# Long-term effect of different tillage systems on the emergence and demography of *Bromus diandrus* in rainfed cereal fields

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**Running head**: Long term effect of tillage on *Bromus diandrus*

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**Summary**

The adoption of no-tillage systems in semiarid cereal fields in northern Europe has resulted in difficulties in controlling *Bromus diandrus*. However, in some fields, lower densities are observed in continuous long-term no-tillage management than in other reduced tillage systems. A cumulative effect on the seed bank could promote changes in the period of seedling emergence and in population demography. The present study evaluated the effect of long-term mouldboard plough (MbP), chisel plough (ChP), subsoiler (SS) and no-tillage (NT) on the population dynamics of *B. diandrus*. The work was carried out in a barley (*Hordeum vulgare*) - wheat (*Triticum aestivum*) - barley rotation during three seasons where these soil management systems had been applied for the last 22 years.

Cumulative emergence (CE) and densities of *B. diandrus* followed a gradient of ChP > SS > NT > MbP. This cumulative effect over time resulted in significant differences in population demography. A previous hydrothermal emergence model developed for this species estimated the percentage of emergence prior to the date of sowing to be: 71%, 92% and 53% for the seasons 2008-09, 2009-10 and 2010-11, respectively. Furthermore, the reduction in CE observed was on average 53% in SS, 92% in NT and 98% in MbP in comparison with that recorded in ChP. The long-term effect of different tillage systems tended to cause changes to soil characteristics (photo-inhibition of germination, soil temperature, water availability) affecting *B. diandrus* demography, reaching equilibrium in weed densities over years, which were significantly lower in MbP and NT than in ChP or SS.

**Keywords:** great brome, no-tillage, reduced tillage, cumulative effect, weed emergence, weed density.

## Introduction

The adoption of conservation tillage systems (both minimum and no tillage) is increasing in semiarid areas because of environmental benefits and savings in time and economic inputs (Holland, 2004; Sánchez-Girón *et al.*, 2007). However, these systems, and especially no-tillage (NT), have resulted in difficulties in controlling certain weed species. One species in particular, *Bromus diandrus* Roth, has become especially problematic in NE Spain, where it is widespread (García-Baudín, 1983; Riba & Recasens, 1997; Moreno *et al.*, 2007), since the adoption of conservation tillage. Until a few years ago, in NT, *B. diandrus* was only controlled by non-selective herbicides (mainly glyphosate) applied pre-sowing, owing to the absence of effective post-emergence herbicides. Continuous use of this control method, together with an early cereal sowing in the area in the first years of no-till implementation, led to high infestations of *B. diandrus* (García *et al.*, 2014). As a consequence, some growers have moved to delaying the date of sowing in order to control *B. diandrus*. Interestingly, several farmers in Catalonia (NE Spain) that began no-tillage-direct drilling systems more than 25 years ago, recently noted that the problems caused by *B. diandrus* have declined since the initial adoption of conservation tillage, and in some cases the densities are lower than those observed in fields where intensive chisel plough is still being applied. No experimental data have yet confirmed these observations.

The effect of different tillage practices on weed population dynamics is well documented and is mostly reflected in the different weed seed distributions in the soil profile (Buhler *et al.*, 1997; Dorado *et al.*, 1999; Ball, 1992; Dorado & López Fando, 2006; Murphy *et al.*, 2006; Mas & Verdú, 2003). However, no specific data are available on the long-term effect of different tillage systems on the population demography of *B. diandrus* in semiarid cereal fields.

Germination of *Bromus diandrus* and other related species is inhibited by light (Froud-Williams, 1981; Hilton, 1984; Ellis *et al.*, 1986; Jauzein, 1989). Accordingly, Del Monte and Dorado (2011) suggest an interaction between water potential and light conditions for germination, in the sense that water potential requirement is significantly lower in darkness. Thus, conditions for seed germination can often be more favourable in NT. These authors suggested that seeds on the soil surface may need only a superficial coverage to perceive darkness and that the light provided by crop residues in NT could favour germination. Furthermore, seed germination in semiarid regions may involve an interaction between temperature and soil water content. Steadman *et al.* (2003) demonstrate such an interaction with *Lolium rigidum* Gaudin; they showed that dormancy declined progressively in a simple relationship with temperature and water content. The increase in water capacity (Bescansa *et al.*, 2006) and in water accumulation in the soil profile (Lampurlanés *et al.*, 2001) in NT compared with other tillage systems has already been confirmed for rainfed cereal systems in NE Spain.

Crop sowing date influences the emergence of *B. diandrus* and the recruitment of weed seeds for the next seasons. In NT, delayed sowing reduces weed density avoiding the maximum peak of emergences and permitting, in wheat, a better efficacy of selective post-emergence herbicides (García *et al.*, 2014). In a long-term scenario in which continuous NT management has been applied, the crop sowing date could drive the population dynamics of *B. diandrus* in a different direction to those that take place in fields where different tillage systems are implemented.

