Assessing microclimate conditions of surface soil layers to improve weed emergence modelling

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Assessing microclimate conditions of surface soil layers to improve weed emergence modelling

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Abstract: *Thermal or hydrothermal models for weed emergence prediction are useful tools for Integrated Weed Management (IWM) and require an accumulation of Growing Degree Days (GDD) to be calculated through the comparison of base temperature for germination with daily average soil temperature. Consequently, the accuracy of measurements or estimations of soil temperature, which has a strong depth-dependant variability, affects the predictive quality. Emergence models for arable conditions adopt soil temperature measured at a depth of 3-5 cm, but this may not be adequate for no-till conditions. Daily and hourly soil temperatures were measured at depths of 2, 5, 10, 20 and 50 cm during the period of weed emergence and the respective means (T_d and T_h) were calculated. Accumulations of GDD were computed for* Abutilon theophrasti, Chenopodium album *and* Sorghum halepense *with values of T_d and T_h measured at depths of 2, 5 and 10 cm. The emergence curves calculated for each species with the AlertInf model were compared to identify estimation variability due to the adoption of values of soil temperature measured at different depths. Despite the great depth-dependent differences observed for T_d and T_h, differences among the emergence curves estimated for each species were not significant from the point of view of weed control. The adoption of T_h measured at a depth of 5 cm could be the best compromise to guarantee model accuracy without complicating measurements. However, further studies are required to adjust and calibrate models developed for arable fields to no-till conditions.*
Keywords: *weed emergence modelling, thermal time, soil temperature profile, Integrated Weed Management.*

Riassunto: *I modelli per la previsione dell'emergenza delle malerbe sono importanti strumenti per la loro gestione integrata (IWM) e richiedono il calcolo dell'accumulo progressivo di Growing Degree Days (GDD) in base al confronto tra temperatura di base per la germinazione e temperatura media giornaliera del suolo. L'accuratezza della misura o della stima di questa variabile del suolo, che presenta un'elevata variabilità legata alla profondità, influenza quindi notevolmente la qualità finale delle previsioni. I modelli di emergenza creati per i campi arati normalmente adottano valori di temperatura del suolo misurati a 3-5 cm di profondità. Tuttavia questo approccio potrebbe rivelarsi inadeguato per i suoli non lavorati. La temperatura giornaliera ed oraria del suolo è stata misurata alle profondità di 2, 5, 10, 20 and 50 cm durante il periodo di emergenza delle infestanti e le rispettive medie (T_d e T_h) sono state calcolate. Accumuli di GDD sono stati stimati per* Abutilon theophrasti, Chenopodium album *and* Sorghum halepense *usando i valori di T_d e T_h misurati a 2, 5 e 10 cm. Le curve di emergenza stimate con il modello AlertInf sono state confrontate per identificare la variabilità nella stima dovuta all'adozione di valori di temperatura del suolo misurati a diverse profondità. Nonostante la variabilità legata alla profondità osservata per T_d e T_h, le differenze tra le diverse curve di emergenza stimate per le tre specie non sono significative dal punto di vista pratico. L'adozione della T_h misurata a 5 cm di profondità potrebbe esser il giusto compromesso per migliorare l'accuratezza del modello senza complicare eccessivamente l'acquisizione degli input. Tuttavia, i modelli sviluppati per la previsione delle emergenze di infestanti nei terreni lavorati non possono esser semplicemente trasferiti alle condizioni del terreno non-lavorato perché questo tipo di gestione del suolo influenza diversi fattori ambientali che controllano la dormienza ciclica e la dinamica di germinazione di molte specie infestanti. Ulteriori studi dovranno esser condotti per adattare e calibrare i modelli messi a punto per i campi arati alle condizioni del suolo non-lavorato.*
Parole chiave: *modelli di emergenza delle infestanti, tempo termico, profilo termico del suolo, Gestione Integrata delle Infestanti.*

1. INTRODUCTION

Predictive models for weed emergence are useful tools for the development of efficient Integrated IWM strategies (Grundy, 2003; Bullied *et al.*, 2012). Indeed, they can provide information to choose the correct timing for herbicide application (Masin *et al.*, 2005). 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 scouting in maize fields (Masin *et al.*, 2011). Many weed emergence models have been developed according to the thermal or hydrothermal approach (Bradford, 2002; Dorado *et al.*, 2009; Garcia *et al.*, 2013; Izquierdo

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et al., 2009; Leguizamon *et al.*, 2005; Masin *et al.*, 2010a, 2012). The driving variables considered for weed germination process are GDD for thermal approach or GDD and soil water potential for hydrothermal approach. In the first step the driving variables are calculated and in the second one a non-linear regressions (e.g., logistic, Gompertz, Weibull) are used to estimate the percentage of total seedling emergence corresponding to a time evolution of the driving variables.

