establishment. Of course agronomic management factors influence the weed flora composition but, as suggested by Swanton et al. (1999) and confirmed by Shrestha et al. (2002), long-term changes in weed flora are driven by the interaction of disturbance (tillage) and site conditions (soil, temperature, moisture), highlighting the importance of environment factors on selection of weed species. Anyway, the change in weed composition due to change in cropping system first becomes evident quantitatively and then qualitatively (Zanin et al., 1997). Although general differences can arise in weed species composition due to environmental characteristics of a specific site, there is overall agreement about some common biological traits of ecological settling in undisturbed agroecosystems. In conservation tillage systems the absence of soil disturbance permits the seeds to remain near or on soil surface, which is a more favourable condition for germinating and seedling establishment in some species (García et al., 2013). Species with surface germination would be favoured in this scenario. In particular it is recognized that germination of some weed seeds is triggered by fluctuating temperatures, as found in diurnal temperature changes characteristic of the surface soil layers. Seeds with this type of requirement will germinate if close to the soil surface rather than if they are deeply buried (Thompson, 1974). Another feature related to surface germination is seed size. Reduced tillage causes fewer weed seeds to be buried, which favours the germination of small-seeded species (Yenish et al., 1992). Grime et al. (1981), testing 400 species of the British weed flora, found a strong relation between germination and seed shape and that smaller and more elongated seeds had higher germination rate probably due to the fact that the amount of water required by a given seed depends on its mass. Therefore the area to mass ratio could influence the seed imbibition process (Gardarin et al., 2011). Moreover, reduced tillage soils are reported to have lower temperature and higher moisture contents than conventional tilled fields (Wicks et al., 2000; Addae et al., 1991) due to the presence of vegetation cover that prevents soil water loss by evaporation from soil surface, controls soil erosion by intercepting rainfall and runoff and improves infiltration capacity (De Baets et al., 2011; Gómez et al., 2009). Some authors have also observed that wind-disseminated species are strongly associated with reduced tillage (Derkensen et al., 1993; Foster, 1984; Froud-Williams et al., 1981). If compared with minimum or conventional tillage plots, no tillage is found to increase the total number of weeds (Cardina et al., 1991). To contrast this, greater demand for herbicides would be necessary in conservation tillage compared to conventional cropping systems (Reddy et al., 2003). The result is that to keep the weeds and crop yield at an acceptable level, more chemical treatments should be done in non-inverted plots than in ploughed fields where post-emergence herbicides application gives sufficient weed control (Tørresen et al., 2003). In addition to the loss of cost effectiveness advocated by some supporters of conservation agriculture, but still to be clarified with further studies, this scenario would represent a devaluation of conservative management from an environmental sustainability point of view. With the decline in the number of selective products available for chemical weed control and the increase in herbicides resistance to a range of chemical groups reducing the options available for farmers, the importance of using alternatives to chemicals for weed control has become fundamental, above all in conservation systems where further restriction in weed control is represented by the lack of mechanical operations. In this sense, a promising approach seems to be the development of weed forecasting models. In weed-crop competition the timing of intervention plays a key role in cropping systems as the time of seedling emergence determines whether a plant will be able to compete successfully for resources (space, light, water, nutrients). A better understanding of the factors affecting timing of weed emergence in a field and how much they interfere with crop establishment, could aid in improving models predicting weed emergence dynamics. Information obtained from such a model may be useful in weed management strategies in order to optimize the timing of herbicides application and reduce overall chemicals use (Harker and O'Donovan, 2013; Grundy, 2002). Several approaches have been used to develop weed emergence predictive modelling but recent studies are in agreement that the hydrothermal time concept is suitable for predicting emergence patterns (Garciá et al., 2013). The hydrothermal time concept, which attempts to model seed germination combining thermal time above a base temperature and hydro time above a base water potential, has been successfully applied to describe seedling emergence of several crops and weeds (Bradford, 2002; Colbach et al., 2002; Dahal and Bradford, 1994; Finch-Savage and Phelps, 1993; Bradford, 1990). A given weed seed needs a certain amount of hydrothermal time to germinate. Hydrothermal time (HT) is accumulated according to the comparison between soil microclimate conditions (soil temperature and water potential) and specific biological parameters varying among species (T_b base temperature and Ψ_b base water potential). Consequently, HT accumulation in a day *i* can be estimated with the following equation (Masin et al., 2005):

$$HT_i = (n * \max(T_{si} - T_b, 0) + HT_{i-1})$$

$$T_{si} \leq T_o \qquad n = \begin{Bmatrix} 0 \; if \; \Psi_{si} \leq \Psi_b \\ 1 \; if \; \Psi_{si} > \Psi_b \end{Bmatrix}$$

$$T_{si} > T_o \qquad n = \begin{Bmatrix} 0 \; if \; \Psi_{si} \leq \Psi_b + K_t(T_{si} - T_o) \\ 1 \; if \; \Psi_{si} > \Psi_b + K_t(T_{si} - T_o) \end{Bmatrix}$$

where T_{si} and Ψ_{si} are the average soil temperature and water potential on day i; T_o is the optimum temperature for germination and K_t is the slope of the relationship between T_{si} and Ψ_b in the supra-optimal temperature range. The parameters T_b, Ψ_b, T_o and K_t have to be estimated with laboratory and field experiments. Generally, emergence potential and timing are based on cumulative hydrothermal time. Although this approach would be not adequate in conditions of water stress, when crops are irrigated and water potential does not represent a limiting factor, a hydrothermal time-based model can be represented by a simple sigmoidal curve with cumulative emergence (CE) as a function of soil hydrothermal time (Dorado et al., 2008). Although a germination and emergence model can enhance crop management by facilitating the implementation of more effective weed control strategies optimizing the timing of weed control, to date weed dynamics models have been developed for a relatively small number of species even though weed populations in crop fields vary according to many factors. Despite the importance of predictive emergence models in order to facilitate strategic farming decisions, to date the knowledge on and application of modelling is still limited.

There are many factors limiting or, on the contrary, favouring the adoption of a new technology: scientific research, information transfer and local policies. In the agricultural sector, scientific research is called upon to answer many technical questions ranging from biology of living organisms to physical and mechanical tasks. The change of just one factor causes a shift in the balance among several elements constituting agroecosystems. Yet a majority of studies suggest that application of the techniques associated with conservation agriculture, especially during the transition phase, have modest advantages over conventional practices on this account (FAO, 1997). Information and its communication become especially important as the level of complexity of new findings increases (Nowak, 1987). Although conservation agriculture has been providing benefits in many countries worldwide, this practice still encounters resistance from farmers who often show a degree of mistrust for its complexity of application (Stagnari et al., 2010; Knowler et al., 2007). Whatever is considered a limiting factor in adopting conservation agriculture techniques for a farmer somewhere, may already have been resolved elsewhere. Agbamu (1995) demonstrated that research alone will not promote adoption of a new discovery if information dissemination is ineffective, inaccurate or inappropriate. Government policies can do much to promote the adoption of conservative techniques by farmers especially when the need arises to invert negative trends due to increasing agrochemical use, intensification of soil tillage and loss of natural resources as has been happening in the last twenty years. In response to these concerns, the European Community, with the Council Regulation (EC) No 1698 of 20 September 2005 on support for rural development by the European Agricultural Fund for Rural Development (EAFRD), subsidizes each Member State to prepare own rural development National Strategy Plan constituting the reference framework for the preparation of rural development programmes. The Regulation highlights that "*to ensure the sustainable development of rural areas it is necessary to focus on a limited number of core objectives at*

Community level relating to agricultural and forestry competitiveness, land management and environment […]”. In Italy, the regulation of environmental concerns is the responsibility of the individual Regions. Veneto Region introduced a variety of programmes to encourage the adoption of conservation practices as a form of sustainable development for rural areas. In this context the need arose for studying what has resulted from the application of conservation agriculture in Veneto Region, firstly at weed biology and ecology level, and later verifying the possibility of applying the forecasting model AlertInf (Masin et al., 2012), developed for predicting weed emergence in maize fields in conventional tillage, in conservation cropping systems.

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CHAPTER I

Determination Of Base Temperature For Four Weed Species (Asteraceae) With Different Methods Of Estimation

Introduction

The growing interest in soil productivity and awareness of environmental issues has led governments and farmers to explore alternative production methods that maintain good levels of productivity with minimal soil disturbance. For some years interest in reducing the impact of agriculture on natural resources such as soil, water and microbial populations, has been increasing. In the light of this, the adoption of conservation agriculture practices seems to be a promising approach to improve crop production while concurrently protecting and enhancing the land resources on which production depends (Dumanski et al., 2006). Conservation agriculture, in fact, aims to conserve, improve and make more efficient use of natural resources through the integrated management of available soil, water and biological resources combined with external inputs. It contributes to environmental conservation as well as to enhanced and sustained agricultural production (FAO, 2001). The main difference between conservation and conventional systems is soil tillage, which is either reduced or completely eliminated in the former (Reddy et al., 2003). As soil tillage operations are necessary to prepare a good seedbed, by burying all surface residues and alleviating physical constraints of soil, and also to control weeds (Gajri et al., 2002), the transformation from a conventional to conservation system requires a series of adjustments and specific solutions for weed control. In fact, the control of weeds requires the development of specific weed management programmes which take into account that changes in the tillage patterns can lead to a shift in weed flora composition (Locke et al., 2002) because of concomitant changes in weed seedling microsites (Stahl et al., 1999) and herbicide-use patterns (Derksen et al., 1996). Moreover, the increasingly frequent appearance of herbicide-resistant weeds and resistance to herbicide groups due to the repetitive use of compounds with similar mode of action, have been restricting the weed control options available to the farmers adopting non-inversion tillage practices (Morris et al., 2010). Reddy et al. (2003) demonstrated that no tillage may be a practical and potentially sustainable option for farmers who are looking for practices that provide environmental benefits. At the same time, an increase in the cost of herbicides is associated to conservation agriculture systems because of the greater demand placed on them for weed control compared with conventional tillage, especially during the transition phase (Knowler and Bradshaw, 2007). The lack of mechanical weed control and the reduced possibilities for chemical weed control make weed management more difficult under conservation tillage than in conventional cropping systems (Moyer et al., 1994) so specific strategies and solutions should be studied in order to avoid intensive herbicide applications. In this respect, weed emergence predictive models can be useful tools to suggest the best application timing for chemical weed control and rates of the available herbicides, optimizing the interventions in terms of efficacy, costs and environmental impact. Various types of forecasting models have been developed to predict cumulative weed emergences and most are based on the hydrothermal time concept (Alvarado and Bradford, 2002). As reported by García et al. (2013) and Forcella et al. (2000), hydrothermal time (HTT) models are frequently more suitable for predicting emergence than thermal time based models. On the basis of the hydrothermal time concept, described for the first time by Gummerson (1986), seeds accumulate hydrothermal time according to daily environmental conditions, soil temperature and water potential, and specific biological requirements for germination, base temperature and base water potential (Masin et al., 2012). This implies that threshold biological parameters have to be estimated for each species (Grundy, 2003). Although seed germination is influenced by several factors such as dormancy, light requirements and soil moisture, temperature is the main environmental factor governing germination of non-dormant seeds in non-hydric stress conditions (Rochè et al., 1997; Garcia-Huidobro et al., 1982). Especially in conservation cropping systems, temperature plays a key role in providing the correct conditions for weed seeds germination. It is demonstrated, in fact, that the presence of surface crop residues acts on soil temperature in different ways (Shinners et al., 1994) and in particular, provides shade that typically reduces the amount of solar radiation reaching the soil surface (Sauer et al. 1998). Since wind-disseminated weed species are favoured in no tillage management (Froud-Williams et al., 1983b), the primary objective of this research is to estimate the minimum temperature required for the germination of 4 weed species representative of north-eastern Italian conservative cropping systems, i.e., *Taraxacum officinale* (W.) (TAROF), *Conyza* spp. (L.), *Senecio vulgaris* (L.) (SENVU) and *Sonchus oleraceus* (L.) (SONOL), testing different methods of base temperature estimation. Base temperature (T_b) is defined as the temperature below which germination will not occur (Gummerson, 1986). Several estimation methods and approaches can be found in the literature. Steinmaus et al. (2000) compared several conventional and alternative methods that have been used to estimate base temperature for germination and he found that the most robust estimate was provided by the x-intercept of the linear regression of an inverse transformation of 50% germination time on temperature. Most studies, in fact, estimate the base temperature using the x-intercept method (Gardarin et al., 2010), with the exception of Roché et al. (1997) who instead used a quadratic model to calculate the base temperature of *Crupina vulgaris*. Since temperature is demonstrated to be the single most important factor regulating germination of non-dormant seeds (Steinmaus et al., 2000), studies on how this parameter acts on germination and the subsequent seedling development are necessary and the findings can be considered as starting point for improving emergence modelling in integrated weed management programmes.

The aims of this research are i) to estimate base temperature (T_b) for germination of *Taraxacum officinale*, *Conyza* spp., *Senecio vulgaris* and *Sonchus oleraceus*, ii) to assess the values of T_b under constant and alternating temperature regimes and iii) to compare two methods of estimation using linear and non-linear regression between temperatures and germination rates.

Materials and Methods

Seeds of *T. officinale*, *S. vulgaris* and *S. oleraceus* were collected from senescing plants at the Padova University Experimental Farm in the Po Valley, north-east Italy. Plants of *C. sumatrensis*, *C. canadensis* and hybrids between the two were found on the farm, so for a correct representation of the local *Conyza* population a mixture of seeds of all the species were used in the experiment. Seeds were kept in paper bags in the dark at room temperature until the experiment began in spring 2012. Three replicates of 100 seeds of each species were placed on a single layer of filter paper in a 9 cm plastic petri dish. The filter paper was moistened with 2 ml of calcium sulphate 10 mM. Before placing the seeds on the filter paper, they were sterilized with PPM$^{\text{TM}}$ (Plant Preservative Mixture) 2% v/v for 10 minutes to reduce fungal and bacterial contamination. Petri dishes were sealed with parafilm to avoid the solution evaporating, especially at high temperatures, and then placed in growth chambers at nine different constant temperatures (6-9-12-15-18-21-24-27-30 °C) and eight regimes of alternating temperatures (12.5/2.5-15/5-17.5/7.5-20/10-22.5/12.5-25/15-27.5/17.5-30/20 °C). Photoperiod was set at 12:12 h light:dark for both types of tests. Seeds were considered germinated when the radicle was visible and the number of germinated seeds was recorded every 24 h until no further germination occurred for 5 days. The germination time course was analysed using a logistic function in the Bioassay97 program (Onofri, 2001) in order to define the time necessary to reach 50% of germination (t50). The base temperatures (T_b) were estimated by regressing germination rate (1/t50) against incubation temperature and by extrapolation to the intercept with the abscissa. Two different mathematical functions were used to fit germination rate: a linear regression (figure 1) and a quadratic model. The quadratic model was a parabolic function (figure 2):

$$1/t50 = aT^2 + bT + c$$

where T is the incubation temperature and a, b and c are constant coefficients.