According to these observations, we hypothesised that the cumulative effect of different tillage systems in a long-term scenario (>20 years) could affect the soil seed bank and therefore the population dynamics of *B. diandrus*. Information on emergence patterns, infestation levels, final fecundity and seed rain in different long-term tillage systems could confirm whether *B. diandrus* populations can really become stabilised at different equilibrium densities depending on the tillage system applied. To this end, in three growing seasons we monitored an experimental cereal field trial initiated 22 years ago, in which different tillage systems were continuously implemented.

## Materials and Methods

### *Study site*

The experiment was conducted over three seasons (2008-09, 2009-10 and 2010-11) in Agramunt, Lleida, Spain (41º 48´N, 1º 07´E) in a dry-land cereal field managed for more than 22 years by the Agronomy Research Group of the University of Lleida. The field had a natural infestation of *B. diandrus* throughout the 22 years and no selective herbicide control methods had been applied. The field is 330 m a.s.l. and has a continental Mediterranean climate. The soil was a Fluventic Xerocrept (100-120 cm deep) with 30% sand, 52% silt and 18% clay, 2% organic matter and a pH of 8. Daily rainfall and maximum and minimum air temperatures were obtained from a standard meteorological station located at the experimental field during the study period. Monthly mean temperature and rainfall recorded at the site and long-term averages are presented in Table 1.

*Table 1 near here*

*Tillage and cropping systems*

Since 1986, the following soil management systems have been continuously implemented in this field trial: chisel plough (ChP), subsoiler (SS), mouldboard plough (MbP) or NT. ChP was performed to a depth of 10-15 cm. SS was performed with three 4 cm-wide shanks spaced 35 cm apart to a depth of 20-25 cm. MbP consisted of cultivation with a mouldboard plough with three bottoms of 0.50 m width, with one operation to a depth of 25-30 cm plus one or two hoe cultivator passes (15 cm depth). In the tilled systems, a roller was used before sowing to break clods and promote germination. ChP, MbP and SS were implemented a few days before sowing. In all treatments, sowing was performed with a 3 m-wide no-till disc drill, regulating the sowing depth according to the soil management system. Plots were arranged in a randomised complete block design with three replicates. Plot sizes were 50 x 9 m. When the monitoring started, each plot had been under the same tillage treatment for 22 years. The cropping system consisted of a barley-wheat-barley rotation and tillage systems were implemented in early November. In NT and SS, glyphosate (540 g a.i. $ha^{-1}$) (Roundup Plus, N-(phosphono-methyl)-glycine, 360 g a.i. $L^{-1}$, SL, Monsanto Europe S.A.) was sprayed two to six days before sowing to keep the soil free of weeds. Barley (*Hordeum vulgare* L.) was sown on 15 November 2008 and 11 November 2010, whereas wheat (*Triticum aestivum* L.) was sown on 12 November 2009. The sowing rate was always 180 kg $ha^{-1}$ in rows spaced 17 cm apart. The post-emergence herbicide used in 2008-09 was isoproturon plus diflufenican (1743 + 69 g a.i. $ha^{-1}$) (Javelo SC, isoproturon plus diflufenican 410 g a.i. $kg^{-1}$ + 38.5 g a.i. $kg^{-1}$, SC, Bayer CropScience) applied on 19 February 2009. In 2009-10, post-emergence weed control was accomplished by mesosulfuron-methyl plus iodosulfuron-methyl sodium (15 + 3 g a.i. $ha^{-1}$ plus wetting agent) (Atlantis, mesosulfuron-methyl plus iodosulfuron-methyl sodium, 30 + 6 g a.i. $kg^{-1}$, WG, Bayer CropScience) applied on 6 March. In 2010-11, the post-emergence herbicide applied was tribenuron-methyl plus metsulfuron-methyl (10 + 5 g $ha^{-1}$ plus wetting agent) (Biplay, tribenuron-methyl plus metsulfuron-methyl 222 g a.i. $kg^{-1}$ + 111 g a.i. $kg^{-1}$, SG, DuPont) on 30 March. In each season, fertilisation was performed in March with N-32% at 150 kg $ha^{-1}$.

*Estimated parameters*

Weekly destructive counts of the emerged seedlings were started on the crop sowing date in 2008-09 and 2009-10 and in September in 2010-11 in five permanent quadrats (0.1 $m^2$) until the end of April. In each plot, periodic samplings of weed densities (pl $m^{-2}$) were collected with ten 0.1 $m^2$ quadrats randomly thrown on the plot. Estimation of densities started before crop sowing.

A functional relationship between cumulative emergence (CE) and hydrothermal time (HTT) was established by applying the sigmoid Chapman equation described by García *et al.* (2013) for *B. diandrus*

$$y = 100\,(1 - [\exp\{-0.013x\}])^{21.4389} \qquad (1)$$

where $y$ is the percentage of CE after the first autumn rains and $x$ is time expressed as HTT. This model was based on the equation described by Roman *et al*. (2000) and HTT estimated using the Soil Temperature and Moisture Model ($SMT^2$) developed by Spokas and Forcella (2009). In this model, base temperature and base water potential were established at 0ºC and -1.35 MPa, respectively.

Fecundity was estimated in June 2010 and 2011, when *B. diandrus* seeds were fully matured. Twenty plants from each plot were collected and the number of caryopses per plant was estimated. Seed rain in each treatment was estimated by multiplying fecundity by final density.