The soil micrometeorological variables required for the first step can be directly measured in the field or estimated through other correlated weather measurements such as air temperature and precipitation (Garcia *et al.*, 2013; Masin *et al.*, 2012; Bullied *et al.*, 2014a; Royo-Esnal *et al.*, 2010). However, the precision of these measurements or estimations strongly influences the model prediction accuracy, which could theoretically be improved by taking into account the spatial and temporal fluctuations of soil temperature and water potential (Bullied *et al.*, 2012). Indeed, soil temperature and water potential show a great depth-dependant variability, with wide seasonal and daily fluctuations in the upper soil layer (0-2 cm), which is directly exposed to external conditions, such as wind, rain and solar radiation. However, these fluctuations narrow with depth with notable differences even in the upper 10 cm of soil (Bullied *et al.*, 2014a). Direct measurements of soil temperature and water potential close to the surface are also problematic for the same reasons (Flerchinger and Hardegree, 2004). As a consequence, emergence models developed for arable field conditions, where weed seeds are assumed to be distributed in the soil layer corresponding to tillage depth, usually adopt mean daily soil temperature (T_d hereinafter) and soil water potential measured or estimated at a depth of 3-5 cm to calculate GDD (Dorado *et al.*, 2009; Masin *et al.*, 2010a, 2012). This may indeed represent the average condition of the soil layer (0-10 cm) from which weeds can germinate and emerge (Benvenuti *et al.*, 2001). Nevertheless, this approach may not be adequate in the case of no-till conditions where almost all weed seeds are located in the superficial soil layer (Chauhan *et al.*, 2006; Swanton *et al.*, 2000; Refsell and Hartzler, 2009) and exposed to environmental conditions with extreme daily fluctuations. Consequently, the accumulation of GDD calculated according to the T_d at a depth of 5 cm could not represent the conditions of weed seeds situated in the superficial layer.

In their field experiment carried out in the Canadian Prairies, Bullied *et al.* (2014b) observed that the maximum accumulation of thermal time occurred close to the soil surface and decreased with depth. Adopting the mean hourly soil temperature (T_h hereinafter) measured at 2 cm could improve the model predictive accuracy under no-till conditions. For this reason Leguizamon *et al.* (2009) decided to estimate soil temperature at a depth of 2 cm in order to model weed emergence under no-till conditions, although reporting the difficulty in accurately predicting the shallow layer soil temperature.

An experiment was therefore conducted to estimate the specific accumulation of GDD using T_d or T_h measured at different depths for three spring emerging weed species: *Abutilon theophrasti* Medik (ABUTH, Malvaceae), *Chenopodium album* L. (CHEAL, Chenopodiaceae) and *Sorghum halepense* (L.) Pers. (SORHA, Poaceae). These three species were selected because they present different values of base temperature for germination (Masin *et al.*, 2010b) and different seedling emergence dynamics in the field (Masin *et al.*, 2012). *Abutilon theophrasti* and *C. album* are both early-emerging species but *C.album* is usually characterized by a more prolonged emergence period. *Sorghum halepense* instead is a late-emerging species with a normally short emergence period. Weather conditions and timing of seedbed preparation can obviously influence and change the duration of emergence period of these three species slowing down or speeding up the emergence dynamics. GDD accumulation obtained for each species was therefore 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 then compared to identify variability in the model estimation due to the adoption of values of T_d and T_h measured at different depths. The final aim was to assess if T_d at a depth of 5 cm, which can be measured or estimated more easily and accurately than T_h at a depth of 2 cm, could be adopted as input for weed emergence models for no-till conditions.