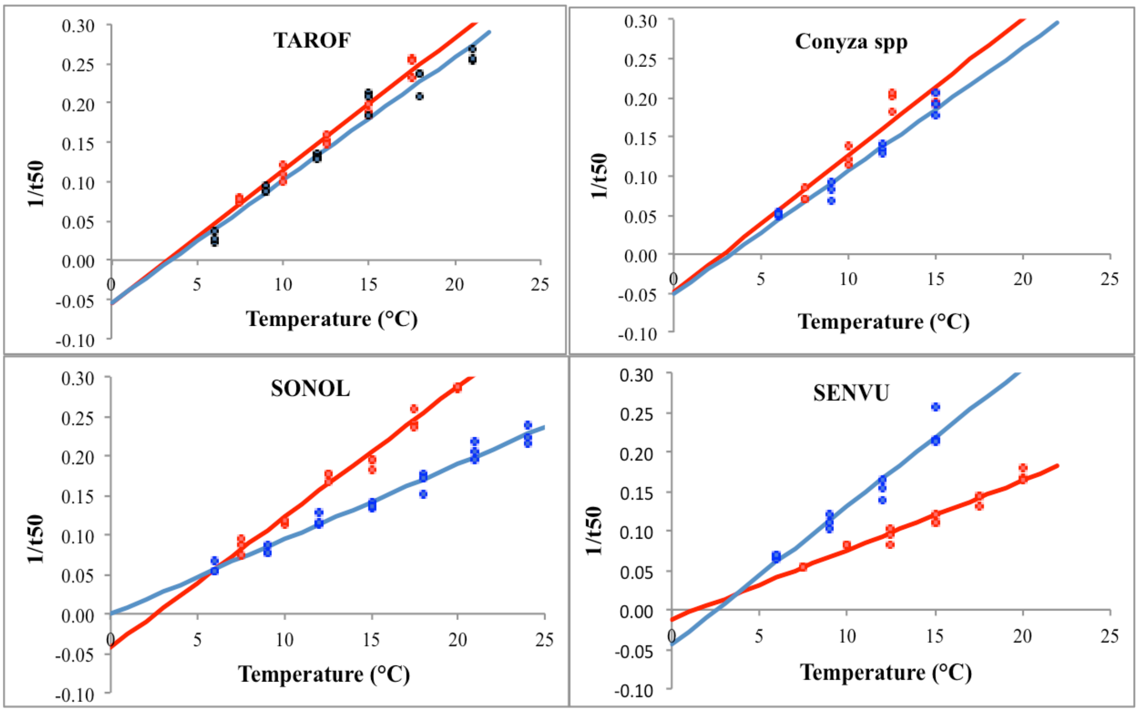

Figure 1: Estimation of base temperature using the linear regression method. Symbols are the observations and the line represents the best regression calculated with the bootstrap method. Red refers to alternating temperature and blue to constant temperature

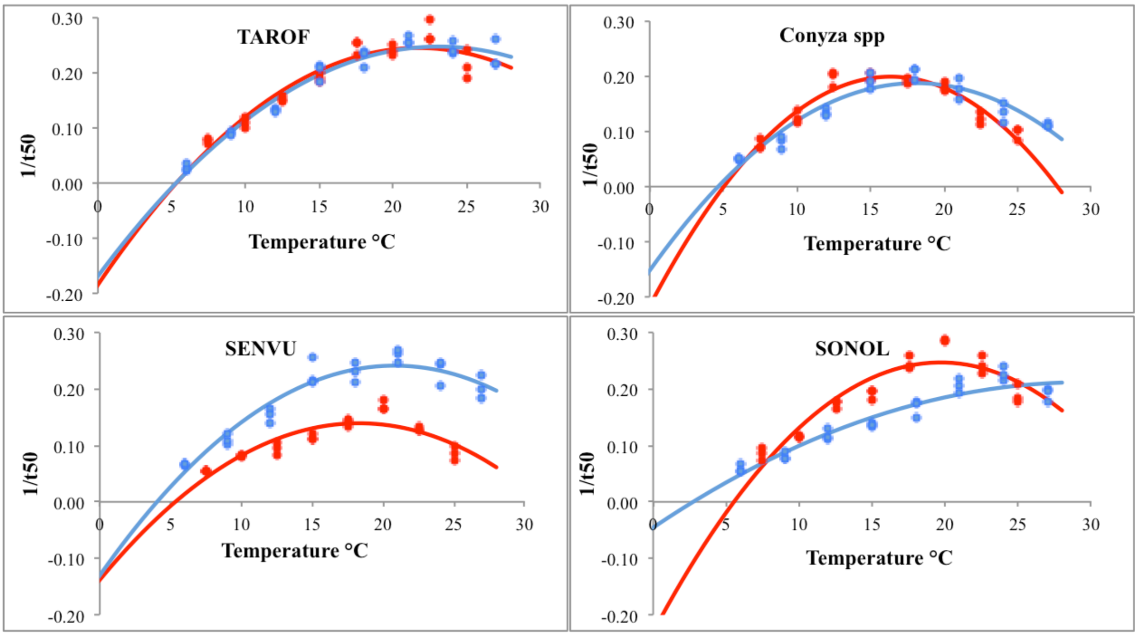

Figure 2: Estimation of base temperature using the parabolic function. Symbols are the observations and the line represents the best regression calculated with the bootstrap method. Red refers to alternating temperature and blue to constant temperature

Statistical confidence intervals for T_b were estimated by the bootstrap method (Efron, 1979). Five thousand samples were taken from each species randomly extracting one of the three replicates of each temperature. Five thousand datasets were created and the linear or the parabolic regression was estimated for each of these to determine the base temperature. The bootstrap distribution of the estimated base temperature was used to determine a 95% confidence interval. Base temperatures were then compared according to the criteria that if their respective confidence intervals did not overlap, they were considered as different.

Results and Discussion

For *T. officinale*, *Conyza* spp. and *S. vulgaris*, T_b values obtained with constant temperature were not significantly different from those estimated with alternating temperature using both linear and parabolic regressions. Only T_b of *S. oleraceus* resulted as being different between the two thermal conditions, as indicated by the 95% bootstrap confidence limits not overlapping. However, the T_b estimates with the linear regression differed from the values determined with the parabolic function in all species.

Linear regression

S. oleraceus showed the lowest T_b values among the studied species, 0.06 and 2.57 °C, respectively at constant and alternating temperature (table 1), *T. officinale* had the highest values (3.47 and 3.26 °C). Intermediate values were found for *Conyza* spp. 3.23 and 2.71 °C and *S. vulgaris* 2.76 and 1.39 °C, as confirmed by Guillemin et al. (2012) who estimated a germination base temperature of 2.5 ± 1.04 °C for this species in France using constant incubation temperature and the linear regression method for fitting the germination rate against incubation temperature.

Table 1: Base temperature (T_b) estimated with liner regression and 95% confidence interval (c. interv)

	T_b cost (°C)	**c. interv** ±	**T_b alt** (°C)	**c. interv** ±
Taraxacum officinale	3.47	0.58	3.26	0.96
Conyza spp	3.23	0.91	2.71	1.37
Sonchus oleraceus	0.06	1.40	2.57	0.94
Senecio vulgaris	2.76	1.02	1.39	0.96

Even if *T. officinale* is a well-documented species in terms of its ecology, economic importance as a medicinal plant and geographical distribution, the determination of temperature threshold for germination has never, to our knowledge, been attempted before. Nonetheless, the study conducted by Luo and Cardina (2012) reports that *T. officinale* is able to germinate over a wide range of temperatures, but the best germination response is reached at low and medium temperatures, whereas high temperatures lead to reduced germination (Martinková and Honêk, 1997). Additionally, most studies showed that germination of *T. officinale* is favoured by alternating temperatures and light (Collins, 2000; Noronha et al., 1997). These aspects would confirm that germination of *T. officinale* and subsequent seedling emergence in the field is favoured by the presence of the seeds at or near the soil surface, where the availability of light and diurnal temperature fluctuation are non-limiting factors. Similar conditions seem to be suitable for *S. oleraceus* germination since increasing abundance of this species is often related to higher seedling emergence under conservation agriculture than conventional (Widderick et al., 2010; Chauhan et al., 2006; Widderick et al., 2004). For *S. oleraceus*, in fact, no-till systems are an optimal environment for germinating because after flowering, a large amount of seeds remain on, or close to, the soil surface where germination is stimulated by alternating temperatures (Gresta et al., 2010). In our study, base temperature for *S. oleraceus* calculated at constant temperatures has resulted as 0.06 °C, a very low value from the ecological point of view, given that temperature thresholds below zero have never been used in modelling because they have no biological meaning (Spano et al., 1999). Instead a value of 2.57 °C was calculated in alternating temperature conditions, a higher threshold value that may confirm that germination of *S. oleraceus* is strongly affected by fluctuating temperatures, and that may incline towards the use of the alternating temperatures method. Our finding seems to be in contrast with the result obtained by Steinmaus et al. (2000) who estimated the base temperature for *S. oleraceus* as varying from 5.3 to 6.8 °C, according to the germination rate indices linearly regressed on temperature. However, as these authors conducted their experiment in California where winters are warmer than in Italy, it is reasonable to suppose that such differences in estimates of the parameter could be due to an adaptive characteristic of the population depending on the site of origin. Regarding *Conyza* spp., the ability of the species within the genus to hybridize is widely documented, with intermediate forms arising, mostly among *C. canadensis* and *C. sumatrensis* (Thébaud and Abbott, 1995). To date a limited amount of documented experimentation is available on the minimal temperature threshold of *C. canadensis* and the biology and ecology of *C. sumatrensis* have remained poorly studied (Weaver, 2001), despite the *Conyza genus* being a growing problem worldwide, particularly where reduced tillage and no-till practices are used (Zambrano-Navea et al., 2013; Buhler and Owen, 1997; Bhowmilk and Bekech, 1993; Brown and Whitwell, 1988). As for *S. oleraceus*, the only estimate available in the literature of base temperature for *Conyza* spp. was made by Steinmaus et al. (2000) who reported a value closer to 13 °C for C. *canadensis* in California. On the contrary, there are no data published concerning base temperature for *C. sumatrensis* but some articles report that *Conyza* spp., including *C. sumatrensis*, are able to germinate over a broad range of temperatures and seedling emergence can potentially occur at any time (Zambrano-Navea et al., 2013). Furthermore, there is evidence that base temperature may differ between species and within a species, between genotypes and populations (Ellis et al., 1987), but also between investigation methods. *Conyza* spp. are found in the literature as winter or summer annuals, or both (Davis and Johnson, 2008; Wu et al., 2007; Steinmaus et al., 2000; Regehr and Bazzaz, 1979) according to their geographical site of origin.

Parabolic regression

Extrapolation of the parabolic function (table 2) to the abscissa gave base temperatures ranging from 2.73 (*S. oleraceus*) to 5.33 °C (*S. oleraceus* and *S. vulgaris*). Also for parabolic regression, the estimates of base temperature did not differ between constant and fluctuating temperatures within species having overlapping 95% bootstrap confidence intervals, with the exception of *S. oleraceus* and *S. vulgaris*.

Table 2: Base temperature (Tb) estimated with parabolic regression and 95% confidence interval (c. interv)

	T_b cost (°C)	**c. interv** ±	**T_b alt** (°C)	**c. interv** ±
Taraxacum officinale	5.29	0.47	5.31	0.31
Conyza spp	4.65	0.18	5.04	0.20
Sonchus oleraceus	2.73	1.26	5.33	0.40
Senecio vulgaris	4.04	0.33	5.33	0.37

Comparison of the two estimation methods shows that the minimum temperature threshold values for germination estimated by a quadratic model are significantly higher than those calculated by linear regression for all species and also for both thermal conditions of incubating. Such results were expected since the shape of parabola, by its nature, closes on the x-axis at higher values than a straight line does. Unlike linear models, the fitting with the quadratic function does not need to exclude from the calculation the values of 1/t50 obtained at temperatures up to the optimum. In this way use of the quadratic function allows the estimation of another biological parameter, i.e. the optimal temperature at which germination is most rapid (Bradford, 2002). Graphically this parameter coincides with the vertex of the parabola and, more in general, the parabolic model better describes the observed germination behaviour. In fact, estimation of an optimal temperature for a weed species can improve the accuracy of the extrapolation by defining the upper limit for the temperature range above which development rate accelerates (Roché et al., 1997). From these results it can be concluded that the estimated base temperature varies according to technique, the two methods (linear and quadratic regression) give different results. With the current information it is not possible to decide which method is the more accurate. Anyhow, an important consideration can be made. The base temperature calculated using the linear method was close to zero for *S. oleraceus* (that is difficult to explain biologically). This means that this method estimated a capacity of this species to germinate at a very low temperature that has not been verified physiologically. Given these considerations, it is important to underline that statistical methods must be considered as instruments to evaluate biological parameters that then need to be verified on a physiological basis.