*Statistical analysis*

Because of the different crops and treatments applied in each season, data from each growing season were analysed separately. All data were analysed through ANOVA using SAS 9.0 (PROC NLIN; SAS Institute Inc., Cary, NC, USA), with the type of tillage as the single factor. When differences were detected between treatments, the least squares difference test ($P<0.05$) was used for mean comparisons. Previous to analyses, weed emergence, weed density, fecundity and crop yield were (log (x+1)) transformed to satisfy the homogeneity of variance assumptions. Back-transformed data were presented for clarity. The repeated statement option of SAS was used to compare weed densities and CE between assessment dates. Sigma Plot program 11.0 was used for density and emergence graphics.

## Results

*Weather characteristics of the growing seasons*

The annual average temperatures in the three growing seasons were slightly below the long-term average temperature (10.9, 10.6 and 11.4ºC in the three seasons vs. 11.71ºC). Rainfall in the first two growing seasons was above the long-term average of 378 mm. Total rainfall from September to June (at harvest time) was 500 mm in 2008-09, 637 mm in 2009-10 and only 190 mm in 2010-11 (Table 1). In 2008-09, the autumn-winter average precipitation was 234 mm (October to February), with the highest value in October (84 mm). Spring was wet, with 150 mm in April. In 2009-10, autumn-winter was wetter (357 mm), while spring was dryer than the previous season (85 mm). In 2010-11 autumn-winter was extremely dry (13 mm), but spring was wet (156 mm).

*Weed emergence patterns*

Cumulative Emergence (CE) of *B. diandrus* differed between treatments (Table 2) and followed a similar decreasing gradient, ChP > SS > NT > MbP, during the three growing seasons. Observed values for ChP were always significantly different to those for NT and MbP and values for SS were also significantly different to those for MbP. The highest values of CE in ChP (1117 pl $m^{-2}$) and SS (489 pl $m^{-2}$) were observed in 2009-10, whereas the lowest values in NT (13 pl $m^{-2}$) and MbP (2 pl $m^{-2}$) were observed in 2010-11.

*Table 2 near here*

The emergence of *B. diandrus* extended until the end of April in all seasons (Fig. 1). In 2008-09, significantly higher values of emergence were recorded in ChP and SS from mid-December until mid-January (with values close to 200 pl $m^{-2}$ and 70 pl $m^{-2}$, respectively on three sampling dates in a row). In 2009-10, a few days after crop sowing, a flush of emergence was observed in ChP (>600 pl $m^{-2}$) and in SS (>250 pl $m^{-2}$), showing significant differences between them and between these values and those for the other treatments. In January and February, another flush of emergence was observed in all tillage systems, with the highest values in ChP (>100 pl $m^{-2}$). In 2010-11, emergence was sampled from September, before crop sowing, and ChP showed significantly greater values of CE. In this season, new minor flushes of emergence were recorded until mid-April.

The hydrothermal emergence model developed for *B. diandrus* in a previous work (García *et al.*, 2013) was applied successfully for the different tillage systems across seasons. According to this model, the percentage of total CE that occurred before the sowing date was 71%, 92% and 53% for the seasons 2008-09, 2009-10 and 2010-11, respectively.

The predicted and observed CE results are represented separately for each tillage system (Fig. 2). Considering that the highest CE occurred in ChP, a value of 100% was assigned to this tillage system. Accordingly, reductions in CE in the remaining systems were between 48% and 59% in SS, 89% and 95% in NT and 97% and 99% in MbP during the three seasons. The model predicted 50%, 75% and 90% of CE at 264, 329 and 406 HTT, respectively, after the first autumn rainfalls, which occurred on different dates in each season (Table 3).

Furthermore, the model reflects differences in time of emergence in contrasting management systems. In Fig. 3, the CE observed the first weeks after sowing are compared across treatments. In 2008-09 and 2010-11, the higher values observed in NT confirmed that emergence was greater and occurred earlier than in ChP. In 2009-10, the autumn was wet and values of CE were similar.

*Table 3 near here*

*Figure 1 near here*

*Figure 2 near here*

*Figure 3 near here*

*Weed density*

As for CE, significant differences in density were detected between the tillage systems in each season, with a similar pattern (Fig. 4): values for ChP were significantly higher than those for SS, and simultaneously values of both systems were also significantly higher than those for MbP and NT in mid-February, early March and mid-April. In 2008-09 a high density was observed in mid-April in ChP and SS, with values higher than 200 pl $m^{-2}$. In 2009-10 significantly higher densities were observed in ChP and SS during the whole growing period (with maximum values of 593 and 298 pl $m^{-2}$, respectively). In 2009-10, observations made in mid-October and early November revealed a rapid increase in density in NT previous to crop sowing and its depletion after the pre-sowing herbicide application. In 2010-11 density values were low in all tillage systems, and only those observed in ChP were significantly higher from mid-December until mid-April.