2. MATERIALS AND METHODS

2.1. Soil temperature monitoring

The field experiment was conducted at the experimental farm of the University of Padova at Legnaro, Northeastern Italy. The local climate (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 was designed to measure the soil temperature at precise depths by determining the thermal gradients between a certain specific depth and the reference point, set at 50 cm. The sensor design improved the positioning accuracy, the uncertainty of which was usually high when using a series of separate sensors. This made the temperature gradient measurement more reliable, which subsequently improved 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. A trench 50 cm depth was excavated in the soil allowing an undisturbed side of the pit south oriented suited for sensors installation. The STP01 probe was placed vertically in the soil along a thin 60-cm-long access and after the pit was carefully refilled, avoiding perturbations as far as possible, to reach the same level of the surrounding soil surface. The instrumental set-up was performed during autumn 2011 and soil temperature measurements began the following spring allowing a perfect soil-sensor contact minimizing air spaces creation that could alter temperature measurements. 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 the 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, in fact, would reduce the daily maximum soil temperature and consequently also the daily mean temperature and magnitude of the daily soil temperature fluctuations (Norsworthy, 2004). No relevant soil cracks were observed at the experimental site throughout the monitoring period. Both T_d and T_h were calculated, obtaining two series of data for each depth.

2.2. Calculation of GDD accumulations and comparison of emergence curves

T_d and T_h measures at the depths of 2, 5 and 10 cm were used to estimate two different accumulations of GDD for each species at each depth, hereinafter called GDD_d and GDD_h for accumulation based on daily and hourly data respectively. The temperatures recorded at depths of 20 and 50 cm 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 main 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 area of Legnaro, and ended on 31st July as seedling emergence of the studied species rarely occurs after this date. Thermal time expressed as cumulative GDD (GDD_d and GDD_h) was calculated according to the following formulas:

$$GDD_d = \sum_{i=0}^{n} \left[T_d(i) - T_b \right] \qquad (1)$$

$$GDD_h = \sum_{i=0}^{n} \frac{\sum_{h=1}^{24} \left[T_h(i) - T_b \right]}{24} \qquad (2)$$

where GGD represents thermal time expressed in cumulative degree days (GDD_d or GDD_h) for the period 0 — n days. T_d is the mean daily soil temperature, T_h is the mean hourly soil temperature and T_b is the specific base temperature for germination. When $T_d > T_c$ (ceiling temperature) or $T_h > T_c$, the specific T_c was used instead of T_d or T_h. The values of base and ceiling temperature for germination for the three species adopted for this calculation are shown in Tab. 1. Negative values of GDD were considered as zero.

	Tb[1] (C°)	T c[2] (C°)	Gompertz coeff.[2] a	b
ABUTH	3.9	32	10.28	0.02
CHEAL	2.6	28	3.56	0.01
SORHA	11.8	28	4.49	0.03

[1] Estimated in a previous study (Masin *et al.* 2010b)

[2] Estimated in a previous study (Masin *et al.* 2012)

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

Tab. 1 - Valori di temperature base (Tb) e temperatura massima (Tc) di germinazione adottati per il calcolo dei GDD e coefficienti (a e b) dell'equazione Gompertz usata per modellizzare l'emergenza cumulata di A. theophrasti, C. album e S. halepense *(ABUTH, CHEAL e SORHA).*

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 Masin *et al.* (2012):

$$CE = 100 \exp(-a \exp(-b\ GDD)) \quad (3)$$

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 (Tab. 1) were estimated in a previous study (Masin *et al.*, 2012). Six different emergence curves were therefore obtained for each species.

Dates when the percentage of cumulated emergence reached the threshold values of 1, 25, 50, 75 and 95% were identified for each emergence curve. Those dates were defined as threshold dates (D1, D25, D50, D75 and D95). Corresponding threshold dates of the six emergence curves of the same species were compared to identify possible variability in the model estimation caused by the adoption of values of soil temperature measured at different depths or by using T_h instead of T_d. Particular attention was paid to threshold dates D50 and D75 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 scouting the field to estimate weed density, an input often requested by DSS for weed control (Masin *et al.*, 2011). Thus, over- or underestimating the D50 or D75 by just a few days could lead to an inappropriate choice of control timing and consequently relevant yield losses.

