Universitat de Lleida

Integrated Management of *Bromus diandrus* in dry land cereal fields under no-till

Addy Laura García

Dipòsit Legal: L.703-2013
http://hdl.handle.net/10803/116328

ADVERTIMENT. L'accés als continguts d'aquesta tesi doctoral i la seva utilització ha de respectar els drets de la persona autora. Pot ser utilitzada per a consulta o estudi personal, així com en activitats o materials d'investigació i docència en els termes establerts a l'art. 32 del Text Refós de la Llei de Propietat Intel·lectual (RDL 1/1996). Per altres utilitzacions es requereix l'autorització prèvia i expressa de la persona autora. En qualsevol cas, en la utilització dels seus continguts caldrà indicar de forma clara el nom i cognoms de la persona autora i el títol de la tesi doctoral. No s'autoritza la seva reproducció o altres formes d'explotació efectuades amb finalitats de lucre ni la seva comunicació pública des d'un lloc aliè al servei TDX. Tampoc s'autoritza la presentació del seu contingut en una finestra o marc aliè a TDX (framing). Aquesta reserva de drets afecta tant als continguts de la tesi com als seus resums i índexs.

ADVERTENCIA. El acceso a los contenidos de esta tesis doctoral y su utilización debe respetar los derechos de la persona autora. Puede ser utilizada para consulta o estudio personal, así como en actividades o materiales de investigación y docencia en los términos establecidos en el art. 32 del Texto Refundido de la Ley de Propiedad Intelectual (RDL 1/1996). Para otros usos se requiere la autorización previa y expresa de la persona autora. En cualquier caso, en la utilización de sus contenidos se deberá indicar de forma clara el nombre y apellidos de la persona autora y el título de la tesis doctoral. No se autoriza su reproducción u otras formas de explotación efectuadas con fines lucrativos ni su comunicación pública desde un sitio ajeno al servicio TDR. Tampoco se autoriza la presentación de su contenido en una ventana o marco ajeno a TDR (framing). Esta reserva de derechos afecta tanto al contenido de la tesis como a sus resúmenes e índices.

WARNING. Access to the contents of this doctoral thesis and its use must respect the rights of the author. It can be used for reference or private study, as well as research and learning activities or materials in the terms established by the 32nd article of the Spanish Consolidated Copyright Act (RDL 1/1996). Express and previous authorization of the author is required for any other uses. In any case, when using its content, full name of the author and title of the thesis must be clearly indicated. Reproduction or other forms of for profit use or public communication from outside TDX service is not allowed. Presentation of its content in a window or frame external to TDX (framing) is not authorized either. These rights affect both the content of the thesis and its abstracts and indexes.

Universitat de Lleida

Departament d` Hortofruticultura, Botànica i Jardineria

Escola Tècnica Superior d`Enginyeria Agraria

Universitat de Lleida

Integrated Management of *Bromus diandrus* in dry land cereal fields under no-till

Memoria para optar al grado de doctor presentada por:

Addy Laura García

Tesis realizada bajo la dirección y tutoría académica de:

Jordi Recasens Guinjuan

Lleida, abril de 2013

Integrated Management of *Bromus diandrus*
in dry land cereal fields under no-till

Memoria de tesis doctoral presentada por Addy Laura García para optar al título de doctor por la Universitat de Lleida

Este trabajo de investigación se ha realizado bajo la dirección y tutoría de Dr. Jordi Recasens Guinjuan del Departamento de Hortofruticultura, Botánica y Jardinería de la Universidad de Lleida

Addy L. García
Doctoranda

Dr. Jordi Recasens Guinjuan
Director de la tesis

Preámbulo

Este proyecto de tesis se ha desarrollado en el seno del grupo de investigación de Malherbología y Ecología Vegetal de la Universidad de Lleida y en el marco de dos proyectos de investigación del Plan Nacional I + D: AGL2007-60828 y AGL 2010-22084-C02-01. Su autora ha sido beneficiaria de una beca pre-doctoral otorgada por la Universidad de Lleida en el periodo 2008-2012, y a su vez de una ayuda para la realización de una estancia de dos meses en USDA-Morris (Estados Unidos).

Como resultado de la tarea llevada a cabo durante la etapa pre-doctoral se han realizado diferentes publicaciones y comunicaciones a congresos que se mencionan a continuación

Publicaciones en revistas científicas indexadas:

A. L. García, J. Recasens, F. Forcella, J. Torra, A. Royo-Esnal. (2013) Hydrothermal emergence model for Ripgut Brome (*Bromus diandrus*). *Weed Science* 61: 146-153.