*Table 4 near here*

*Weed demographic behaviour and crop yield*

Table 4 shows the different values of density and fecundity at the end of each growing season in each tillage system. Each season the decreasing gradient observed in CE and density values was maintained until harvest: ChP > SS > NT > MbP. The highest values were always observed in ChP, with 266, 241 and 75 plants $m^{-2}$ in 2008-09, 2009-10 and 2010-11, respectively. Significant differences in weed density were observed between NT and ChP in 2009-10 and 2010-11 and between NT and SS in 2009-10. The lowest final densities were observed in MbP (6.3 pl $m^{-2}$), NT (2.7 pl $m^{-2}$) and MbP (0.3 pl $m^{-2}$) in 2008-09, 2009-10 and 2010-11, respectively.

The herbicide application provided an unequal control depending on the tillage system and season (data not shown). Only mesosulfuron-methyl plus iodosulfuron-methyl sodium in 2009-10 showed a good control in NT (93%), whereas for other tillage systems the protracted seedling emergence until spring masked the control effect. Furthermore, herbicides applied on barley in the seasons 2008-09 and 2010-11 were not effective against *B. diandrus*.

No fecundity data were available for the first season, but this parameter ranged between 11 and 31 seeds $pl^{-1}$ in June 2010 and between 42 and 56 seeds $pl^{-1}$ in June 2011 (Table 3). According to the observed density and fecundity levels, estimated seed rains in the second and the third seasons were significantly highest in ChP (5434 and 4191 seeds $m^{-2}$, respectively) and significantly lowest in NT in 2009-10 (33 seeds $m^{-2}$) and in MbP in 2010-11 (15 seeds $m^{-2}$).

Crop yields varied considerably between seasons, but differences were also observed between tillage systems within seasons. Overall, the highest yields were obtained in the first season. In 2008-09, when barley was grown, significantly higher yields were obtained in MbP (5230 kg $ha^{-1}$) and in NT (5360 kg $ha^{-1}$) than in ChP (3690 kg $ha^{-1}$). In 2009-10, wheat yields were significantly higher in MbP (4280 kg $ha^{-1}$) and in NT (4380 kg $ha^{-1}$) than in ChP (3240 kg $ha^{-1}$). In 2010-11, significantly higher barley yields were obtained in NT (2900 kg $ha^{-1}$) than in MbP (1680 kg $ha^{-1}$).

*Figure 4 near here*

## Discussion

In the present work, CE and densities of *B. diandrus* monitored during three growing seasons in a long-term management experiment (22 years) in a cereal field followed a gradient from ChP > SS > NT > MbP (Table 2 and Fig. 4). These results contradict previous works in which the highest emergences and densities of *B. diandrus* were observed in NT compared with other soil tillage systems (Gill & Blacklow, 1985; Kon & Blacklow 1988; Riba & Recasens, 1997; Kleemann & Gill, 2006). Higher infestation levels were found in tillage systems in which seeds are superficially buried in the soil (ChP and SS) than in MbP and NT. In a long-term study of 25 years of cereal-leguminous rotation system in Spain, Hernández-Plaza *et al.* (2011) also found lower densities of *B. diandrus* in NT (0.09 pl $m^{-2}$) than in ChP (0.14 pl $m^{-2}$), and this species was considered one of the least important observed in NT. Furthermore, Bàrberi and Lo Cascio (2001) noted that the seed bank density of *B. diandrus* did not rank it among the 12 major weed species observed in the soil after 12 years of application of four tillage systems (including NT).

Apart from the effectiveness of MbP, which buries seeds in the soil to a position at which emergence is not possible, the differences obtained in our experiment between the other tillage systems could be explained by the conditions created in the upper soil layers, which can promote a different response in dormancy release and seedling emergence after the same long-term management. It is well known that germination of many weed seeds can be promoted by light (Baskin & Baskin 1998), in the sense that buried seeds perceive the light signal mainly during soil disturbance (Jurozsek & Gerhards, 2004). However, the species of the genus *Bromus* show a marked sensitivity to light as a form of negative photoblastism, especially at low temperatures (Froud-Williams, 1981; Hilton, 1984). This photosensitivity is more significant in the subgenus *Anisantha* (Jauzein, 1989), to which *B. diandrus* belongs. In *Bromus* species, the phytochrome operates in exactly the opposite direction to that found in the vast majority of photoblastic seeds, and Pfr (the active form of phytochrome) inhibits germination (Benech-Arnold *et al.,* 2000). It is difficult to determine the level of light present in the soil surface in NT systems. A possible cover effect of straw could be a determinant for

*B. diandrus* seeds situated on the NT soil surface, facilitating the dormancy break and earlier emergence. Furthermore, Dyer (1995) and Benech-Arnold *et al.* (2000) noted that, in general, higher levels of residues at the soil surface decrease the soil thermal amplitude and prevent light penetration.

Del Monte and Dorado (2011) noted that in no-tillage sowing techniques such as those applied in cereals in central Spain, *B. diandrus* seeds remaining on the soil surface only need a superficial covering to perceive darkness. As long as the embryo remains buried, it is likely to germinate, and this is facilitated by the way the seeds fall onto the ground and can be wedged into the soil. In long-term conditions of NT, such as those of the present study, it would be feasible to assume that the perception of darkness by seeds is easier with field stubble or straw cover. In this situation, fully ripened seeds of *B. diandrus* can germinate rapidly in autumn if temperature and water availability are not limiting. However, in our study, most seeds were covered by soil in ChP and SS and experienced similar conditions of darkness for germination. Differences in light penetration, temperature fluctuations and soil water content, especially in autumn after the first rains, probably cause changes in the period of germination and cause the different flushes of emergence observed according to the tillage system. In Spanish rainfed cereal fields, NT favours greater water storage and deeper accumulation in the soil profile than other tillage systems (Bescansa *et al.*, 2006; Lampurlanés et al., 2001).