3. RESULTS AND DISCUSSION

As expected, soil temperatures recorded at a depth of 2 cm showed the greatest seasonal and daily fluctuations throughout the period of the experiment (15th April – 31st July 2012), while fluctuations narrowed as depth increased and reach the minimum at 50 cm (Fig. 1). This resulted as being more evident for T_h than for T_d (Fig. 1). T_h in the upper layer was strongly affected by environmental conditions, rising and falling more and faster than at greater depth. As a consequence, daily maximum and minimum values of T_h were reached earlier at a depth of 2 cm and delays increased with depth (Fig. 2). Moreover, differences were greater among the maximum values of T_h reached during the day at the different depths than among the minimum T_h values during the night (Fig. 2). Considering the whole experiment, the highest soil temperatures were recorded at a depth of 2 cm with values of 33.2 and 44.2 °C for T_d and T_h respectively (Tab. 2). The lowest soil temperature was 6.3 °C at a depth of 2 cm for T_h, while minimum values around 12 °C were estimated for T_d at all depths. Finally, the mean values of T_h and T_d, calculated considering the entire monitored period (April – July) for each depth, did not differ, but a progressive increase was detected passing from 20.3-20.5 °C at 50 cm to 24.5-24.7 °C at 2 cm.

The six accumulations of GDD, calculated for each species adopting values of T_d (GDD_d) or T_h (GDD_h) measured at depths of 2, 5 and 10 cm, did not notably differ (data not shown) and consequently the resulting six emergence curves also revealed almost identical trends for *A. theophrasti* (Fig. 3) and *C. album* (Fig. 4). Only in the case of *S. halepense* small variances could be observed among the estimated emergence curves (Fig. 5) and the adoption of T_h instead of T_d slightly increased these differences. This situation is also observed 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 six emergence curves of each species (Tab. 3). The maximum observed differences were 4 days at D50, D75 and D95 between the emergence curves estimated for *S. halepense* based on GDD_h at 2 cm (the earliest) and GDD_d at 10 cm (the latest). Regarding *A. theophrasti* and *C. album*, differences among the six emergence curves were 2 days or less for all threshold dates.

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. Therefore the quasi-identical daily sum of GDD at the three depths could be due to the fact that the higher soil temperatures reached at a depth of 2 cm during the day than at 5 or even more so at 10 cm, were balanced by lower soil temperatures during the night. Moreover, when soil temperature exceeded the maximum temperature for germination (Tc) of a given species, Tc was adopted for the daily calculation of GDD. This procedure smoothed the weight of high temperatures recorded on an hourly basis (T_h), which were often observed at 2 cm, on the GDD_h cumulative computation. No relevant differences were therefore shown among the accumulations of GDD_d and GDD_h at all soil depths.