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CHAPTER II

Assessing Microclimate Conditions Of Surface Soil Layers To Improve Weed Emergence Modelling

Introduction

Predictive models for weed emergence are useful tools for the development of efficient Integrated Weed Management strategies (Grundy, 2002) as they can provide information to choose the correct timing for herbicide application (Colbach et al., 2005; Masin et al., 2005; Leblanc et al., 2004). Emergence models may also be included in Decision Support Systems to develop automated machinery for weed control (Young, 2012) or identify the right timing for weed sampling in maize fields (Masin et al., 2011). Many weed emergence models have been developed according to the thermal or hydrothermal approach (Garcia et al., 2013; Dorado et al., 2009; Izquierdo et al., 2009; Leguizamon et al., 2005; Alvarado and Bradford, 2002; Bradford, 2002; Harvey and Forcella, 1993; Carberry and Campbell, 1989; Gummerson, 1986). The first step in both approaches is the calculation of a progressive accumulation of Growing Degree Days (GDD) according to the comparison of biological characteristics of the different weeds (base temperature and base water potential for germination) and local trends of soil microclimatic conditions (daily average soil temperature and water potential). In the second step, non-linear regressions (e.g. logistic, Gompertz, Weibull) are used to estimate the percentage of total seedling emergence corresponding to a given accumulation of GDD. The microclimatic parameters (soil temperature and water potential) required for the first step can be directly measured in the field or estimated starting from other weather parameters such as air temperature and precipitation (Garcia et al., 2013; Masin et al., 2012; Royo-Esnal et al., 2010). In any case, the correctness of these measurements or estimations strongly influences the final predictive accuracy of weed emergence models (Grundy, 2002). Moreover, soil temperature and water potential present a depth-dependant variability, with wide seasonal and daily fluctuations in the superficial soil layers (0-2 cm), which are directly exposed to weather agents, such as wind, rain and solar radiation, while these fluctuations lessen as depth increases. For the same reasons, direct measuring with probes or sensors of soil temperature and water potential is more problematic in the superficial soil layer (Flerchinger and Hardegree, 2004). As a consequence, emergence models developed for arable fields, where weed seeds are uniformly distributed in the soil layer corresponding to tillage depth, usually adopt soil temperature and soil water potential measured or estimated at 3-5 cm of depth to calculate GDD (Dorado et al., 2009; Masin et al., 2012, 2010). This indeed represents the average condition of the soil layer (0-10 cm) from which weeds can germinate and emerge (Benvenuti et al., 2001). However, this approach might not be adequate in the case of emergence models developed for no-till conditions where almost all weed seeds are located in the superficial soil layer and exposed to those specific climatic conditions (Chauhan et al., 2006; Swanton et al., 2000; Refsell and Hartzler, 2009). Consequently, the accumulation of GDD calculated according to the soil conditions at 3-5 cm depth could not represent the situation of weed seeds situated in the superficial layer. For this reason Leguizamon et al. (2009) decided to estimate soil temperature at 2 cm of depth in order to model weed emergence under no-till conditions. However, they reported inaccuracies in the soil temperature estimation that complicated the creation of a single emergence model in their study. An experiment was therefore conducted to measure soil temperature at different depths and to estimate the specific accumulation of GDD at each depth for three spring emerging weed species: *Abutilon theophrasti* Medik (ABUTH, Malvaceae), *Chenopodium album* L. (CHEAL, Chenopodiaceae) and *Sorghum halepense* (L.) Pers. (SORHA, Poaceae). The three species were selected because they present different base temperatures for germination (Masin et al., 2010) and different seedling emergence dynamics in the field (Masin et al., 2012). The accumulations of GDD, obtained for each species on the basis of soil temperature measured at a given depth, were then used to estimate the progressive seedling emergence according to a pre-existing model called AlertInf (Masin et al., 2012). The different emergence patterns calculated for each species were lastly compared to identify variability in the model estimation due to the adoption of soil temperature values measured at different depths. The final aim was to establish if soil temperature at 5 cm of depth, which can be measured or estimated more easily and accurately than at 0-2 cm depth, could be adopted as input for weed emergence models for no-till conditions.

Materials and Methods

Soil temperatures monitoring

A field experiment was conducted at the experimental farm of the University of Padova at Legnaro, Northeastern Italy. The climate of Legnaro (45°20’N, 11°58’E) is characterized by cold winters, hot summers and a mean annual rainfall of about 850 mm. The soil is a silt loam (fulvi-calcaric Cambisoil, FAO 2006).

The soil temperature profiles were measured at depths of 2, 5, 10, 20 and 50 cm by STP01 probe (Hukseflux Thermal Sensors B.V., Delft, The Netherlands), which is designed to measure the soil temperature at specific depths by determining the thermal gradients between a certain specific depth and the reference point. It improves the accuracy in positioning, which is usually highly uncertain when using a series of separate sensors. This makes the temperature gradient measurement more reliable, which subsequently improves the accuracy of the absolute temperature measurement. The measurement range of STP01 is from – 30 °C to 70 °C, with an accuracy of ± 0.02 °C. The STP01 probe was placed in the soil during autumn 2011 and soil temperature measurements began the following spring. Soil temperatures were measured at 1 second intervals, averaged over 15 min and registered on a CR3000 datalogger (Campbell Scientific Inc., Logan, Utah, USA). The time series data used for this study were collected from 15th April 2012 to 31st July 2012, which corresponded to the local period of weed seedling emergence in spring crop fields. Plant residues and emerged seedlings were continuously removed from soil surface to maintain a bare soil condition throughout the experiment in order to maximize fluctuations of soil temperature. Light interception by plant canopy or residues would in fact reduce the daily maximum soil temperature and consequently also the daily mean temperature and magnitude of the daily soil temperature fluctuations (Norsworthy, 2004). Mean daily and hourly temperatures (T daily and T hourly respectively) were calculated, obtaining two independent series of data for each depth.

Calculation of GDD accumulations and comparison of emergence curves

In order to emphasize the effect of daily soil temperature fluctuations, mean hourly temperatures (T hourly) at the depths of 2, 5 and 10 cm were used to estimate three different accumulations of GDD for each species. The series of temperatures recorded at 20 and 50 cm depths were not included in the data analysis because weeds are unable to germinate and emerge from such deep soil layers (Benvenuti et al., 2001). Since the principal aim of this study was to analyze the effect of depth-dependent variability of soil temperature on the estimation of GDD, soil water potential was considered as a not limiting factor for weed germination throughout the experiment. The accumulation of GDD started for all three species on 15th April, which was considered as a common date for seedbed preparation in the

Legnaro area, and ended on 31st July as seedling emergence of the studied species rarely occurs after this date. The daily accumulation of GDD was calculated according to the following formula:

$$\mathrm{GDD} = \frac{\sum \mathrm{Th} - \mathrm{Tb}}{24}$$

where Th is the mean of hourly soil temperature and Tb is the base temperature for germination. The values of base temperature for germination for the three species adopted for this calculation (Table 1) were estimated in a preceding study (Masin et al., 2010). Negative values of daily accumulation of GDD were considered as zeroes.

Table 1: Values of base temperature (Tb) for germination adopted for the GDD calculation and Gompertz coefficients (a and b) used for modeling the cumulated emergence of *A. theophrasti*, *C. album* and *S. halepense* (ABUTH, CHEAL and SORHA)

	Tb[1]	**Gompertz coeff.**[2]	
	(°C)	a	b
A. theophrasti	3.9	10.28	0.02
C. album	2.6	3.56	0.01
S. halepense	11.8	4.49	0.03

[1] Estimated in a preceding study (Masin et al., 2010)
[2] Estimated in a preceding study (Masin et al., 2012)

Cumulated percentage of seedling emergence normalized to 100% (CE) was calculated for the three depths for each species by a Gompertz function, as follows, according to a previous work by Masin et al. (2012):

$$\mathrm{CE} = 100 * \exp\left(-\mathrm{a} * \exp(-\mathrm{b} * \mathrm{GDD})\right)$$

where a is related to a GDD lag before emergence starts, and b is related to the slope of the curve. The values of Gompertz coefficients (a and b) used for modelling the cumulated emergence of three species (Table 1) were estimated in a previous study (Masin et al., 2012). Three different emergence curves were therefore obtained for each species.

Dates when the percentage of cumulated emergence exceeded the threshold values of 1, 25, 50, 75 and 95% were identified for each emergence curve. These were defined as threshold dates (TD1, TD25, TD50, TD75 and TD95). Corresponding threshold dates of the three emergence curves of the same species were compared to identify possible variability in the model estimation caused by the adoption of soil temperature values measured at different depths. Particular attention was paid to threshold dates TD50 and TD75 because this interval of the weed emergence curve corresponds to the initial part of the Critical Period for Weed Control (CPWC), i.e. a period during the crop cycle in which weed control is required to avoid yield losses (Otto et al., 2009), and also represents the right timing for weed sampling in maize fields (Masin et al., 2011). Thus, estimating the TD50 or TD75 with even a few days of inaccuracy could lead to an inappropriate choice of control timing and consequently relevant yield losses.

Results and Discussion

Soil temperatures recorded at 2 cm depth presented the greatest seasonal and daily fluctuations throughout the period of the experiment (15th April – 31st July 2012), while these fluctuations narrow as depth increases to reach a minimum at 50 cm depth (Fig 1).

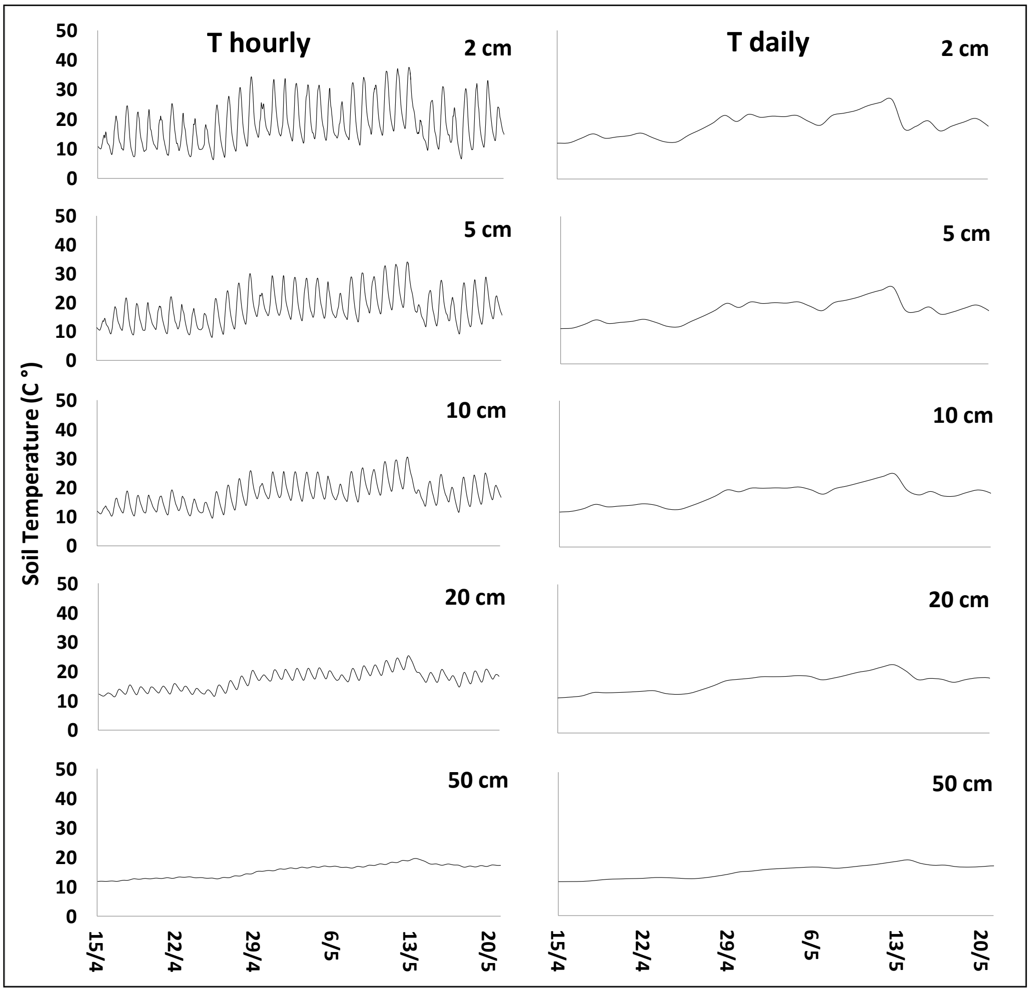


Figure 1: Mean daily and hourly temperatures (T daily and T hourly) measured at 2, 5, 10, 20 and 50 cm depths

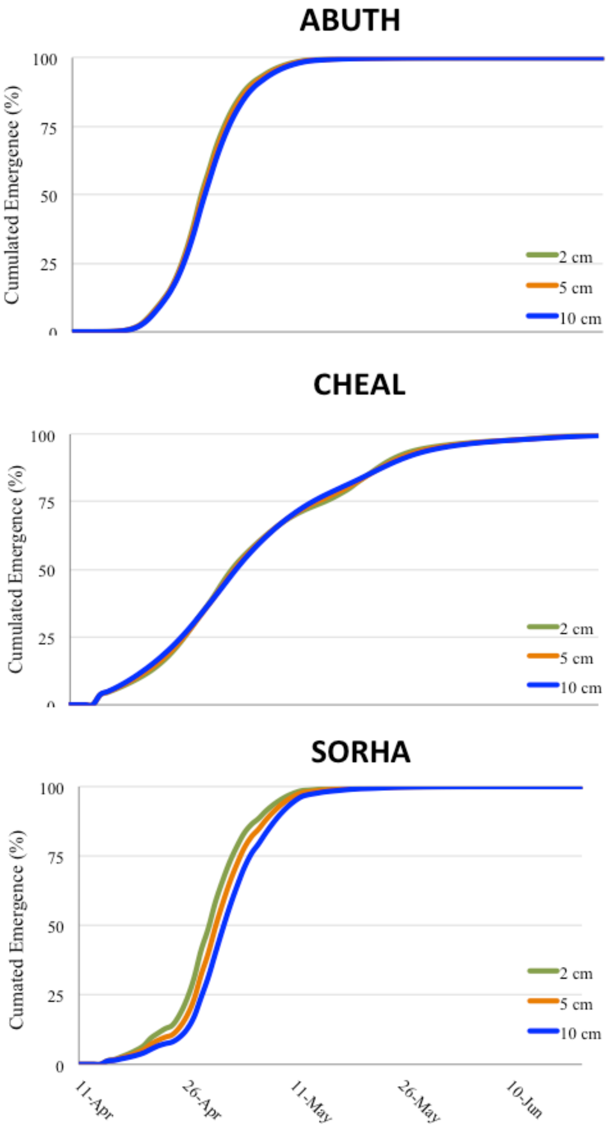
This phenomenon is more evident if mean hourly temperature (T hourly) is considered instead of mean daily temperature (T daily). The maximum values of soil temperature were estimated at 2 cm depth, 33.2 and 44.2 °C for T daily and T hourly respectively (Table 2). The minimum value of soil temperature was 6.3 °C at 2 cm depth for T hourly, while minimum values around 12 °C were estimated for T daily at all depths. Finally, the medium values of T hourly and T daily estimated for each depth did not differ, but a progressive depth-dependant increase was detected passing from values of 20.3-20.5 °C at 50 cm to 24.5-24.7 °C at 2 cm of depth.

Table 2: Mean daily and hourly soil temperatures (T daily and T hourly) measured at different depths. Maximum, medium and minimum values (Max, Med and Min) were estimated considering the whole period of the experiment (15th April – 31st July 2012)

	T daily					**T hourly**				
	50 cm	20 cm	10 cm	5 cm	2 cm	50 cm	20 cm	10 cm	5 cm	2 cm
Max	26.3	29.9	31.4	32.3	33.2	26.5	32	36.7	40.2	44.2
Med	20.3	22.6	23.6	24	24.5	20.5	22.8	23.7	24.2	24.7
Min	11.8	11.8	11.9	12	12.1	11.8	11.3	9.5	7.9	6.3

The three accumulations of GDD, calculated for each species adopting values of soil temperature measured at 2, 5 and 10 cm depths, did not differ (data not shown) and consequently also the three emergence curves estimated for each species presented almost identical trends (figure 2).