In our study, the interaction of factors such as the decreasing soil thermal amplitude, prevention of light penetration and greater water availability could cause an earlier and more concentrated period of emergence before sowing in NT (Fig. 3) than in ChP or SS. Thus, based on these data and the patterns of autumn rainfall, delaying crop sowing may be considered a viable management strategy for the control of *B. diandrus* in NT systems.

Kon and Blacklow (1988) noted that there is a high heritable variation within Australian populations of *B. diandrus* that would allow further adaptations to changing environments. Kleemann and Gill (2013) also observed great differences in germination patterns between *B. diandrus* populations and noted a possible interaction between seed dormancy and crop management practices. Del Monte and Dorado (2011) suggest that low temperatures (<10ºC) limit the germination of Spanish populations, particularly when temperatures drop at the end of autumn, and they observed two main flushes of emergence, one before the cool period (in autumn) and one after it (in late winter). In our study, these two main flushes of weed emergence (October and February) were observed in ChP and SS in 2009-10 and 2010-11 (Fig. 1), whereas lower levels of emergence were also recorded in December and January. This delayed emergence must have happened in the seeds with prolonged dormancy according to the conditions of temperature and water availability.

In our study, in NT the lower fluctuations of temperature that seeds perceive under stubble (probably due to lower maximum temperatures) and the greater water availability in comparison with ChP or SS could be determining factors explaining differences in seedling emergence and densities of *B. diandrus*. In other words, the hydrothermal time plays a key role. According with the model developed by García *et al*. (2013), the reduction of CE compared with those observed in ChP was between 50% and 99%, depending on the system in the three seasons (Fig. 2).

No differences were observed in *B. diandrus* fecundity in relation to tillage systems; however, differences in weed density resulted in different levels of seed rain. For all tillage systems, fecundity was lower in 2009-10 than in 2010-11 as a consequence of the effect of the selective herbicide mesosulfuron-methyl plus iodosulfuron-methyl affecting the fecundity of the surviving plants. Kleemann and Gill

(2009) recorded similar contrasting fecundities, 71 and 22 caryopses per plant, respectively, in non-treated populations and populations treated with mesosulfuron-methyl herbicide.

The differences in crop yield observed between seasons are in accordance with the different climatic conditions recorded. The lower yields observed in all tillage systems in 2010-11 were due to the severe drought, whereas the seasons 2008-09 and 2009-10 averaged similar yields to those obtained previously in the region. Focusing on these two first seasons, the highest crop yields were obtained in NT and MbP. Apart from the lower competition caused by lower *B. diandrus* densities in these two systems, in NT an added effect of water accumulation and water use efficiency by the crop could take place (Cantero-Martínez *et al.* 2007). Lampurlanés *et al.* (2002), comparing different tillage systems in a similar experimental field in the region, also observed higher crop yield in NT and confirmed that this management favoured greater and deeper water accumulation in the soil profile.

## Conclusions

The present study showed that the conditions present in different soil management systems in a semiarid cereal field in NE Spain led to a different long-term response of *B. diandrus* populations. After 22 years continuous tillage practices, *B. diandrus* CE and density measured over three growing seasons decreased along a gradient of ChP > SS > NT > MbP. The model estimated a population suppression of 71%, 92% and 53% on the sowing date for the seasons 2008-09, 2009-10 and 2010-11, respectively. Furthermore, the reduction in CE observed was on average 53% in SS, 92% in NT and 98% in MbP in comparison with that recorded in ChP. In our study, an integrated effect of different factors led to an earlier and more concentrated period of emergence in NT than in ChP or SS, in which emergence was protracted. These processes were the result of the same continuous soil management affecting *B. diandrus* demography and finally driving populations to reach equilibrium in weed density according to the management type.

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## Captions of illustrations

**Fig. 1** Observed emergence of *Bromus diandrus* in function of soil management during three growing seasons. ChP, chisel plough; SS, subsoiler; MbP, mouldboard plough; NT, no-tillage. Asterisks indicate significant differences between soil managements ($P < 0.05$).

**Fig. 2** Estimated total emergence for each soil management and season based on the observed cumulative emergence after sowing dates and predicted emergence by the model from García *et al.* (2013) before sowing dates.

**Fig. 3** Predicted and observed cumulative emergence in no-tillage (NT) and chisel plough (ChP) in the first weeks after sowing date each season.

**Fig. 4** Density of *Bromus diandrus* in the four soil management systems during three growing seasons. ChP, chisel plough; SS, subsoiler; MBP, mouldboard plough; NT, no-tillage. Asterisks indicate significant differences between soil management ($P < 0.05$). Arrows indicate date of application of post emergence herbicide.