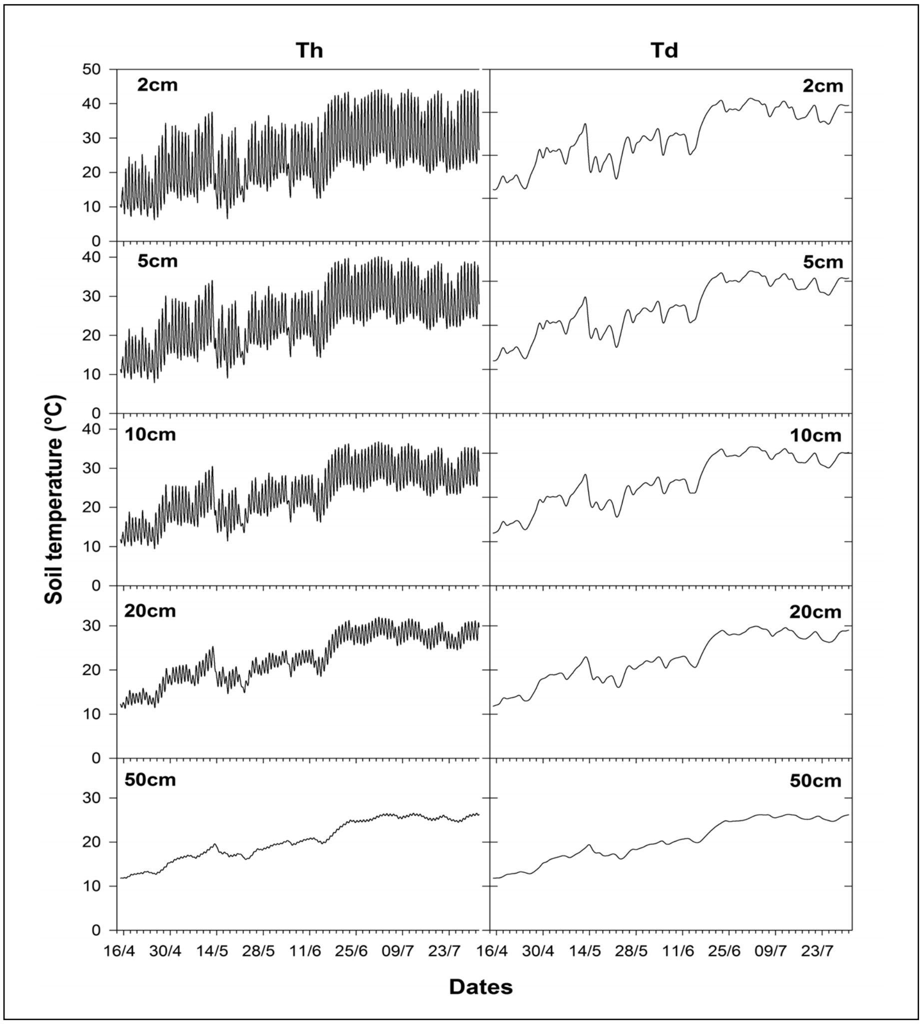

Fig. 1 - Mean hourly and daily soil temperatures (T_h and T_d respectively) measured at depths of 2, 5, 10, 20 and 50 cm.

Fig. 1 - Temperatura media oraria e giornaliera del suolo (T_h e T_d rispettivamente) misurate alla profondità di 2, 5, 10, 20 e 50 cm.

The differences among the six emergence curves estimated by the AlertInf model for the three species could be considered as not significant from the point of view of emergence modelling for weed control optimization. It could therefore be suggested that T_d measured at a depth of 5 cm could be adopted as input for emergence models for the three species in no-till fields, given that the bare soil condition maintained throughout the experiment should have maximized daily fluctuations and depth-dependent differences in soil temperature. Nevertheless, the adoption of T_h measured at a depth of 5 cm may be suggested as the right compromise to make accurate predictions, especially for *S. halepense* emergence, without excessively complicating input acquisition or GDD calculation.

However, emergence models developed for arable field conditions, such as AlertInf (Masin *et al.*, 2012), cannot simply be transferred to no-till

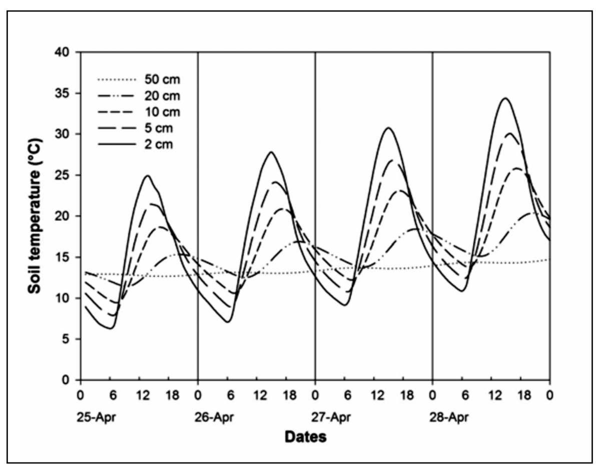

Fig. 2 - Subset of daily fluctuations of mean hourly soil temperatures (T_h) measured at depths of 2, 5, 10, 20 and 50 cm from 25th to 28th April 2012.

Fig. 2 - Intervallo delle oscillazioni giornaliere della temperatura media oraria del suolo (T_h) misurata alla profondità di 2, 5, 10, 20 e 50 cm dal 25 al 28 Aprile 2012.

	Td					Th				
	50 cm	20 cm	10 cm (°C)	5 cm	2 cm	50 cm	20 cm	10 cm (°C)	5 cm	2 cm
Max	26.3	29.9	31.4	32.3	33.2	26.5	32.0	36.7	40.2	44.2
Med	20.3	22.6	23.6	24.0	24.5	20.5	22.8	23.7	24.2	24.7
Min	11.8	11.8	11.9	12.0	12.1	11.8	11.3	9.5	7.9	6.3

Tab. 2 - Mean daily and hourly soil temperatures (T_d and T_h respectively) 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).
Tab. 2 - Temperature medie giornaliere e orarie (rispettivamente T_d e T_h) misurate a varie profondità del suolo. Valori massimi, medi e minimi (Max, Med e Min) sono stati calcolati considerando l'intero periodo dell'esperimento (15 Aprile – 31 Luglio 2012).

conditions without 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 (Chauhan *et al.*, 2012). In particular the absence of tillage and the crop residues left on the soil surface can maintain soil moisture content, creating good conditions for seed germination, but also reduce the magnitude of soil temperature fluctuations and modify the quality and quantity of light that reaches the soil surface. Given that these factors have a stimulating effect on seed germination 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.