Figure 2: Cumulative emergence (CE) curves estimated adopting values of soil temperature measured at 2, 5 and 10 cm depths for *A. theophrasti*, *C. album* and *S. halepense* (ABUTH, CHEAL and SORHA)



Only in the case of *S. halepense* a slight delay could be noticed for the emergence curves estimated with the values of soil temperature measured at 5 and 10 cm depths in comparison with the one corresponding to the values of soil temperature at 2 cm depth. This situation was also confirmed by the comparison of threshold dates. The threshold values of cumulated emergence (1, 25, 50, 75 and 95%) were indeed exceeded on similar dates by the three emergence curves of each species (Table 3). The maximum difference was three days (9th May – 12th May) regarding TD95 for *S. halepense*. Regarding TD50 and TD75, differences among the three emergence curves were 2 days or less for the three species. Despite the differences in the daily fluctuations of soil temperature recorded at the three depths (2, 5 and 10 cm), the corresponding accumulations of GDD maintained almost overlapping patterns throughout the experiment.

Table 3: Comparison of threshold dates (TD) of the emergence curves estimated adopting values of soil temperature measured at 2, 5 and 10 cm depths for *A. theophrasti*, *C. album* and *S. halepense* (ABUTH, CHEAL, SORHA)

		Depths		
		2 cm	5 cm	10 cm
Species	**TD**	**Date**		
ABUTH	1	19-Apr	19-Apr	19-Apr
	25	26-Apr	26-Apr	26-Apr
	50	28-Apr	29-Apr	29-Apr
	75	1-May	2-May	2-May
	95	7-May	8-May	8-May
CHEAL	1	15-Apr	15-Apr	15-Apr
	25	27-Apr	26-Apr	26-Apr
	50	3-May	3-May	3-May
	75	15-May	14-May	13-May
	95	29-May	30-May	31-May
SORHA	1	15-Apr	15-Apr	15-Apr
	25	27-Apr	28-Apr	29-Apr
	50	30-Apr	1-May	2-May
	75	3-May	4-May	5-May
	95	9-May	10-May	12-May

The daily accumulation of GDD has therefore been identical among the three depths probably because the higher soil temperatures reached at 2 cm depth during the day, in comparison with 5 or even more so with 10 cm depth, were balanced by equivalent lower soil temperatures during the night. As a consequence, differences among the three emergence curves estimated by the Alertinf model for each species could be considered as not significant from the point of view of emergence modeling for weed control optimization. It may therefore be supposed that soil temperature measured at 5 cm depth could be adopted as input for weed emergence models for no-till fields, also given that the bare soil condition maintained throughout the experiment should have maximized daily fluctuations and depth-dependent differences of soil temperature. The presence of emerging seedlings or crop residues, which is a common situation for no-till fields, would indeed intercept light and reduce the magnitude of daily soil temperature fluctuations (Norsworthy, 2004). However, emergence models developed for arable field conditions, such as AlertInf (Masin et al., 2012), could not be simply transferred to the no-till conditions without considering any preliminary evaluations and possible modifications because the different soil management affects several environmental parameters that control the dormancy cycling and germination dynamics of many weed species. Indeed, the absence of tillage and the conservation of crop residues can maintain soil humidity, creating good conditions for seed germination, but also reduce magnitude of soil temperature fluctuations and modify the quality and quantity of light reaching the soil surface. Given that these factors have a stimulating effect on seeds of several weeds, as exhaustively reviewed by Benech-Arnold et al. (2000), soil conditions under no-till management could hinder or reduce dormancy break and germination for these species. Further studies and experiments are therefore required to assess the real accuracy and transferability of existing emergence models to no-till fields and possibly adjust and calibrate them according to the different environmental conditions.

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CHAPTER III

Effect Of Soil Tillage On Weed Emergence Magnitude And Dynamics Under Simulated Conditions

Introduction

The first important step to develop an accurate predictive model is to identify which factors influence the pattern of seedling emergence in terms of magnitude and dynamics. Numerous studies have recognized that the most important factor is represented by the interaction of environmental conditions and cropping system. However, among different factors that characterize agricultural management systems, soil tillage is considered to be able to profoundly modify weed seedling emergence (Buhler et al., 1997; Mohler, 1993) by acting on the vertical weed seed distribution in the soil profile (Yenish et al, 1992; Pareja et al., 1985). The burial depth at which a seed is found has the potential to change weed-population emergence and dynamics as different burial depths differ in availability of moisture, temperature, light exposure, pH and microbiological activity (Chauhan et al., 2012; Nandula et al., 2006; Koger et al., 2004; Chachalis and Reddy, 2000; Shaw et al., 1991; Taylorson 1987). Cropping technique, and in particular soil tillage system, affects weed flora selection process by the fact that in a certain area only species that take advantage of a recruitment pattern will be able to establish themselves there. Generally in fact, the response of weed seedling recruitment to tillage is species specific (Buhler and Daniel, 1988) as for the case of *Sonchus oleraceus* which is considered a dominant weed and has increased in prevalence in conservation tillage managed fields of the subtropical grain region of Australia (Widderick et al., 2010). Thomas et al. (1997) reported that increased stubble retention and reduced tillage have reduced soil water loss from the soil surface and minimized seed burial, creating optimal conditions for *S. oleraceus* establishment over the years. *Conyza canadensis* is one of the most common and troublesome weeds in reduced and no-tillage systems in the central United States (Buhler and Owen, 1997). Recently, Zambrano-Navea et al. (2013) focused attention on the increase in *Conyza bonariensis* prevalence associated with the adoption of conservation cropping system in southern Spain. Because of the strong link between vertical seed distribution in the soil, which is mainly due to tillage effects, and seedling emergence behaviour (Chauhan et al., 2006a), it is of prime importance to acquire better knowledge on emergence ability of various weed species in relation to different soil depths in order to improve weed control programmes. Field emergence models are essential tools for supporting farmers in the design of suitable weed control strategies while optimizing crop yield (Forcella et al., 2000), but to develop models capable of providing the most correct timing of intervention, long-term laboratory and field experiments are necessary to acquire information about weed seedling emergence magnitude and dynamics. In fact the magnitude of a flush of emergence will have an impact on the size and competitive pressure of a weed population (Vleeshouwers and Bouwmeester, 2001), whilst the timing of the flush of emergence relative to the crop is critical in targeting and optimizing the timing of weed control (Berti et al., 1996). Due to the interest in studying the response in terms of emergence magnitude and dynamics of different weed species to different soil tillage systems, this research started in 2011 with the aim of comparing weed emergence patterns under simulated conditions of tilled and no-tilled soil in order to verify the possibility of predicting weed emergence in conservation tillage systems by using AlertInf (Masin et al., 2012).

Materials and Methods

Two field experiments were conducted in 2011-2012 and 2012-2013 to compare emergence behaviour of some weed species in arable and no-till management. The species studied were *Abutilon theophrasti* Medik. (ABUTH), *Amaranthus retroflexus* L. (AMARE), *Sonchus oleraceus* L. (SONOL) and *Sorghum halepense* L. (Pers.) (SORHA) in the first experiment while *Taraxacum officinale* L. (TAROF) was also included in the second. The experiments were conducted at the experimental farm of the University of Padova at Legnaro, Northeastern Italy. The climate of Legnaro (45°20’N, 11°58’E) is characterized by cold winters, hot summers and a mean annual rainfall of about 850 mm. The soil is a silt loam (fulvi-calcaric Cambisoil, FAO 2006). Two treatments were performed to simulate conditions of weed seeds in arable (treatment T: seeds buried overwinter in the soil and affected by soil disturbance due to spring seedbed preparation) and no-till managements (treatment NT: seeds overwinter on soil surface without any further disturbance). Four 100-seed replicates were included for each treatment. For treatment T seeds were placed in metallic mesh bags and buried in the soil at 20 cm depth. The burial dates were 19th December 2011 and 5th December 2012 for the first and second experiment respectively. Bags were exhumed the spring after the burial in correspondence to the period of seedbed preparation for spring crops in the Legnaro area. Bags were opened and seeds were mixed with soil under direct sunlight to simulate the effect of light flashes on seeds which normally occur during soil tillage. On the same day the mixture of seeds and soil was spread in 3 cm–deep furrows so seeds were randomly distributed in this soil layer. This operation took place on 1st March 2012 for the first experiment, while it was delayed till 15th May 2013 for second experiment due to an extremely rainy spring 2013. For treatment NT seeds were directly sown on the soil surface and there was no further soil disturbance until seedling emergence. Sowing dates for treatment NT were 19th December 2011 and 11th January 2013 for the first and second experiment respectively. Emerged seedlings were counted and removed at least weekly from spring till the end of emergence period corresponding approximately with the end of August. Daily rainfall and soil temperature at 0 cm depth were monitored throughout the experiment at the ARPA (Regional Environmental Protection Agency) weather station located 500 metres from the experimental site.

Data from the two experiments 2011-2012 and 2012-2013 were analyzed separately. At the end of each experiment, emergence dynamics of each replicate was modelled using the logistic function (1) in the Bioassay97 program (Onofri, 2005) from which the time of 50% relative emergence (t50) was estimated. t50 was expressed as number of days after 1st March for both experiments.

$$\mathrm{CE} = 100/(1 + \exp(\mathrm{a}(\ln(\mathrm{t} + 0.0000001) - \ln(\mathrm{b})))) \qquad (1)$$

where CE is the percentage of cumulated emergence, t is the time (days), *a* represents the slope of the curve, and *b* the inflexion point.

Average percentages of germinated seeds were calculated for each species, treatment and their combinations. Factorial ANOVA (p=0.05) was performed using General Linear Models module of Statistica 7.1 (StatSoft Inc., 2005) to analyze the effect of species, treatment and their interaction on percentage and t50 of total emerged seedlings. Post-hoc multiple comparisons were performed using Tukey HSD test (p>0.05) for mean separation.

Results and Discussion

Effect of tillage on weed emergence percentage

The influence of tillage systems on weed emergence patterns has been confirmed by statistical analysis that identified a significant effect of the interactions between species and treatment factors on weed emergence percentage. Seedling emergence of *A. theophrasti*, *A. retroflexus* and *S. halepense* were found to be significantly higher under conventional treatment in the first year of experimentation, whilst emergence of *S. oleraceus* was not significantly influenced by type of soil tillage (figure 1). In the second year, which was characterized by a more complex weed emergence pattern, *A. theophrasti* and *A. retroflexus* emergence percentage was still higher in tilled plots than in undisturbed ones. These results are consistent with the findings of Buhler and Daniel (1988), who reported that *A. theophrasti*, being a species with a hard seed coat, has more likelihood of surviving in arable fields where soil tillage can scarify seed coats by soil-particle movement. In contrast to the pattern observed in the first year, for *S. oleraceus* the greatest seedling emergence in 2013 was observed from the no-till plot where seeds were placed on the soil surface. Also *T. officinale*, which was only studied in 2013, proved to be favoured by the no-tillage system since its emergence in simulated no-tillage conditions was 10 times higher than in the ploughed plot. *S. oleraceus* and *T. officinale* showed a distinct preference for undisturbed soil for seedling recruitment, as attested by several authors who noticed that these weed species are more problematic under reduced tillage system (Widderick et al., 2010; Chauhan et al., 2006b; Hamill, 1997; Blackshaw et al., 1994; Légère et al., 1993).

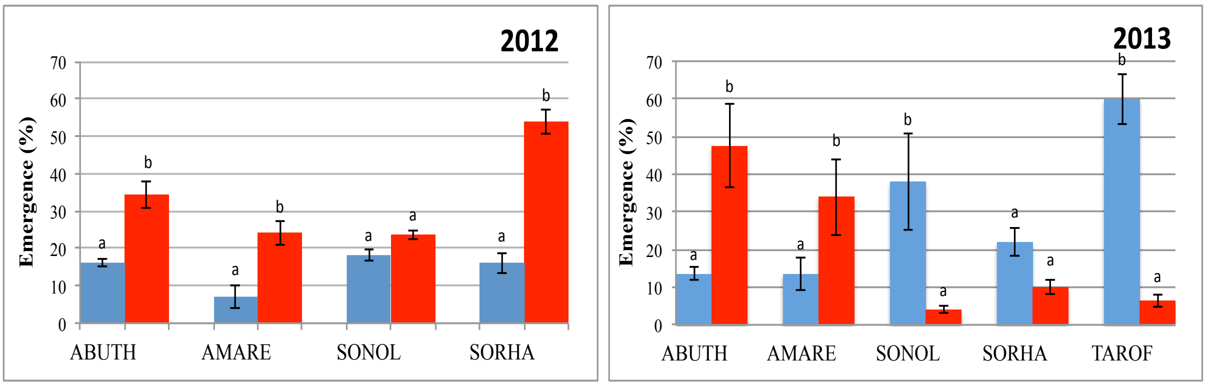

Figure 3:Effect of soil tillage on weed emergence percentage (mean ± SE). Different *letters* above bars indicate significant differences at 0.05 level with Tukey test. Red refers to conventional tillage and blue to no-tillage plots

The response for *S. halepense* in terms of emergence percentage was more complex in 2013 and there was no consistent trend evident between two types of soil treatment. Looking at climatic conditions it is clear that the two experimental seasons were characterized by very different weather regimes. Notably, the period of 2013 involved in the experiment was colder and wetter than the corresponding period in the previous year, which was closer to the typical climatic conditions of the site.

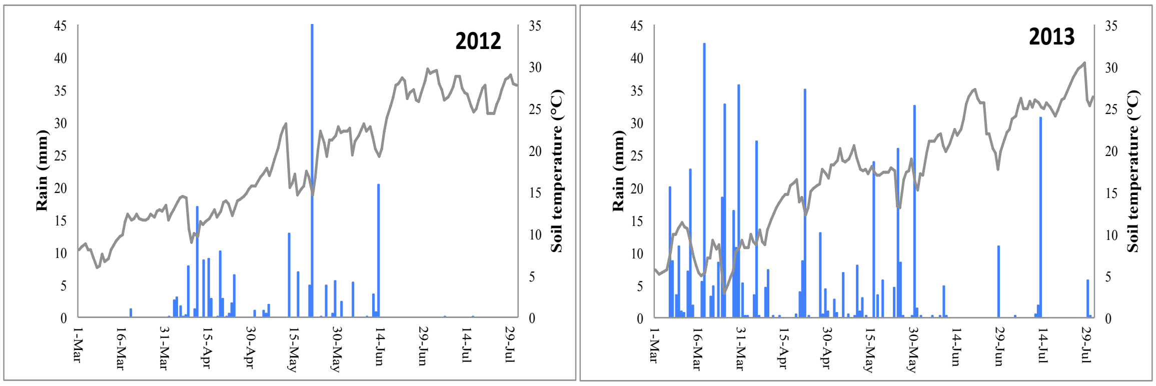

Figure 4: Soil temperature (°C) measured at 0 cm and rain (mm) in Legnaro in 2012 and 2013

These contrasting climatic conditions in the two years could explain such strange emergence behaviour of *S. halepense*. In fact seeds of *S. halepense* seem to be induced to break dormancy by several factors linked to environmental thermal conditions. Benech-Arnold et al. (1990) demonstrated that for this perennial weed species, release from dormancy is completed only after the seeds have been exposed to fluctuating temperatures and that the number of cycles and the average temperature of this thermal fluctuation plays an active role in favouring the germination process. In the present study, it is retained that a possible cause of the low emergence percentage could be related to the unusually low temperatures that occurred during the second year.