**Table 1** Mean temperature and monthly rainfall at Agramunt in the 2008-09, 2009-10 and 2010-11 seasons, and long-term averages

| | Mean monthly temperature ºC | | | Long-term mean[a] | Rainfall (mm) | | |
|---|---|---|---|---|---|---|---|
| | 2008/2009 | 2009/2010 | 2010/2011 | 1975-2011 | 2008/2009 | 2009/2010 | 2010/2011 |
| September | 18 | 19 | 19 | 20 | 36 | 55 | 21 |
| October | 14 | 15 | 13 | 14 | 84 | 69 | 1 |
| November | 6 | 9 | 6 | 8 | 31 | 5 | 0 |
| December | 3 | 4 | 3 | 4 | 29 | 112 | 0 |
| January | 4 | 3 | 3 | 4 | 56 | 132 | 0 |
| February | 5 | 4 | 6 | 6 | 34 | 39 | 12 |
| March | 8 | 7 | 9 | 9 | 55 | 64 | 36 |
| April | 11 | 12 | 15 | 13 | 150 | 26 | 20 |
| May | 18 | 14 | 19 | 17 | 5 | 59 | 27 |
| June | 22 | 19 | 21 | 22 | 20 | 76 | 73 |
| TOTAL | | | | | 500 | 637 | 190 |

[a] Rainfall and temperature data averaged from 1975 to 2011

**Table 2** Total cumulative emergence of *Bromus diandrus* (pl $m^{-2}$) (and estandard Error) in different tillage systems during three different growing seasons.

Different letters indicate significant differences between soil management inside each season ($P$ < 0.05; df 2)

| Tillage system | 2008-09 | 2009-10 | 2010-11 |
|---|---|---|---|
| Chisel plough | 684 ±290 a | 1117 ±353 a | 259 ±216 a |
| Subsoiler | 282 ±243 ab | 489 ±267 ab | 138 ±108 ab |
| Mouldboard plough | 20 ±5 c | 21 ±5 c | 2 ±1 c |
| No-tillage | 73 ±41 bc | 50 ±26 bc | 13 ±7 bc |

**Table 3** Dates at which 50%, 75% and 90% of emergence was predicted each year according to the emergence model developed by García *et al.* (2013)

| Percentage of emergence | HTT | Date at which the corresponding HTT is achieved | | |
|---|---|---|---|---|
| | | 2008-09 | 2009-10 | 2010-11 |
| 50 | 264 | 9 Nov | 26 Oct | 8 Nov |
| 75 | 329 | 18 Nov | 30 Oct | 9 Dec |
| 90 | 406 | 13 Dec | 7 Nov | 20 Feb |

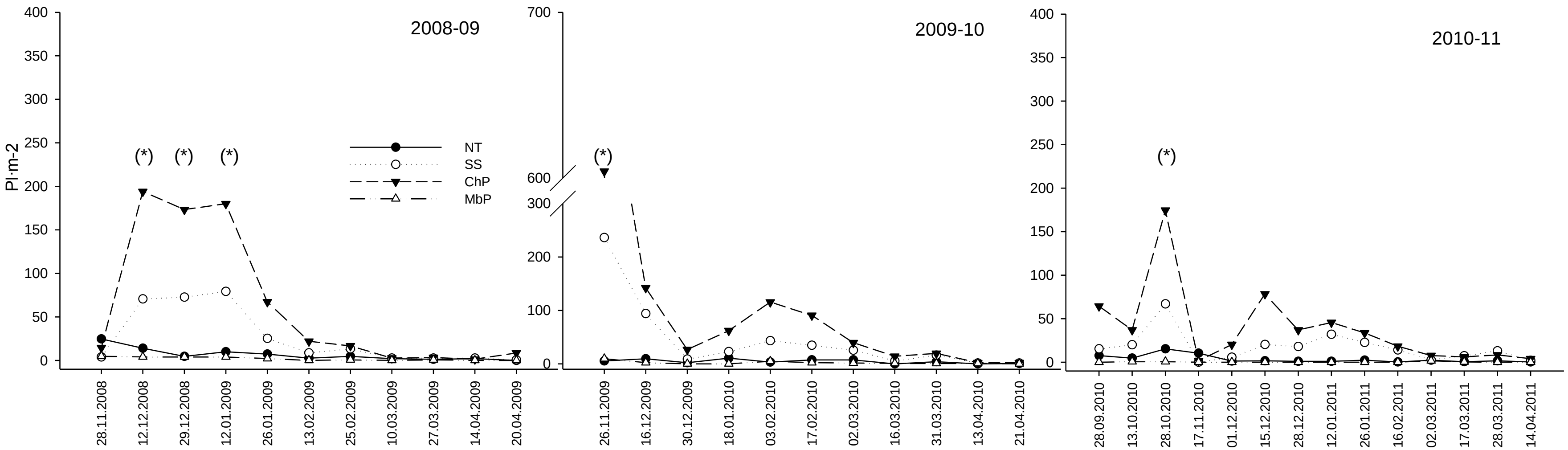
HTT: Hydrothermal time

**Table 4** Density (at the end of the season), fecundity and seed rain of *B. diandrus* and crop yield for different soil management systems during three cropping seasons