Publicaciones en revistas de divulgación científica:

A. L. García, J. Torra, A. Royo, C. Maján, C. Cantero, J. Recasens. (2010) Modelización de la emergencia de *Bromus diandrus* en cereales de invierno en sistemas de siembra directa. *Phytoma* 216: 28-32.

A. L. García, J. Torra, A. Royo, C. Cantero, J. Recasens. (2011) Efecto acumulado del sistema de laboreo sobre la densidad de malas hierbas en un cultivo de cebeda. *Tierras*, 181: 73-75.

J. Recasens, J. Torra, X. O. Solé, A. Juárez, A. L. García, J. A. Conesa, A. Royo-Esnal. (2012) ¿La implementación de la siembra directa como medida agroambiental en secanos cerealistas permite mantener también la diversidad vegetal? *Tierras* 194: 52-54.

A. L. García, A. Royo, J. Recasens, J. Torra. (2012) Aptitud biológica de *Bromus diandrus* en un campo de cereal con siembra directa. *Tierras* 195: 67-69.

Comunicaciones orales a congresos:

A. L. García, C. Maján, J. Torra, A. Royo, C. Cantero & J. Recasens. (2009) "Modelización de la emergencia de *Bromus diandrus* en cereales de invierno en sistemas de siembra directa". XII Congreso de la Sociedad Española de Malherbología, XIX Congreso de la Asociación Latinoamericana de Malezas y el II Congreso Iberoamericano de Ciencia de las Malezas. Lisboa, Portugal.

A. L. García; J. Torra; A. Royo; C. Cantero; J. Recasens. (2010) "Maneig cultural d'infestacions de *Bromus diandrus* en cereals d'hivern en sembra directa". IX Jornadas de Protección Vegetal. Barcelona, España.

A. L. García, J. Torra, A. Royo, C. Maján, C. Cantero & J. Recasens. (2010) "Efecto acumulado del sistema de laboreo sobre la densidad de malas hierbas en un cultivo de cebada". European Congress on Conservation Agriculture. Madrid, España.
Recasens, J. Torra, X. O. Solé, A. Juárez, A. L. García, J. Pedrol, J. A. Conesa & A. Royo-Esnal. (2010) "La flora arvense como indicador ecológico de las técnicas de siembra directa como medida agroambiental en secanos cerealistas". European Congress on Conservation Agriculture. Madrid, España.

A. L. García, A. Royo, J. Torra, C. Cantero, J. Recasens. (2011) "Management of delay sowing date in rainfed cereal systems in NE of Spain for control of *Bromus diandrus*" European Weed Research Society. Weed management in arid and semi-arid climate and weed management systems in vegetables. Huesca, España.

A. L. García, A. Royo, J. Recasens, J. Torra. (2011) "Aptitud biológica de *Bromus diandrus* en un campo de cereal con siembra directa". XIII Congreso de la Sociedad Española de Malherbología. San Cristóbal de la Laguna, España.

Comunicaciones en posters a congresos:

J. Torra, A. L. García, C. Majan, A. Royo, C. Cantero, J. Recasens. (2009) **"**Weed emergence patterns in winter cereals under zero tillage in dry land areas". "XIII Colleque Internacional sur la Biologie des Mauvaises Herbes" ENESAD-Dijon, Francia.

A. L. García, J. Torra, A. Royo, C. Cantero, J. Recasens. (2010) "Cultural practices to manage weeds in winter cereals Ander no tillage in dry land fields" 15 th Symposium European Weed Research Society. Kaposvár, Hungría.

Agradecimientos

Son muchas las personas que hicieron posible la realización de esta tesis doctoral y quiero comenzar por agradecer a mi tutor, el Dr. *Jordi Recasens* por la dirección y tutoría de este trabajo, por depositar su confianza en mí para realizar esta tesis, y por el co-financiamiento del 15% de mi ayuda pre-doctoral. Al personal técnico e investigador, por su colaboración en las tareas de campo, a *Aritz*, por su ayuda, revisión y correcciones realizadas en cada capítulo, especialmente en el primer artículo, a *Joel* por su co-dirección en mi proyecto final de máster, contribuciones en congresos y revisión de los capítulos de esta tesis, a *Núria* por su ayuda en la preparación del material de laboratorio y por tantos días de campo. A todos los ayudantes que han pasado por el laboratorio y que también han colaborado en diferentes tareas de campo: *Sergi*, *Anna*, *Jordi*, *Lluc*, así como también a las personas que realizaron sus proyectos final de carrera o trabajo final de máster y por haber colaborado con la recolección de datos, a *Cristina*, *Noemí* y *Laura*.