Effect of tillage on weed emergence dynamics

For this study it was chosen to compare weed dynamics in different tillage systems by the t50 parameter that is the point in time at which 50% emergence is reached. Tukey HSD test ($P < 0.05$) identified a significant difference only in *A. retroflexus* in 2012 and *S. halepense* in 2013 (table 1). Both species showed no significant difference in emergence dynamics in the other year's experiment. Observing the emergence dynamics in 2012 in figure 3, it is interesting to notice that the dynamics are overlapped throughout the whole emergence period, with the exception of *A. retroflexus*, which reached higher emergence percentage earlier in tilled soil, and *S. oleraceus*, which showed an earlier emergence only in the first phase of emergence (till 20%). In 2013, even if the t50 was reached on about the same date by all species (with the exception of *S. halepense*), weed emergence dynamics showed pauses of emergence in one tillage system which were not observed in the other, i.e. *A. theophrasti* had a brief pause of emergence between the end of May and beginning of June in no-tilled soil that was not observed in tilled soil, on the contrary *T. officinale* had a long pause in June in tilled soil that was not observed in no-tilled soil. Apparently, there is no easy explanation for this different behaviour of the various species in the two tillage systems. The only possible conclusion with the data available so far is that differences of emergence dynamics in the two years could be explained by the very different weather conditions in 2012 (warmer and drier) and 2013 (colder and wet). However, for a correct interpretation of these results, in addition to a different species requirement in terms of temperature and soil water potential for germination, it would be essential to know soil microclimate and seed-soil contact of seeds in the soil surface layer, and the effect of tillage on surface and near-surface conditions. A deeper knowledge of the modification of magnitude and fluctuation of temperature and soil water potential on the surface seems to be the first step for a better comprehension of germination-emergence in no-till system and for a future modelling of this important phase of the weed life. This issue is discussed in the next chapter of this thesis.

Table 1: mean time to 50% emergence with standard error for different treatments (T= tilled soil; NT= no-till soil) in 2012 and 2013. Letters identify significant differences among values of the same groups according to Tukey HSD test

2012					**2013**				
Species	Treatment	t50	St.er	Tukey	Species	Treatment	t50	St.er	Tukey
A. theophrasti	T	41.7	0.92	a	*A. theophrasti*	T	87.8	3.17	a
	NT	43.5	1.42	a		NT	93.9	8.89	a
A. retroflexus	T	44.3	1.32	a	*A. retroflexus*	T	99.4	1.52	a
	NT	55.9	4.31	b		NT	108.3	7.44	a
S. oleraceus	T	43.1	2.46	a	*S. oleraceus*	T	104.0	2.50	a
	NT	47.2	0.93	a		NT	104.7	3.71	a
S. halepense	T	49.4	0.55	a	*S. halepense*	T	100.0	5.02	a
	NT	51.5	0.60	a		NT	82.2	2.64	b
					T. officinale	T	99.0	6.19	a
						NT	95.9	1.98	a

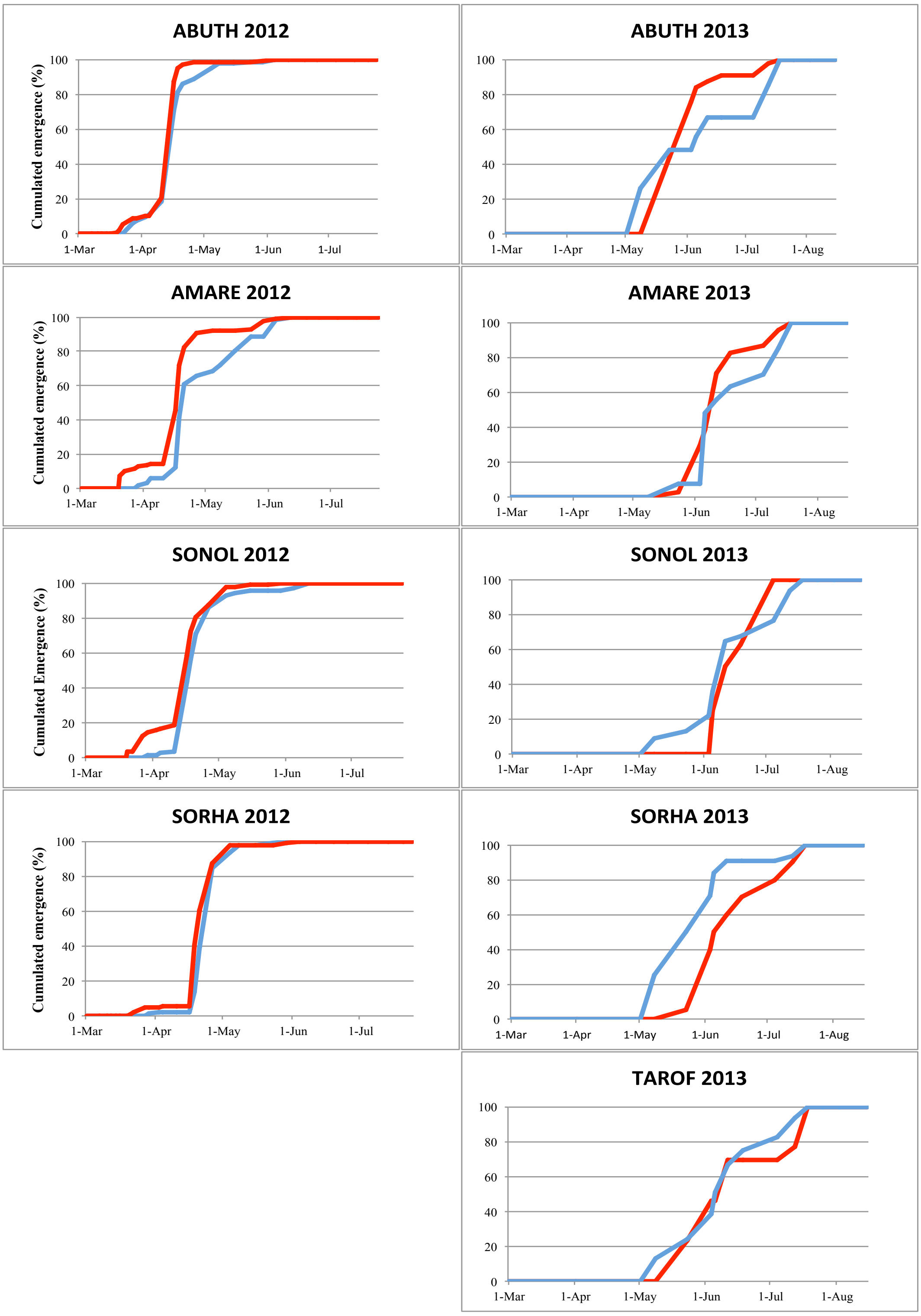

Figure 3: Emergence dynamics in two soil tillage systems in Legnaro in 2012 and 2013. Red refers to conventional tillage and blue to no tillage plots

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CHAPTER IV

Effect Of Soil Tillage System On Weed Species Composition And Emergence Dynamics In Field

Introduction

The type and timing of tillage practices influences the distribution of seeds in the soil profile and can act changing the dormancy status (Forcella et al., 1997). A reduction in tillage increases the amount of seeds on the soil surface (Hartzler et al., 2009; Chauhan et al., 2006; Swanton et al., 2000), where crop residues alter the soil microclimate and create a variety of conditions that affect weed germination pattern. In these systems, best known as conservation cropping systems, weed control is highly dependent on herbicides use since mechanical control is reduced or eliminated. In addition, the overuse of chemicals is imputed to be the cause of the rapid evolution of herbicide-resistant weeds and populations with multiple resistance. The need to reduce the dependence on agrochemicals in favour of more sustainable cropping systems has therefore challenged weed researchers to increase emphasis on alternative weed control methods and make those already available more effective, such as improving the timing of operations. Herbicides application can provide a high level of efficacy on weed control. The major cause of poor control is improper application timing, which may be either too early or too late with respect to the infestation density (Battla and Benech-Arnold, 2007). The timing of weed control operations is therefore crucial to their efficacy (Swanton and Murphy, 1996). Much effort has been made to predict the timing of key developmental stages of weeds as a means for maximizing the impact of management events aimed at their control (Holst et al., 2007). The availability of predictive tools for weed emergence will allow the optimization of herbicide application timing, and this is an increasingly important goal for environmental and economic reasons (Leguizamon et al., 2009) because it permits the amounts of chemicals used to be reduced. However to create an accurate predictive model for improving weed management, a better understanding of weed emergence behaviour in relation to cropping practices is required (Grundy et al., 2003; Vleeshouwers, 1997). It is important to keep in mind that the cropping system plays an important role in influencing weed flora and modifying its emergence pattern (Chauhan et al., 2012). The objective of this study was to assess the difference in weed flora in maize managed with conventional tillage and no-till and to analyse the difference in emergence dynamics in order to evaluate the possibility of developing a mathematical model of the emergence pattern in a no-till system.

Material and Methods

Field experiments were conducted from 2011 to 2013 in two experimental farms, SASSE (Rovigo) and DIANA (Treviso), in the northeastern Po Valley (northeast Italy). In each site and year, two field plots were managed under conventional and conservative farming practices: in the conventional system, seedbed preparation was done according to local practices consisting of primary tillage with autumn mouldboard ploughing and spring harrowing; in the conservative system, maize was directly sown without any tillage and with the previous crop residues remaining on the soil surface. Maize was sown on different dates from April to May in rows spaced 0.75 m apart, at a density of about 7.4 and 7.8 seed/m^2 for the conventional and conservative system, respectively. The crop was not irrigated.

Weed control strategy was similar for both systems and included pre-sowing application of glyphosate (400-600 g/ha of a.i. according to weed density and size) to clear the seedbed plus post-emergence application of foramsulfuron and dicamba (40-60 g/ha and 15-25 g/ha of a.i. respectively according to weed density and size). Inter-row soil cultivation was also performed in the conventional system. No post-emergence herbicide application or inter-row soil cultivation were performed on sampling areas in both systems. Weed emergence was monitored in each experiment in 11 fixed sampling areas (0.3 x 0.3 m) placed on the soil in the inter-row. Weed seedlings in these areas were counted, classified and removed about every 7 days until the end of the growing season. The emergence data obtained from each of the 11 areas were summed for each sampling date and cumulated to obtain the emergence dynamics. Daily precipitation and air temperature (2 m) were recorded by ARPA (Regional Environmental Protection Agency of Veneto) meteorological stations located near (less than 10 km) each experimental site.

Results and Discussion

Weed infestation

A total of 17 weed species were observed during the study (table 1). *Chenopodium album* had the highest relative abundance. In general weed infestation was very different among sites and years. Weed density over the course of the study was generally lower in no-till than in conventional maize. In the conventional system the species with higher density were: *Anagallis arvensis*, *Abutilon theophrasti*, *Digitaria sanguinalis*, *Echinochloa crus-galli*, and *Setaria viridis*. These species are all very common in conventional maize. Species with higher density in the conservative system were: *C. album*, *D. sanguinalis*, *Polygonum persicaria*, *Senecio vulgaris*, and *Sonchus* spp. It is interesting to note that the more abundant species in no-till system have small seeds, with the exception of *C. album*. Other research confirms that annual grass and wind-disseminated weeds tend to be favoured in reduced and zero-tilled systems; whereas non-wind-disseminated dicotyledonous annual species tend to be found in ploughed systems (Swanton et al., 1999; Tørrensen and Skuterud, 2002).

Table 1: Weed infestation in the field trials

	Conventional system					Conservative system				
	DIANA 2011	SASSE 2011	DIANA 2012	SASSE 2012	SASSE 2013	DIANA 2011	SASSE 2011	DIANA 2012	SASSE 2012	SASSE 2013
	plants/m^2					plants/m^2				
Anagallis arvensis	0,0	0,0	31,8	0,0	0,0	2,1	0,0	-	0,0	12,3
Abutilon theophrasti	3,1	0,0	2,1	7,2	18,5	0,0	0,0	-	5,1	0,0
Amaranthus retroflexus	2,1	3,1	1,0	1,0	0,0	0,0	0,0	-	0,0	31,8
Chenopodium album	1,0	18,5	23,6	5,1	9,2	0,0	7,2	-	6,2	1567,2
Cirsium arvense	0,0	0,0	0,0	6,2	0,0	0,0	0,0	-	0,0	0,0
Convolvulus arvensis	0,0	0,0	5,1	10,3	0,0	1,0	0,0	-	0,0	0,0
Cynodon dactylon	0,0	0,0	0,0	5,1	0,0	0,0	0,0	-	0,0	0,0
Digitaria sanguinalis	2,1	0,0	51,3	0,0	0,0	61,5	2,1	-	2,1	0,0
Echinocloa crus-galli	40,0	13,3	156,9	11,3	0,0	12,3	0,0	-	1,0	2,1
Polygonum aviculare	0,0	9,2	3,1	1,0	0,0	0,0	0,0	-	14,4	0,0
Polygonum persicaria	0,0	0,0	1,0	7,2	5,1	0,0	2,1	-	153,8	0,0
Portulaca oleracea	0,0	0,0	0,0	0,0	2,1	1,0	0,0	-	2,1	6,2
Senecio vulgaris	0,0	0,0	0,0	0,0	0,0	24,6	0,0	-	5,1	90,3
Setaria viridis	0,0	1,0	37,9	0,0	0,0	0,0	0,0	-	0,0	1,0
Solanum nigrum	5,1	2,1	0,0	1,0	0,0	0,0	0,0	-	0,0	0,0
Sonchus sp.	0,0	8,2	3,1	0,0	0,0	28,7	155,9	-	35,9	47,2
Sorghum halepense	0,0	0,0	5,1	10,3	0,0	0,0	0,0	-	9,2	0,0

- data not available

From comparison of the emergence dynamics in conventional and conservative systems (figure 1), no difference was observed in *Sonchus* spp. dynamics expressed as percentage normalized to 100, even if their density was very different between tillage systems: just 8 plants/m^2 in conventional maize and 152 plants/m^2 in no-tilled maize. In this study, the presence of *P. persicaria* also resulted as higher in the no-till system. It is evident that caution must be exercised in asserting that this species is advantaged by a no-till system, because this result is due only to the field considered in this comparison (Sasse 2012) and, in general, because there are too few data in this study to make this assertion (table 1). The dynamics expressed as percentage are very similar between the two tillage systems, even if in conventional tilled maize the initial emergence more quickly reaches a higher percentage. *C. album* is a common weed species in conventional maize in Italy, nevertheless in this study it was also found with very high density in no-tilled maize, in particular in Sasse 2013 (table 1). In the comparison between emergence dynamics in conventional and no-till systems, the emergence of this species was favoured by tillage that determined an earlier emergence in the first phases, until reaching 50%, when the two dynamics became overlapped. Observing the rainfall conditions during the experimental period (figure 2), it seems evident that the initial emergence of *Sonchus* spp. in 2011, in both tilled and no-tilled maize, was a consequence of the rainfall on 15 May that probably created adequate soil water availability for the germination-emergence of this species. *C. album* emergence in no-till system may also have been induced by the rainfall of 15 May, but the same was not observed in the conventional system. Indeed, in tilled soil the emergence of *C. album* started with the rainfall at the beginning of May. A possible explanation for this is that in the no-till system rainfall infiltrates less into the soil and subsequent soil drying is faster than in tilled soil, especially after a scarce amount of rainfall, therefore seeds on the soil surface may not imbibe sufficient water to germinate. It is also important to underline that seeds located on the soil surface have a reduced seed-soil contact and therefore even if the underlying soil has sufficient water potential for germination of seeds in the soil, soil water potential is lower adjacent to the seed on the soil surface (Bullied et al., 2012).