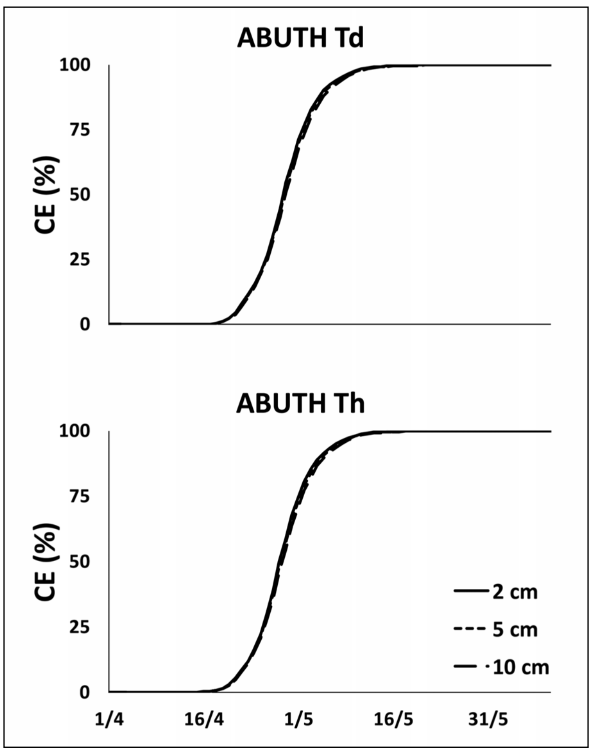

Fig. 3 - Cumulative emergence (CE) curves estimated adopting values of mean daily and hourly soil temperature (T_d and T_h respectively) measured at depths of 2, 5 and 10 cm for *A. theophrasti* (ABUTH).
Fig. 3 - Curve di emergenze accumulate (CE) stimate adottando valori di temperature media giornaliera e oraria del suolo (T_d e T_h rispettivamente) misurata a 2, 5 e 10 cm per A. theophrasti *(ABUTH).*

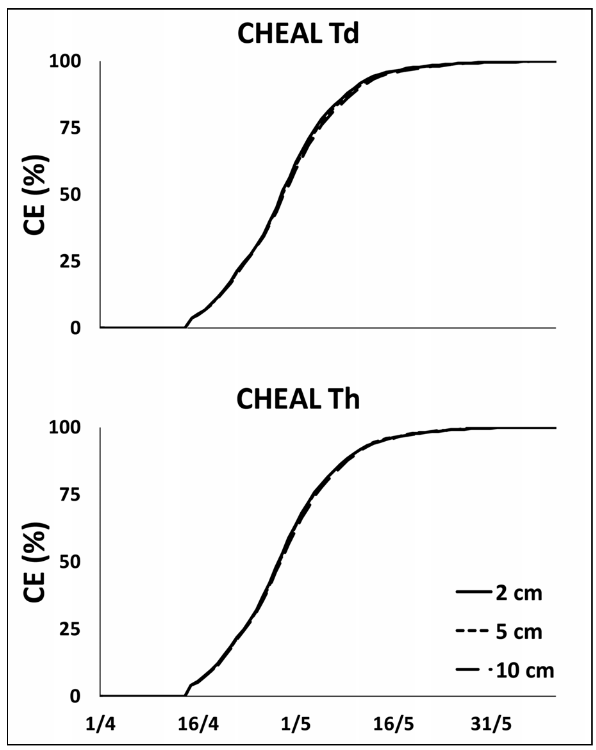

Fig. 4 - Cumulative emergence (CE) curves estimated adopting values of mean daily and hourly soil temperature (T_d and T_h respectively) measured at depths of 2, 5 and 10 cm for *C.album* (CHEAL).
Fig. 4 - Curve di emergenze accumulate (CE) stimate adottando valori di temperature media giornaliera e oraria del suolo (T_d e T_h rispettivamente) misurata a 2, 5 e 10 cm per C.album *(CHEAL).*