Al Dr. *Carlos Cantero-Martínez*, del grupo de Agronomía del Departamento de Producción Vegetal y Ciencia Forestal de la Universidad de Lleida, por cedernos las parcelas experimentales, y brindarnos su experiencia, conocimiento y predisposición en todo momento. A *Carlos Cortés* por las tareas de seguimiento y operaciones de campo.

A mis queridos compañeros y amigos de despacho, que me brindaron tan buenos momentos durante estos años, dentro como fuera de la universidad: *Xavi*, *Alex*, *Valentina*, *Irene*, *Harry* y *Bárbara*. *Xavi* y *Alex*, por tantas mañanas entre mates y cafés, por su disposición y apoyo para ayudarme siempre y en cualquier tema, a *Valentina* por ser una gran compañera y amiga, por todo el tiempo compartido y su ayuda especialmente con inglés, a *Irene*, por los almuerzos, charlas, cafés compartidos de cada día, risas y buenos momentos.

Al profesor *Jordi Voltas*, por su ayuda y predisposición en los análisis estadísticos.

Al Dr. *Frank Forcella*, *Dean Peterson* and *Jim* y a toda la gente del laboratorio de suelo del United State Department of Agriculture, Agricultural Research Service, que hicieron de mi estancia en Morris, (Minesotta) una experiencia única y muy agradable.

A *Isis*, *Daia*, *Mikel* y *Raziel*, mis grandes amigos de aventuras, gracias por tantos momentos, salidas y por compartir todo lo que implica realizar la tesis.

A mis padres, *Ana María* y *Pedro*, a mis hermanos, *Flopy* y *Nico*, a mi abuela *Ana*, y a las estrellitas que me guían desde el cielo, gracias por apoyarme, acompañarme y brindarme soporte en mis decisiones siempre y en cada momento a lo largo de todo este tiempo. A mi otra familia *García*, por abrirme las puertas y dejarme entrar en cada uno de ustedes.

A *Álvaro*, por su paciencia, comprensión y cariño incondicional, gracias por entender mis buenos y malos momentos a lo largo de esta tesis.

Índice

RESUMEN

La presente memoria de tesis doctoral incluye diferentes estudios con el fin de analizar el comportamiento biológico de poblaciones de *Bromus diandrus* y su respuesta a diferentes estrategias de manejo en sistemas cerealistas de secano bajo siembra directa, durante las campañas 2008-09, 2009-10 y 2010-11. Estos estudios se desarrollaron en dos parcelas de ensayos experimentales (parcela 1 y parcela 2), pertenecientes al grupo de Agronomía de la Universitat de Lleida y ubicadas en un campo de cereal en la localidad de Agramunt, Lleida. La parcela 1 consistió en un campo donde a lo largo de tres campañas se estableció una rotación cebada – trigo – trigo donde el factor principal considerado fue la fecha de siembra del cultivo. Las fechas de siembra fueron F1: mitad de octubre; F2: mitad de noviembre y F3: principios de diciembre. En la parcela 2 se estableció un ensayo donde desde hace más de 22 años (iniciado la campaña 1990-91) se realizan de forma contínua cuatro tipos distintos de manejo del suelo: chisel, subsolador, siembra directa y vertedera. Durante las tres campañas analizadas se estableció una rotación cebada – trigo – cebada en la parcela 2. En ambas parcelas se utilizó el herbicida mesosulfuron metil + iodosulfuron metil sodio las campañas que se sembró trigo para controlar la población de *B. diandrus*.

Con el fin de describir la emergencia de *B. diandrus* en función de grados hidrotérmicos, se desarrolló un modelo utilizando datos de la cohorte F1 de las campañas 2008-09 y 2009-10 de la parcela 1 y se validó con datos de F1 de la campaña 2010-11 así como también con datos suministrados procedentes de otras localidades. El modelo fue aplicado con éxito en la tercera campaña de la parcela 1 y en tres manejos de la parcela 2.