Different letters indicate significant differences between soil management systems inside each season ($P < 0.05$).

| **2008-09 season (barley)** | Density ($pl \cdot m^{-2}$) | Fecundity ($seeds \cdot pl^{-1}$) | Seed rain ($seeds \cdot m^{-2}$) | Crop yield ($kg\ ha^{-1}$) |
|---|---|---|---|---|
| Chisel plough | 266 a | | | 3690 b |
| Subsoiler | 208 ab | | | 4698 ab |
| Mouldboard plough | 6 b | | | 5228 a |
| No-tillage | 45 ab | | | 5354 a |
| **2009-10 season** | | | | |
| **(wheat)** | | | | |
| Chisel plough | 241 a | 23 a | 5434 a | 3239 b |
| Subsoiler | 135 a | 31 a | 4162 a | 3983 a |
| Mouldboard plough | 6.0 b | 11 a | 68 b | 4279 a |
| No-tillage | 3 b | 12 a | 33 b | 4379 a |
| **2010-11 season** | | | | |
| **(barley)** | | | | |
| Chisel plough | 75 a | 56 a | 4191 a | 1947 ab |
| Subsoiler | 41 ab | 42 a | 1690 ab | 1963 ab |
| Mouldboard plough | 1 c | 51 a | 15 c | 1676 b |
| No-tillage | 8 bc | 56 a | 425 bc | 2896 a |

**Fig 1**



2008-09
2009-10
2010-11
Pl·m-2
NT
SS
ChP
MbP
(*)
0
50
100
150
200
250
300
350
400
600
700
28.11.2008
12.12.2008
29.12.2008
12.01.2009
26.01.2009
13.02.2009
25.02.2009
10.03.2009
27.03.2009
14.04.2009
20.04.2009
26.11.2009
16.12.2009
30.12.2009
18.01.2010
03.02.2010
17.02.2010
02.03.2010
16.03.2010
31.03.2010
13.04.2010
21.04.2010
28.09.2010
13.10.2010
28.10.2010
17.11.2010
01.12.2010
15.12.2010
28.12.2010
12.01.2011
26.01.2011
16.02.2011
02.03.2011
17.03.2011
28.03.2011
14.04.2011

**Fig. 2**

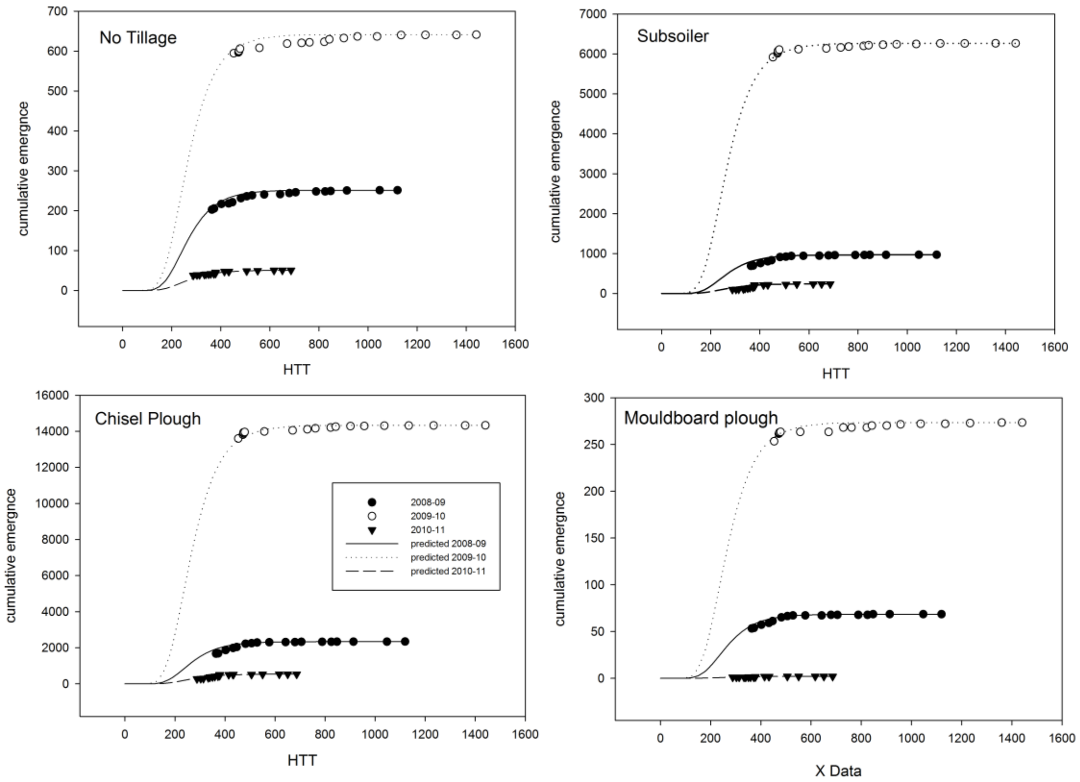

No Tillage
Subsoiler
Chisel Plough
Mouldboard plough
cumulative emergnce
HTT
X Data
2008-09
2009-10
2010-11
predicted 2008-09
predicted 2009-10
predicted 2010-11
0
200
400
600
800
1000
1200
1400
1600