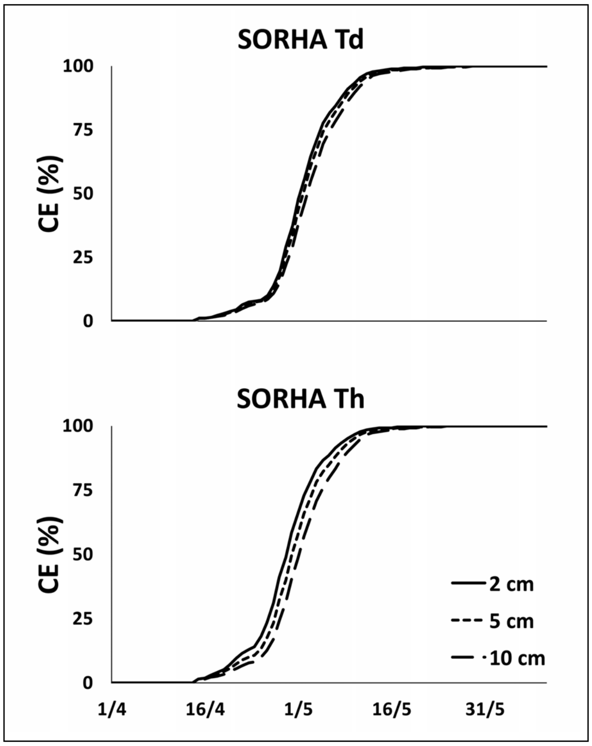

Fig. 5 - Cumulative emergence (CE) curves estimated adopting values of mean daily and hourly soil temperature (T_d and T_h respectively) measured at depths of 2, 5 and 10 cm for *S. halepense* (SORHA).
Fig. 5 - Curve di emergenze accumulate (CE) stimate adottando valori di temperature media giornaliera e oraria del suolo (T_d e T_h rispettivamente) misurata a 2, 5 e 10 cm per S. halepense *(SORHA).*

Further studies and experiments are therefore required to assess the accuracy and real transferability of existing emergence models to no-till fields and possibly adjust and calibrate them according to the different environmental conditions.

ABUTH						
	T_d			T_h		
	2 cm	5 cm	10 cm	2 cm	5 cm	10 cm
D1	19/4	19/4	19/4	19/4	19/4	19/4
D25	26/4	26/4	26/4	26/4	26/4	26/4
D50	29/4	29/4	29/4	28/4	29/4	29/4
D75	02/5	02/5	03/5	01/5	02/5	02/5
D95	08/5	08/5	09/5	07/5	08/5	08/5
CHEAL						
	T_d			T_h		
	2 cm	5 cm	10 cm	2 cm	5 cm	10 cm
D1	15/4	15/4	15/4	15/4	15/4	15/4
D25	23/4	24/4	24/4	23/4	24/4	24/4
D50	29/4	29/4	30/4	29/4	29/4	29/4
D75	04/5	05/5	05/5	04/5	04/5	05/5
D95	14/5	15/5	15/5	14/5	14/5	15/5
SORHA						
	T_d			T_h		
	2 cm	5 cm	10 cm	2 cm	5 cm	10 cm
D1	15/4	15/4	15/4	15/4	15/4	15/4
D25	29/4	29/4	30/4	27/4	28/4	29/4
D50	02/5	02/5	03/5	30/4	01/5	02/5
D75	05/5	06/5	07/5	03/5	04/5	05/5
D95	11/5	12/5	13/5	09/5	10/5	11/5

Tab. 3 - Comparison of threshold dates (D1, D25, D50, D75 and D95) of the emergence curves estimated adopting values of soil temperature measured at depths of 2, 5 and 10 cm for *A. theophrasti*, *C. album* and *S. halepense* (ABUTH, CHEAL and SORHA).
Tab. 3 - Confronto delle date soglia (D1, D25, D50, D75 and D95) delle curve di emergenza stimate utilizzando le temperature del suolo misurate alla profondità di 2, 5 e 10 cm per A. theophrasti, C. album *e* S. halepense *(ABUTH, CHEAL e SORHA).*

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