En el ensayo de la parcela 1 se analizó la influencia de la fecha de siembra (F1, F2, F3) sobre la emergencia y demografía de *B. diandrus.* Los resultados indicaron que en las tres campañas la emergencia acumulada siempre fue significativamente mayor en F1. De acuerdo con el modelo hidrotérmico desarrollado, el retraso en la fecha de siembra del cereal permitió, según campañas, reducciones en la emergencia acumulada entre un 82 y un 97% entre F1 y F2, y entre un 80 y un 99% entre F1 y F3. La eficacia del herbicida mesosulfuron metil + iodosulfuron metil sodio se vió aumentada en F2 y F3 por el retraso fenológico que mostraba la población y por su menor densidad.

A partir de plantas tomadas de la F1, F2 y F3 de la parcela 1 se estudió el efecto del momento de emergencia (cohorte) sobre la fitness de *B. diandrus*, tanto en una situación donde no hubo un herbicida selectivo para su control como donde, a priori, si lo hubo (en trigo las campañas 2009-10 y 2010-11). En ausencia de este herbicida, la cohorte F1 mostró mayor densidad y mayor lluvia de semillas y, a su vez, una respuesta denso-dependiente en los distintos parámetros de fitness analizados excepto en el número de cariópsides por espiguillas. Las plantas supervivientes al herbicida utilizado en trigo, mostraron valores menores para la mayoría de parámetros analizados sin diferencias entre cohortes, y a su vez, unos valores mayores de esfuerzo reproductor. La asignación de recursos mostró distinto gradiente en el peso de las cariópsides según su posición, siendo mayor en espiguillas apicales respecto a aquellas basales dentro de la inflorescencia, y en cariópsides basales respecto a apicales dentro de la espiguilla. Las plantas supervivientes al herbicida selectivo mostraron una clara disrupción en esta distribución de recursos.

En el ensayo de la parcela 2, en las tres campañas, se observó un gradiente decreciente en la emergencia acumulada y densidad de *B. diandrus* en el sentido Chisel > Subsolador > Siembra directa > Vertedera. Estos resultados contradicen la idea de una mayor presencia de esta especie en sistemas de no laboreo. Es de suponer que las razones subyacen en las condiciones presentes en los primeros centímetros del suelo en los distintos sistemas comparados. La dormición inducida por la luz (fotoblastismo negativo) presente en esta especie, podría verse reducida en situaciones de siembra directa debido al sombreo ejercido por el rastrojo y la paja, proceso que parece tener lugar de forma preferente antes de la siembra del cultivo. Un manejo continuado similar permitiría reducir el banco de semillas del suelo con los métodos de control previos a la siembra. A su vez, tras muchos años de un mismo tipo de manejo, resultaría posible la existencia de una dormición adaptativa –prolongada incluso varios meses- que sería más manifiesta en situaciones de laboreo superficial.

La integración de las diferentes estrategias de manejo propuestas en esta tesis permiten establecer un correcto programa de manejo de *B. diandrus* en sistemas cerealistas de secano en siembra directa.

ABSTRACT

The present doctoral thesis includes different studies in order to analyze the biological behavior of *Bromus diandrus* populations and their response to different management strategies in rainfed cereal systems under no-till, during the 2008-09, 2009-10 and 2010-11 growing seasons. These studies were carried out in two experimental plots (plot 1 and plot 2), belonging to the Agronomy Group of the University of Lleida, and located in a cereal field in Agramunt, Lleida. Plot 1 consisted in a field where a barley – wheat – wheat rotation was established over the three seasons, and where the main factor considered was the sowing date of the crop. Sowing dates were F1: mid- October; F2: mid- November and F3: early- December. In plot 2 a trial was conducted continuously for more than 22 years with four different types of soil management: chisel plough, subsoiler, no-tillage and mouldboard plough. During the three analysed seasons a barley – wheat – barley rotation was established in plot 2. In both plots when wheat was sown, the herbicide used to control *B. diandrus* populations was mesosulfuron methyl plus iodosulfuron methyl sodium.

A model based on hydrothermal time was develop to describe the emergence of *B. diandrus* using data of two growing seasons (2008-09 and 2009-10) from F1 in plot 1, and validated with data from F1 in 2010-11, as well as with data supplied from other locations. The model was successfully applied in the three seasons in F2 and F3 of plot 1 and in three management systems of plot 2.