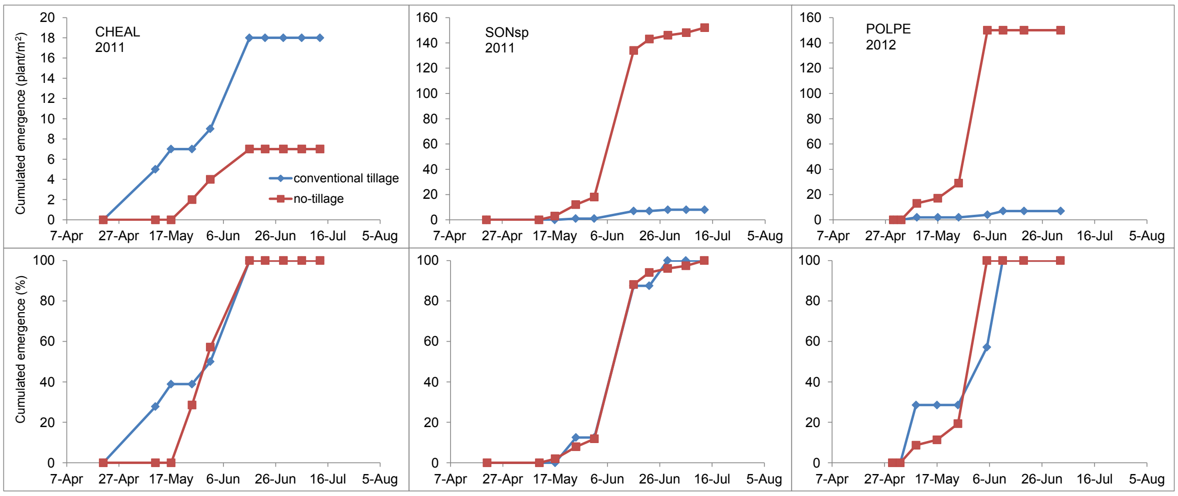

Figure 1: Cumulated emergence of *C. album*, *Sonchus* spp. and *P. persicaria* in conventional tillage and no-till in Sasse 2011 and 2012

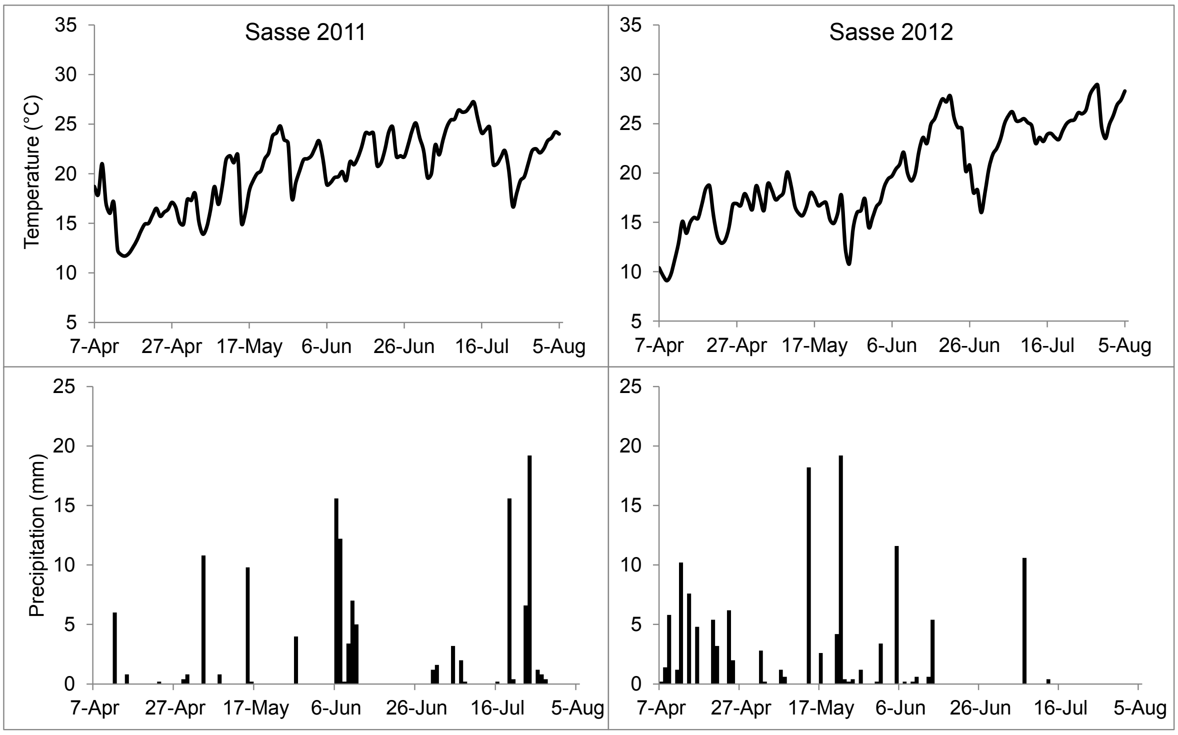

Figure 2: Daily air temperature and precipitation in Sasse in 2011 and 2012

The results from this research showed that weed infestation in no-till and conventional crops can be very different in terms of quality (species) and quantity (density). In the no-till system a reduction was observed of the typical weeds in conventional maize, such as *A. theoprasti*, *E. crus-galli* and *S. viridis*. However, potential problems from other wind-dispersed weeds such as *Sonchus* spp. and *S. vulgaris* seem to appear. However, not enough data were collected in this study to determine a level of association of a weed species with a tillage or cropping system, further research is required to evaluate this association.

Emergence dynamics differed in the first part of the emergence curve (till 50%) between conventional and no-till systems for common species of tilled soil, while *Sonchus* spp. showed a very similar emergence pattern in both systems. These findings are very important for a future modelling and prediction of weed emergence in a no-till system. When soil is not tilled, seeds remain on the surface and it is fundamental to use microclimate characteristics of the soil surface for modelling weed emergence. This seems to be the most important problem to be solved. As stated in chapter II, soil microclimate near the surface is the most difficult to monitor and model. Under the no-till system, it is also important to understand the influence of the crop residues on variations in the temperature of the upper soil layer. In any case, the capacity to predict the onset and pattern of seedling emergence is a powerful tool to optimize the schedule for herbicide spraying operations. From the point of view of crop-weed interactions, the duration of the emergence period may have important consequences for the duration of the competitive period. Using a weed emergence predictive model in no-till systems to refine weed control tactics is very important to improve weed control, but also to avoid a build-up of the weed seedbank.

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CHAPTER V

Evaluation of Weed Emergence Model AlertInf for Maize in Soybean[*]

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[*] This chapter has been accepted as:
Evaluation of Weed Emergence Model AlertInf for Maize in Soybean
Masin R, Loddo D, Gasparini V, Otto S, Zanin G. *Weed Science* accepted on 12th January '14

Abstract

AlertInf is a recently developed model to predict the daily emergence of three important weed species in maize cropped in Northern Italy (common lambsquarters, johnsongrass, and velvetleaf). Its use can improve the effectiveness and sustainability of weed control, and there has been growing interest from farmers and advisors. However, there were two important limits to its use: the low number of weed species included and its applicability only to maize. Consequently, the aim of this study was to expand the AlertInf weed list and extend its use to soybean. The first objective was to add another two important weed species for spring-summer crops in Italy, barnyardgrass and large crabgrass. Given that maize and soybean have different canopy architectures that can influence the inter-row microclimate, the second objective was to compare weed emergence in maize and soybean sown on the same date. The third objective was to evaluate if AlertInf was transferable to soybean without recalibration, thus saving time and money. Results showed that predictions made by AlertInf for all five species simulated in soybean were satisfactory, as shown by the high EF values, and acceptable from a practical point of view. The fact that the algorithm used for estimating weed emergence in maize was also efficient for soybean, at least for crops grown in north-eastern Italy with standard cultural practices, encourages further development of AlertInf and the spread of its use.

Nomenclature: common lambsquarters, *Chenopodium album* L., CHEAL; barnyardgrass, *Echinochloa crus-galli* (L.) Beauv., ECHCG; johnsongrass, *Sorghum halepense* (L.) Pers, SORHA; large crabgrass, *Digitaria sanguinalis* (L.) Scop., DIGSA; velvetleaf, *Abutilon theophrasti* Medik., ABUTH; maize, *Zea mays* L.; soybean, *Glycine max* (L.) Merr.

Key words: Hydrothermal time, modeling, predicting weed emergence dynamics, weed control.

Introduction

Knowledge on the emergence pattern of the main weed species in a crop is critical for devising weed control plans. Since the timing of weed emergence relative to that of the crop strongly influences crop-weed competition, information on weed emergence dynamics can be used to optimize the removal strategies to avoid yield losses (Benjamin et al., 2010; Grundy, 2003). The importance of knowing and predicting weed emergence has been recognized for many years and several studies have been conducted to model weed emergence (Colbach et al., 2007; Dorado et al., 2009; Myers et al., 2004). The introduction of such models in decision support programs can reduce herbicide use and weed control costs compared with standard management practices (Forcella et al., 2000). A proper timing of weed control is particularly important given the increasing frequency of post-emergence control in maize and especially in soybean. These models provide the percentage of cumulated emergence reached every day by weed species and this information can be used by the farmers to select the best timing of mechanical or chemical control (Alvarado and Bradford 2002; Archer et al., 2001; Chantre et al., 2012; Masin et al., 2011). AlertInf (Masin et al., 2012) is one of these weed emergence predictive models, and was recently developed for three important weed species in Italian maize fields: common lambsquarters, johnsongrass and velvetleaf. The model is based on the hydrothermal time concept (Bradford, 2002; Gummerson, 1986), in which the combination of soil temperature and soil water potential is the main factor driving germination and emergence processes. In order to evaluate the interest in and use of the model by farmers and advisors, a simplified version of AlertInf (that uses rainfall instead of soil water potential) has been made available on the website of the ARPAV Agrobiometeorology Unit (www.arpa.veneto.it) (Masin et al., 2010a). The high number of recorded visits to the model webpage (about 2000 hits during the 2010 growing season) suggested a positive response of the users. Nonetheless, one of the limits to its use is the low number of weed species included. In fact the higher the number of simulated species, the more information is provided by the model on the total field infestation present in the field, making the model more flexible and useful for the farmers. Consequently, it is of great interest to extend the weed species list. Modeling the emergence dynamics of selected species using AlertInf requires many years of emergence observations in the field to estimate the parameters of the model equation (i.e. a Gompertz function) and laboratory experiments to estimate the germination threshold parameters (base temperature and base water potential for seed germination) for each species or, more properly, for each ecotype, needed to calculate the hydrothermal time. Studies on threshold parameters for germination reported very different values for populations of the same species growing in diverse geographic locations, showing that the thresholds may differ among ecotypes (Forcella et al., 2000; Gardarin et al., 2010; Loddo et al., 2013; Steinmaus et al., 2000). Nevertheless a recent study (Masin et al., 2010b) reported that threshold parameters did not differ between two ecotypes of various weed species collected in two extreme regions of the main maize-growing area in Italy. The same values may therefore be adopted for these parameters throughout the Italian maize-growing area without estimating specific thresholds for each ecotype. This conclusion was of some importance because the laboratory experiments to obtain the threshold parameters are very time and resources consuming. Since the main weed species in maize are also common in other summer crops in Italy, the same threshold parameters for weed germination can be applied. But crops have different spatial arrangements, plant development, canopy structure and cultural practices, and this may affect weed recruitment, development and competition with the crop differently (Baumann et al., 2001; Hock et al., 2005; Knezevic et al., 2002; Mohler, 1996; Sweeney et al., 2008). Emergence of weeds may be somewhat inhibited as a crop canopy expands and as the growing season progresses because of the changing of the underlying soil microclimate (Forcella et al., 2000). The main factors are soil temperature, soil water potential, and light quality (Norsworthy, 2004). Even if the use of hydrothermal time in the models accounts for the differences in the soil temperature and soil water potential, soil thermal amplitude and light quality have effects which are difficult to consider in models, also because they are not well understood (Forcella et al., 2000) and very variable among weed species. In fact, studies on effects of light and diurnal temperature fluctuations on seed germination reported that these parameters inhibit the germination of some species and are ineffective, or sometimes even a stimulant, on others (Batlla et al., 2000; Huarte and Benech Arnold, 2003; LeBlanc et al., 2002). As a consequence, it is necessary to conduct specific experiments in order to determine whether weed emergence dynamics are the same in different crops and, if so, to recalibrate the model for each crop.

The aim of this study was to improve and generalize AlertInf use by fulfilling three objectives. Given that the last version of AlertInf included three weed species (common lambsquarters, johnsongrass, velvetleaf), the first objective of this study was to add another two important species for maize in Italy, barnyardgrass and large crabgrass, by calculating the biological parameters required by the model (model extension). In Italy maize and soybean grow in the late spring-summer, but maize is traditionally sown about one month before soybean (in April and in May, respectively). In addition, as reported by Vina et al. (2011), the two crops have contrasting canopy architectures (spherical vs. planophile leaf angle distribution) and leaf structures (monocotyledon vs. dicotyledon). Taking these facts into consideration, the second objective of the study was to compare weed emergence in maize and soybean sown on the same date between late April and mid-May (comparison of weed emergence). According to the results of the comparison experiments, the hypothesis was advanced that weeds have the same emergence dynamics in maize and soybean, and consequently the third objective was to evaluate if AlertInf, created for weed species in maize, was transferable to soybean without recalibration, saving time and money (model validation).