**Fig 3**

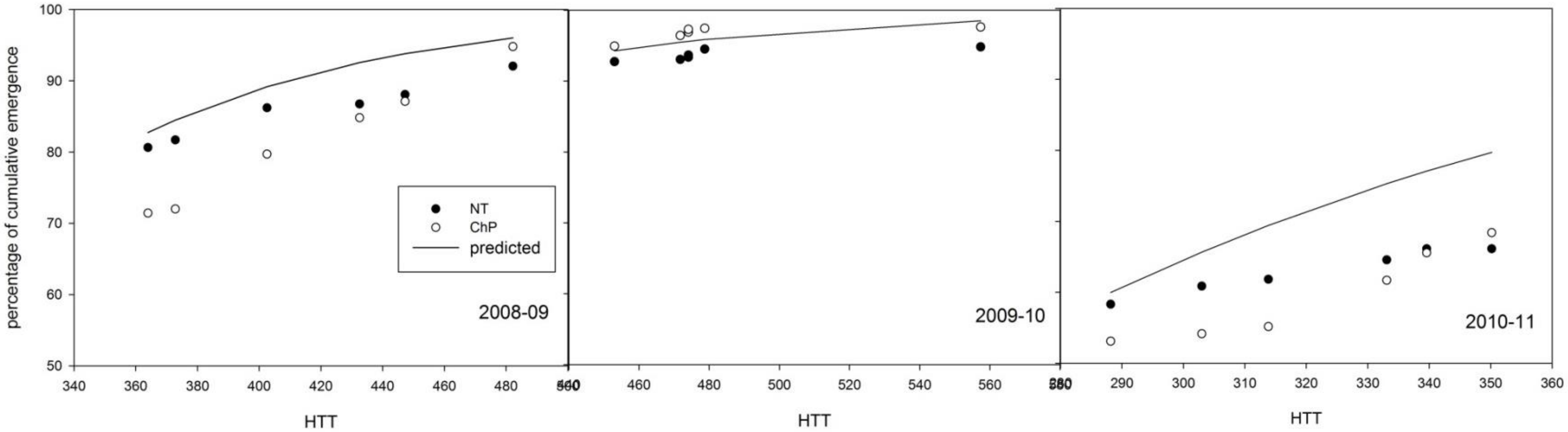
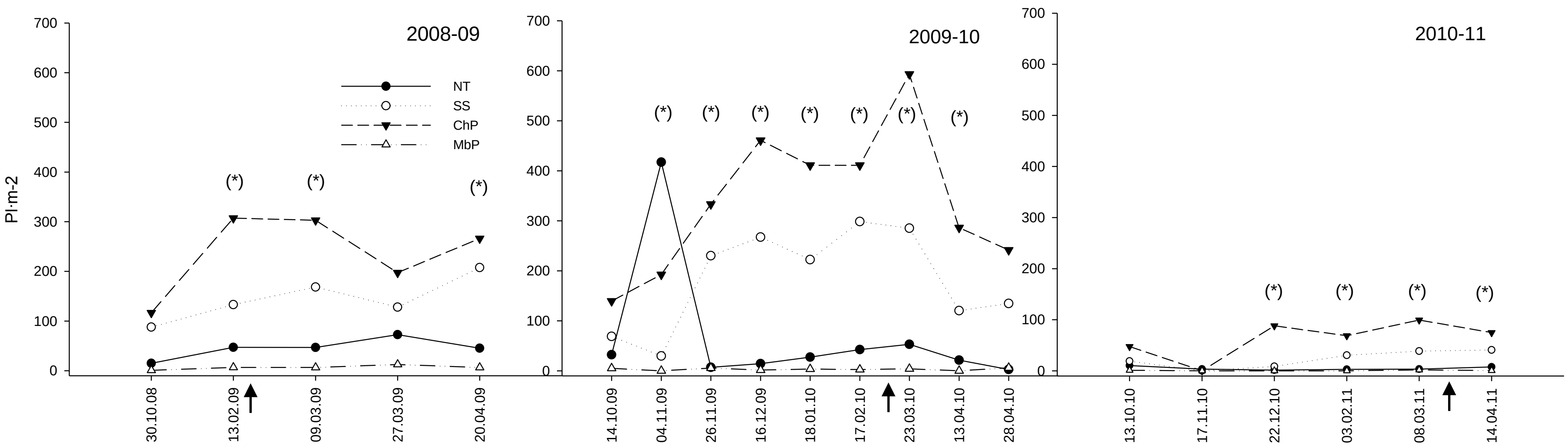

percentage of cumulative emergence
HTT
NT
ChP
predicted
2008-09
2009-10
2010-11

**Fig 4**



2008-09
2009-10
2010-11
NT
SS
ChP
MbP
Pl·m-2
700
600
500
400
300
200
100
0
(*)
30.10.08
13.02.09
09.03.09
27.03.09
20.04.09
14.10.09
04.11.09
26.11.09
16.12.09
18.01.10
17.02.10
23.03.10
13.04.10
28.04.10
13.10.10
17.11.10
22.12.10
03.02.11
08.03.11
14.04.11