In the plot 1 trial, the influence of sowing date (F1, F2, F3) on the emergence and demography of *B. diandrus* was analyzed. The results indicated that cumulative emergence was always significantly higher in F1 in all seasons. According to the hydrothermal model developed, the late sowing date of cereal allowed reductions of cumulative emergence of 82-97% from F1 to F2, and of 80-99% from F1 to F3. The efficacy of mesosulfuron methyl plus iodosulfuron methyl sodium herbicide was higher in F2 and F3 because of the phenological delay showed by these cohorts and their smaller weed densities.

The effect of the emergence moment (cohort) on *B. diandrus* fitness was studied with plants taken from the F1, F2 and F3 of the plot 1, both in non effective herbicide situation (2008-09) and in selective herbicide situation (2009-10 and 2010-11). In absence of the selective herbicide, cohorts of F1 showed higher densities and more

abundant seed rain, which provoked a density dependent response in the different fitness parameters analysed, except in the number of caryopses per spikelets. Plants surviving the selective herbicide used in wheat showed lower values for most parameters analysed, without differences among cohorts, and in turn higher values of reproductive effort. Allocation of resources also showed a clear decreasing gradient in the weight of caryopsis from basal to apical positions inside the spikelet and from apical to basal spikelets inside the inflorescence. The plants surviving the selective herbicide showed a clear disruption in the distribution of these resources.

In the plot 2 trial, a decreasing gradient in the density and cumulative emergence of *B diandrus* was observed every season as follows: chisel plough > subsoiler> no-tillage > mouldboard plough. These results contradict the idea of a greater presence of this species in no-tilled systems. Presumably, different environmental conditions of the first cm in the soil among the tillage systems could explain these results. The light-induced dormancy (negative photoblastism) of this species could have been reduced in no-tillage situations due to the shade caused by the stubble and the straw, process that appears to occur mainly before the crop sowing. A similarly continued management could reduce the soil seed bank with control methods before sowing. In turn, after many years of the same management system, the possibility of an adaptive dormancy –lasting several months- could take place on seeds in the soil surface of the different tillage situations.

The integration of different management strategies proposed in this thesis establishes a proper *B. diandrus* management program in rainfed cereal systems under no-tillage.

RESUM

La present memòria de tesi doctoral inclou diferents estudis amb la finalitat d'analitzar el comportament biològic de poblacions de *Bromus diandrus* i la seva resposta a diferents estratègies de maneig en sistemes cerealistes de secà mitjançant sembra directa, durant les campanyes 2008-09, 2009-10 i 2010-11. Aquests estudis es van desenvolupar en dues parcel·les d'assajos experimentals (parcel·la 1 i parcel·la 2), pertanyents al grup d'Agronomia de la Universitat de Lleida i situades en un camp de cereal a la localitat d'Agramunt, Lleida. La parcel·la 1 va consistir en un camp on al llarg de tres campanyes es va establir una rotació: ordi – blat – blat on el factor principal considerat va ser la data de sembra del cultiu. Les dates de sembra van ser F1: meitat d'octubre; F2: meitat de novembre i F3: principis de desembre. A la parcel·la 2 es va establir un assaig on des de fa més de 22 anys (iniciat la campanya 1990-91) es realitzen de forma contínua quatre tipus diferents de maneig del sòl: chisel, subsolador, sembra directa i arreu de pales. Durant les tres campanyes analitzades es va establir una rotació ordi – blat – blat en la parcel·la 1 i ordi – blat – ordi en la parcel·la 2. En ambdues parcel·les es va utilitzar l'herbicida mesosulfuron metil + iodosulfuron metil sodi les campanyes que es va sembrar blat amb la finalitat de controlar la població de *B. diandrus*.

Amb la finalitat de descriure l'emergència de *B. diandrus* en funció de graus hidrotèrmics, es va desenvolupar un model utilitzant dades de la cohort F1 de les campanyes 2008-09 i 2009-10 de la parcel·la 1 i es va validar amb dades de la cohort F1 de la campanya 2010-11 així com també amb dades subministrades procedents d'altres localitats. El model va ser aplicat amb èxit en la tercera campanya de la parcel·la 1 i en tres manejos de la parcel·la 2.