Material and Methods

Model extension for barnyardgrass and large crabgrass in maize

Field experiments were conducted from 2005 to 2012 in three localities in the northeastern Po Valley (northeast Italy): at Montemerlo (2005), Carbonara (2007 and 2012) and Legnaro (from 2006 to 2010 and 2012) (Table 1, extension dataset in maize) in different soil types (Table 2). The sites are less than 50 km apart and have almost the same sub-humid climatic conditions. Average annual temperature of the area is 12.2 °C, with temperature increases from January (average minimum: − 1.5 °C) to July (average maximum: 27.2 °C). Annual rainfall is about 850 mm and uniformly distributed throughout the year. In all the experimental sites, seedbed preparation was done according to local practices: primary tillage consisted of fall moldboard plowing and spring harrowing. Maize was sown on different dates from March to May in rows spaced 0.75 m apart. The crop was irrigated if required to avoid yield losses (irrigation timing and amounts were considered in the model). Weed emergence was monitored in each experiment in 33 fixed sampling areas (0.3 x 0.3 m) placed at random in the inter-rows (avoiding passing tractor wheels) in an area of the field of about 500 m^2. Weed seedlings in these areas were counted, classified and removed every 4-6 days until the end of the growing season. The emergence data obtained from each of the 33 areas were summed for each sampling date and cumulated to obtain the emergence dynamics.

The emergence data were used to estimate the parameters of the AlertInf equations for barnyardgrass and large crabgrass. AlertInf simulates emergence dynamics as a function of hydrothermal time (HT). There are various methods to calculate the HT. In AlertInf, it is considered that all species accumulate HT in proportion to soil temperature only when soil water potential is above a base value. This base value of water potential increases linearly as soil temperature rises above the optimum temperature until it reaches 0 MPa at a temperature defined as the ceiling temperature. HT is calculated as a combination of soil temperature and soil water potential, as follows:

$$HT_i = n * \max(Ts_i - Tb, 0) + HT_{i-1} \qquad [1]$$

when $Ts_i < To$: $n = 0$ if $\Psi s_i \leq \Psi b$, $n = 1$ if $\Psi s_i > \Psi b$; and when $Ts_i > To$: $n = 0$ if $\Psi s_i \leq \Psi b + Kt\ (Ts_i - To)$, $n = 1$ if $\Psi s_i > \Psi b + Kt\ (Ts_i - To)$; Ts_i and Ψs_i are the average daily soil temperature and water potential at 5 cm depth, Tb and Ψb are the base temperature and base water potential, To is the optimum temperature and Kt is the slope of the relationship between Ψb and Ts_i in the supra-optimal temperature range. Base thresholds of barnyardgrass and large crabgrass had been calculated in previous laboratory experiments (Table 3) (for details see Masin et al. (2010b)). Accumulation of HT starts from the spring tillage date for seedbed preparation. Percentage of seedling emergence (cumulated and normalized to 100%) (CE) is expressed by a Gompertz function, as follows:

$$CE_i = 100 \exp(-a \exp(-b\ HT_i)) \qquad [2]$$

where a is related to an HT lag before emergence starts, and b is related to the slope of the curve. The values of To and Kt were estimated by systematically varying in an iterative fashion until the best simulations were obtained for barnyardgrass and large crabgrass. Hydrothermal time was recalculated for different values of To and at first with Kt = 0; Kt was then varied incrementally to find the combination between the values of Kt and To giving the least squares best fit.

The calculation of HT used the daily average values of soil temperature and soil water potential, which were monitored in all years at Legnaro. Temperature was measured using four HOBO mini loggers (Pendant data logger HOBO UA-001-08, Onset Computer Corporation, Bourne, MA) buried 5 and 10 cm deep. Soil water potential was monitored using water moisture probes (253-L Watermark Soil Matric Potential, Campbell Scientific Inc., Shepshed, UK) buried at a depth of 5 cm and connected to an external data logger (External data logger HOBO 4-Channel U12-008, Onset Computer Corporation, Bourne, MA). The data logger readings of soil temperature and water potential were taken every 2 hours. In the sites where the soil microclimate was not directly measured (Montemerlo 2005 and Carbonara 2007), the Soil Temperature and Moisture model (STM^2) (Spokas et al., 2007) was used to simulate soil temperature and water potential at a depth of 5 cm (Masin et al., 2012), using daily precipitation and air temperature recorded by ARPA (Regional Environmental Protection Agency of Veneto) meteorological stations located near (less than 5 km) each experimental site. The STM^2 model has already been effectively used for the simulation of soil microclimate within the seedling recruitment zone in experimental sites for the simulation of other weed species emergence in AlertInf (Masin et al., 2012), moreover Royo-Esnal et al., (2010) and Spokas and Forcella (2009) have successfully used this model to predict the soil environment for weed emergence modeling and other applications. AlertInf performance in predicting weed emergence was evaluated with an efficiency index (EF) (Loague and Green 1991), calculated as:

$$EF = \frac{\sum_{i=1}^{n}(O_i - \overline{O})^2 - \sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2} \qquad [3]$$

where P_i is the predicted value, O_i the observed value, and $\bar{O}$ the mean of observed values. EF ranges from 1 to negative value. An EF=1 indicates exact predictions, while EF=0 indicates a model of poor fit where the average value would model the relationship as well. An efficiency of lower than zero indicates that the mean value of the observed values would have been a better predictor than the model. Nevertheless, Ramanarayanan et al., (1997) suggested 0.5 as the lower range value for acceptable model prediction. Parameters of AlertInf for barnyardgrass and large crabgrass in maize (extension dataset in maize) are in Table 3.

Comparison of weed emergence in maize and soybean

In order to compare weed emergence under different canopy conditions, emergence dynamics of the five weed species simulated by AlertInf were studied in experiments where maize and soybean were sown in contiguous plots on the same date in each site (Table 1). The experiments were conducted in 2012 at Carbonara, Albettone and Pozzoveggiani. The three sites are 20-30 km from Padova and have different soil types (Table 2). The experiments followed the same method as described above for the model extension in maize. For soil preparation, conventional tillage was used on both maize and soybean, consisting of fall moldboard plowing and spring harrowing. Crops were sown from late April to mid-May. Maize was sown with the same inter-row as in the experiments for model extension, while soybean was sown in rows spaced 0.45 m apart. Nitrogen fertilizer was applied only in maize at rates of 200 kg/ha of urea nitrogen. Daily average values of soil temperature and soil water potential were recorded at a depth of 5 cm during the crop growing season. Weed emergence was monitored using fixed sampling areas (0.3 x 0.3 m) placed on the soil in the inter-row, as described above. The emergence data obtained from these three experiments were used to compare the emergence dynamics of the five species simulated by AlertInf in maize and in soybean.

Model validation with independent dataset in soybean

In order to verify the transferability of the model from maize to soybean, four experiments were conducted in Carbonara (2012) and Legnaro (2011-2012) in soybean fields with sowing dates ranging from April 19th to May 20th (Table 1, validation dataset in soybean). Weed emergence dynamics of the five weed species simulated by AlertInf were monitored as previously described for the other experiments (extension dataset and comparison dataset).
The daily average values of soil temperature and soil water potential were recorded in all the experiments. To verify if the same biological parameters (Tb, To, Ψb and Kt) and Gompertz coefficients (a and b) estimated in maize were usable in soybean, emergence percentage of the

five weed species for all experiments was simulated using AlertInf and the predictions were compared with observations. Overall AlertInf performance was evaluated using EF and the mean bias error (MBE) (Willmott, 1982). The MBE is related to magnitude of values under investigation and is an indication of the average deviation of the predicted from the observed values. It is calculated as:

$$\mathrm{MBE} = \frac{1}{N}\sum_{i=1}^{N}(P_i - O_i) \qquad [4]$$

Where N is the number of observations. When the model, on average, underestimates the observed values, MBE is negative; otherwise, it is positive (Wallach, 2006). For a detailed predicted vs. observed analysis, linear regression and correlation analyses (Pearson's r and Spearman Correlation) were performed (StatSoft Inc. 2011) and a graphical comparison was also used to identify general agreement and trends.

Results and Discussion

Model extension for barnyardgrass and large crabgrass in maize

The densities of barnyardgrass and large crabgrass in the sites used for the emergence model extension were very different among experiments (Table 1, extension dataset). Large crabgrass density ranged from 7.3 p m^{-2} in Legnaro 2009 to 135.4 p m^{-2} in Legnaro 2007b, while the highest density observed for barnyardgrass was 56.6 p m^{-2}. These data were used to estimate the optimal temperature for emergence of the two species. The optimal temperatures resulted as 26 and 29 °C for barnyardgrass and large crabgrass, respectively (Table 3). Barnyardgrass seeds germinate over a wide range of temperatures, and many different optimal temperatures have been reported for this species in the literature: a range between 20 and 30 °C was reported by Rahman and Ungar (1990) and Shipley and Parent (1991), therefore in agreement with the result of the present study, while Manidool (1992) reported a higher optimum germination temperature range of 32-37 °C. The value estimated for large crabgrass was in agreement with that reported by Zhang et al. (2012), who observed the best germination performance between 25 and 30 °C. The model adequately described the cumulated emergence in the experiments used for its extension as shown by the high EF values of the simulation (0.91 and 0.96 for barnyardgrass and large crabgrass, respectively) (Table 3).

Comparison of weed emergence in maize and soybean

The densities of velvetleaf in the comparison experiments was unfortunately too low in all sites to compare the emergence dynamics in maize and soybean. Therefore only the results for barnyardgrass (in Albettone), large crabgrass (in Albettone), common lambsquarters (in Pozzoveggiani) and johnsongrass (in Carbonara) can be used for comparison (Table 1, comparison dataset in maize and soybean). Results show that the observed emergence dynamics of these four weeds in maize and soybean are very similar (Fig. 1) and not affected by the crop canopy differences when the two crops were sown on the same date and standard cultural practices followed. This supported the hypothesis that AlertInf could be directly used to simulate weed emergence in soybean without recalibration.

Model validation with independent dataset in soybean

The simulations of emergence of the five species in soybean performed using AlertInf developed in maize (validation dataset) were in general accurate, with EF index ranging from 0.93 to 0.99 for the single experiments and observed vs. predicted correlations always highly significant (Table 4, Fig. 2). Even if velvetleaf was not found in the maize-soybean comparison experiments (see comparison dataset in Table 1), it is interesting to see that the simulation of this species was satisfactory, as shown by the high EF values (from 0.95 to 0.98). From the graphs (Fig. 3), it can be observed that the real emergence of velvetleaf in Legnaro 2011 second sowing date started 8-9 days later than the simulated emergence. This inaccuracy was observed for all other weed species in this site and year, i.e. barnyardgrass and large crabgrass. It seems that weeds have suffered a soil water potential below the threshold for germination, while that recorded by the moisture probes was higher, which was likely not representative of the soil water potential of the sampled areas. This could be explained by the necessity to wet the soil when the probes are installed (instruction manual of 253-L Soil Matric Potential Sensors, http://s.campbellsci.com/documents/ca/manuals/253_257_man.pdf).

The consequence was that in the days soon after the soil preparation for sowing an incorrect measure of the soil water potential was recorded.

AlertInf simulation of johnsongrass emergence in soybean was very satisfactory (EF of 0.99) in Legnaro 2012, while in Carbonara 2012 the model underestimated the beginning of emergence and overestimated the emergence by over 50%. In particular, it seemed that the real emergence pattern was slower with a lower slope. Nevertheless, following the model simulation, the percentage of emergence is estimated only some days in advance, with a maximum of 4 days earlier on 24th May, it cannot be considered a relevant error for the practical use of the information provided by the model. Furthermore it is interesting to note that this inaccurate estimation cannot be imputed to application in soybean of a model developed in maize, because the pattern of weed emergence in maize in Carbonara 2012, was very similar to that in soybean, with observations almost overlapped (Fig. 3, fourth graph).

The most relevant errors (more than 5 days shift) were in the simulation of common lambsquarters and large crabgrass in Legnaro 2012. For common lambsquarters, AlertInf estimated a cumulated emergence of 68% six days before the real emergence accumulation. This error could be relevant from a practical point of view since it could lead to a too early timing for post-emergence control and consequently a consistent part of weed seedlings would emerge later and escape the treatment. For large crabgrass, AlertInf estimated a cumulated emergence of 80% nine days after the real emergence accumulation, which at that time actually reached more than 90% of total emergence. However, even if the error is bigger than that of common lambsquarters, it is less important from a practical point of view. In fact when the estimation error is at high percentage of emergence (i.e. late in the season) it should not affect the timing of weed control suggested by the model, which is supposed to be done when emergence percentage is around 70% (Otto et al., 2009).

In conclusion, even if simulations were not completely accurate, emergence prediction made by AlertInf for all five species was satisfactory in all sites considered for the validation and, except for just two cases, acceptable also for practical purposes. This means that, even in crops such as maize and soybean, with contrasting leaf structure and canopy architecture, and different agronomic practices, the algorithm for weed emergence estimation used by AlertInf did not require recalibration of parameters, at least for crops grown in Veneto with standard cultural practices. These findings are very important considering that recalibration of AlertInf to simulate weed emergence dynamics in soybean would require many field experiments, in different years and localities, for each weed species. Similar results were reported by Nyamusamba et al. (2008), who conducted experiments with an analogous purpose to this study. They found that the time required for common lambsquarters (as well as for redroot pigweed and green foxtail) to reach 50% and 90% of emergence was comparable among crop species (including maize and soybean) and concluded that the same hydrothermal coefficients were adequate to predict weed emergence in several crops.

The recalibration from maize to soybean is likely not necessary because most weed species complete emergence before the different crop canopy characteristics can influence the inter-row microclimate enough to change the processes of soil heating and water transfer in the seedling recruitment zone. This encourages further development of AlertInf and further studies to test its transferability to other climates and crops (e.g. sunflower or sugarbeet).

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Attachments

Table 1: Observed densities (p m^{-2}) of the five species considered by AlertInf in all the experiments, in maize (M) and soybean (S)

	Experiments: datasets, crops and sites	Sowing date	ABUTH	CHEAL	DIGSA	ECHCG	SORHA
Extension dataset in maize	Montemerlo 2005	March 13th			-	11.1	
	Carbonara 2007	March 14th			-	17	
	Carbonara 2012	April 26th			-	23.3	
	Legnaro 2006a	April 13th			-	52.5	
	Legnaro 2006b	April 13th			-	56.6	
	Legnaro 2007a	March 22nd			127.2	-	
	Legnaro 2007b	May 11th			135.4	-	
	Legnaro 2008	April 28th			18.9	-	
	Legnaro 2009	May 12th			7.3	12	
	Legnaro 2010	April 13th			21.2	-	
	Legnaro 2012	May 3rd			56	33	

	Experiments: datasets, crops and sites	Sowing date	ABUTH	CHEAL	DIGSA	ECHCG	SORHA
Comparison dataset in maize and soybean	Albettone 2012, maize	April 26th			66.7	250	
	Albettone 2012, soybean	April 26th			61.1	236.1	
	Carbonara 2012, maize	April 26th					458.3
	Carbonara 2012, soybean	April 26th					397.2
	Pozzoveggiani 2012, maize	May 4th		13			
	Pozzoveggiani 2012, soybean	May 4th		11			

	Experiments: datasets, crops and sites	Sowing date	ABUTH	CHEAL	DIGSA	ECHCG	SORHA
Validation dataset in soybean	Carbonara 2012	April 26th					397.2
	Legnaro 2011	May 5th	7.7				
	Legnaro 2011	May 20th	8		60	73.3	
	Legnaro 2012	April 19th	9	15.5	110	75.5	35

Table 2: Main soil characteristics of the experimental sites

Description	Unit	Albettone	Carbonara	Legnaro	Montemerlo	Pozzo-veggiani
Sand	%	34	28	16	21	17
Silt	%	42	45	65	36	61
Clay	%	24	27	19	43	22
Texture (U.S.D.A.)	class	L	CL	SL	C	SL
pH	unit	8	7.61	8.04	7.2	8.06
O.M.	%	2.1	2	1.8	2.7	2.5
C.E.C.	meq/100g	17.8	20.4	14.8	22.4	14.2

L = loam; C = clay, CL = clay loam; SL = silt loam

Table 3: Model creation and AlertInf performance for barnyardgrass and large crabgrass in maize (extension dataset in maize): biological parameters (Tb, To, Ψb and Kt) for the calculation of the hydrothermal time (Tb and Ψb estimated by Masin et al. (2010b)), Gompertz coefficients (a and b) for modeling the cumulated emergence, and model efficiency (EF)

Species	**Tb** (°C)	**To** (°C)	**Ψb** (MPa)	**Kt** (slope)	**Gompertz coeff.** a	b	**EF**
DIGSA	10.3	29	-0.74	0.1	6.49	0.01	0.96
ECHCG	11.7	26	-0.97	0.1	4.17	0.02	0.91

Table 4: AlertInf performance for the validation dataset in soybean for the five weed species: model efficiency (EF), mean bias error (MBE), Pearson's r and Spearman rank order correlation of the observed and predicted cumulated emergence

Experiment	Statistic	ABUTH	DIGSA	CHEAL	ECHCG	SORHA
Carbonara 2012	N. of paired data					11
	EF					0.97
	MBE					1.02
	Pearson's r					0.99
	Spearman corr.					0.99
Legnaro 2011 first sowing	N. of paired data	15				
	EF	0.95				
	MBE	1.5				
	Pearson's r	0.98				
	Spearman corr.	0.77				
Legnaro 2011 second sowing	N. of paired data	13	13		13	
	EF	0.97	0.98		0.93	
	MBE	1.2	-1.1		-2.13	
	Pearson's r	0.98	0.99		0.97	
	Spearman corr.	0.81	0.95		0.98	
Legnaro 2012	N. of paired data	11	17	17	17	17
	EF	0.98	0.97	0.96	0.99	0.99
	MBE	-2.88	-3.02	3.09	1.61	1.35
	Pearson's r	0.99	0.98	0.98	0.99	0.99
	Spearman corr.	0.86	0.98	0.89	0.98	0.89
All experiments	N. of paired data	39	30	17	30	28
	EF	0.97	0.97	0.96	0.96	0.98
	MBE	0.17	-1.9	3.09	-0.01	1.22
	Pearson's r	0.98	0.98	0.98	0.98	0.99
	Spearman corr.	0.8	0.95	0.89	0.91	0.94
All experiments and weeds	N. of paired data	144				
	EF	0.97				
	MBE	0.06				
	Pearson's r	0.98				
	Spearman corr.	0.89				

Figure 1: Observed cumulated weed emergence for four weed species in maize (triangles) and soybean (black circles) sown on the same date in each site: Pozzoveggiani May 4th (CHEAL), Albettone April 26th (DIGSA and ECHCG), Carbonara April 26th (SORHA) (comparison dataset)

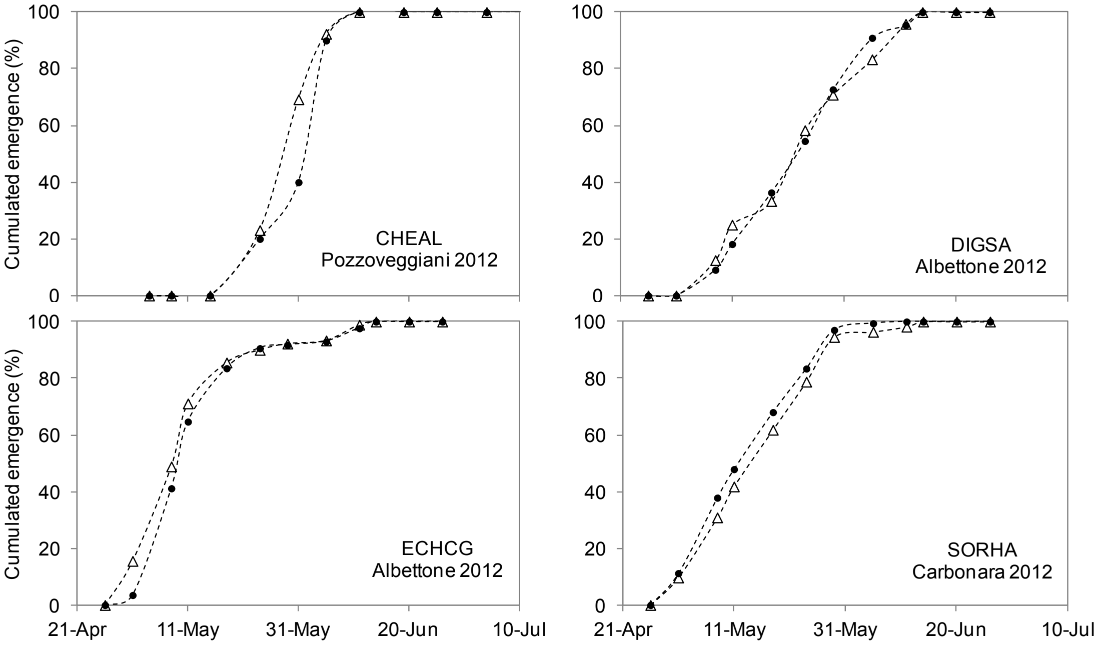


Figure 2: Predicted vs. observed weed cumulated emergence (%) for the five weed species in soybean performed using AlertInf developed in maize (validation dataset). Linear regression line and 95% confidence bands are indicated

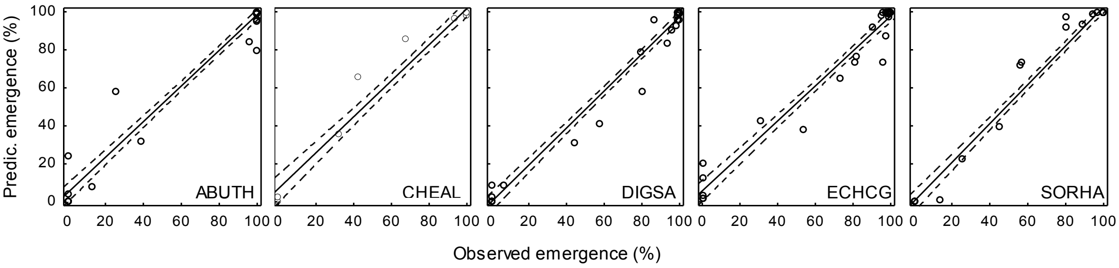
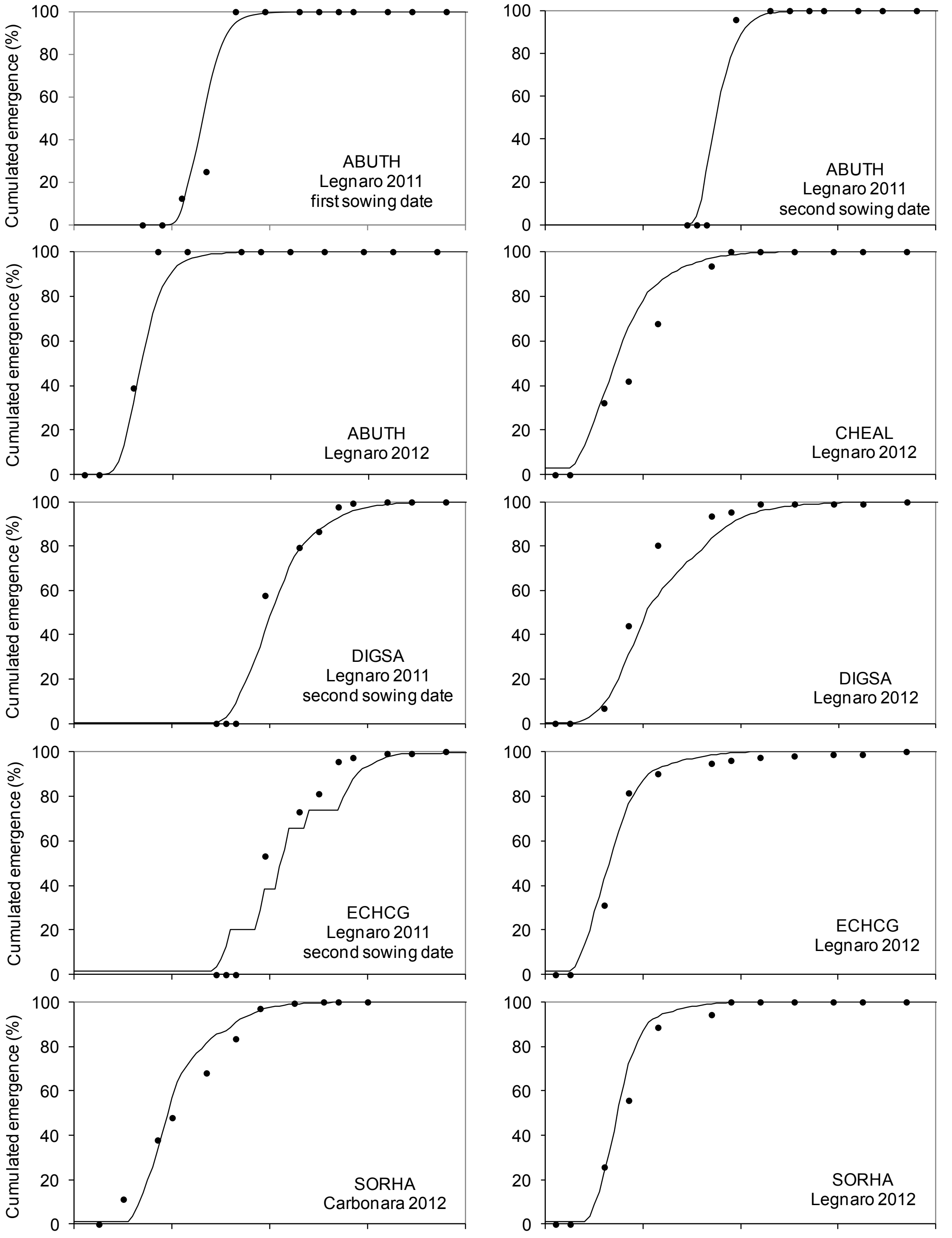


Figure 3: Cumulated weed emergence estimated using AlertInf developed in maize (solid line) and emergence observations (black circles) in soybean of the five weed species in the four experiments conducted in 2011-2012 (validation dataset)



General Conclusions

It is more than ever necessary to detect, in the agricultural sector, sustainable production systems from an economic and environmental point of view. In this sense conservation agriculture seems to match the objectives of sustainability advocated by the farmers on one hand and by public conscience on the other, since it gives the possibility of reducing production costs, time, labour and mechanized systems and has been found to increase quality of crop yields, improve soil fertility and produce environmental benefits. Conservation tillage, which represents a part of the wider conservation agricultural system, has been considered as a means of preventing erosion and maintaining desirable soil properties, an aspect that would certainly have a positive impact on crop production since this depends critically on the quality of the substrate, but at the same time tillage has traditionally been an important component of weed control. The reduction or absence of tillage from crop production systems affects weed management, which results as more complex in conservation agricultural regimes and represents a major deterrent to the adoption of reduced tillage techniques by farmers. This difficulty is due mainly to the changes in weed flora composition with respect to conventional tilled fields. In this sense, the analysis of weeds tending to develop in undisturbed cropping fields is necessary, but, since the time scale for observing significant changes in patterns of species composition is very extensive, long-term studies are desirable. Therefore the study conducted for this thesis on characterization of weed flora composition in no-till system must be considered just a beginning for further research. The possibility of detecting common traits of weed species preferring conservation agricultural systems, allows the most problematic weed species in such systems to be identified and focus the studies on their germination-emergence phase, one of the main important processes of the species lifecycle that strongly influences weed management. In this thesis biological parameters involved in the process of germination and emergence dynamics were analysed for the species more frequently observed in no-till systems, such as *Taraxacum officinale*, *Senecio vulgaris*, *Sonchus oleraceus* and the *genus Conyza*. Another critical point ascribable to the absence of tillage in conservation systems regards weed density, which tends to increase in the absence of mechanical control. In order to avoid massive recourse to the use of herbicides, which would be needed to control weeds and maintain crop yield and quality, a promising solution is represented by the development of predictive models aimed to design sustainable weed control programmes by suggesting the best timing for chemical treatments. Effective forecasting models are demonstrated to be able to increase the information-richness of agronomic management decisions and to enhance the timeliness and cost-effectiveness of standard management operations but in the meantime the most critical need for improving models is integration of microclimate data and agricultural management variables. Current emergence models use estimates of soil microclimate at only single soil depth to make predictions. In conservation cropping systems, where the weed seeds remain on soil surface, integration of microclimate data for the upper soil surface, although difficult to estimate because of rapid changes in response to atmospheric conditions, is needed to better predict seedling emergence. In this thesis it has been shown that the use of temperature at only one depth in the germination zone of the soil could be correct in tilled soil, but more accuracy in the monitoring or estimation of the surface layers is necessary in no-till systems. Another crucial step to create accurate predictive models is to provide a weed emergence timing dataset as large and detailed as possible. This means that many years of field experiments are necessary and that weed dynamics information has to be acquired. One of the main objectives of this thesis was to verify the possibility of transferring AlertInf, an existing model developed to predict weed emergence in conventionally tilled maize fields, to no-till fields. This has not yet been possible because weed emergence dynamics in no-till systems, as expected, are highly dependent on surface microclimate and seed-soil contact in the surface layer. Therefore the difficulty in obtaining accurate measures of soil surface temperature and water potential makes weed emergence simulation more complicated. Further studies and experiments are therefore required to evaluate the feasibility of emergence predictive models in no-till system.

RINGRAZIAMENTI

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… e sperando di non aver fatto dimenticanze clamorose, posso finalmente scrivere

THE END