En l'assaig de la parcel·la 1 es va analitzar la influència de la data de sembra (F1, F2, F3) sobre l'emergència i demografia de *B. diandrus*. Els resultats van indicar que en les tres campanyes l'emergència acumulada sempre va ésser significativament major en F1. D'acord amb el model d'emergència desenvolupat, el retard en la data de sembra del cereal va permetre, segons campanyes, reduccions en l'emergència acumulada de *B. diandrus* entre un 82 i un 97% entre F1 i F2, i entre un 80 i un 99% entre F1 i F3. L'eficàcia de l'herbicida mesosulfuron metil + iodosulfuron metil sodi es va veure

augmentada en F2 i F3 pel retard fenològic que mostrava la població de mala herba i per la seva menor densitat.

A partir de plantes preses de la F1, F2 i F3 de la parcel·la 1 es va estudiar l'efecte del moment d'emergència (cohort) sobre la fitness de *B. diandrus* tant en una situació on no va haver-hi un herbicida selectiu per al seu control, com on, a priori, si ho es va utilitzar (en blat les campanyes 2009-10 i 2010-11). En absència d'aquest herbicida, la cohort F1 va mostrar major densitat i major pluja de llavors i, al seu torn, una resposta denso-dependent en els diferents paràmetres de fitness analitzats, excepte en el nombre de cariòpsides per espiguetes. Les plantes supervivents a l'herbicida utilitzat en blat, van mostrar valors menors per a la majoria de paràmetres analitzats sense diferències entre cohorts, i al seu torn uns valors majors d'esforç reproductor. L'assignació de recursos va mostrar també un clar gradient decreixent en el pes de les carióps ides des de posicions basals a apicals a l'interior de l'espigueta i des de posicions apicals a basals entre espiguetes dins la inflorescència. Les plantes supervivents a l'herbicida selectiu van mostrar una clara disrupció en aquesta distribució de recursos.

En l'assaig de la parcel·la 2, en les tres campanyes, es va observar un gradient decreixent en l'emergència acumulada i densitat de *B. diandrus* en el sentit chisel > subsolador > sembra directa > arreu de pales. Aquests resultats contradiuen la idea d'una major presència d'aquesta espècie en sistemes de sembra directa. És de suposar que les raons rauen en les condicions presents en els primers centímetres del sòl en els diferents sistemes comparats. La dormició induïda per la llum (fotoblastisme negatiu) present en aquesta espècie, podria veure's reduïda en situacions de sembra directa a causa de l'ombreig exercit pel rostoll i la palla, procés que sembla tenir lloc de forma preferent abans de la sembra del cultiu. Un maneig continuat similar permetria reduir el banc de llavors del sòl amb els mètodes de control químic previs a la sembra. Així, després de molts anys d'un mateix tipus de maneig, resultaria possible l'existència d'una dormició adaptativa –perllongada fins i tot diversos mesos- que seria més manifesta en situacions de labor superficial.

La integració de les diferents estratègies de maneig proposades en aquesta tesi permeten establir un correcte programa de maneig integrat de *B. diandrus* en sistemes cerealistes de secà en sembra directa.

INTRODUCCIÓN GENERAL

Introducción general

Antecedentes

Bromus diandrus es una gramínea anual de invierno, de origen mediterráneo que se ha extendido por diversas regiones del mundo. Su distribución actual alcanza todos los países de la cuenca mediterránea, sudoeste de Europa, América del Norte y Australia (Smith, 1980; Riba y Recasens, 1997). En España, ha sido descrita como una mala hierba en los campos de cereales de muchas zonas de la meseta norte (García- Baudín, 1983). A partir de ahí, el nivel de infestación en los campos de cultivo fue aumentando de forma significativa (Riba y Recasens, 1997). En las últimas décadas, el monocultivo de cereales de invierno, la implementación de técnicas de agricultura de conservación, especialmente la siembra directa, y la ausencia de herbicidas específicos en post-emergencia, han convertido a *B. diandrus* en uno de los problemas mas importantes en estos agro-ecosistemas (Riba y Recasens 1997, Young y Thorne, 2004, Kleemann y Gill, 2006).

La emergencia constituye el evento más importante en el ciclo de las malas hierbas anuales ya que determina el subsiguiente éxito y supervivencia de la planta (Forcella *et al*., 2000). Es por ello que el uso de modelos hidrotérmicos de emergencia, basados en datos de temperatura y potencial hídrico del suelo (Spokas y Forcella, 2009), son una herramienta útil para el manejo integrado de malas hierbas en sistemas cerealistas ya que ayudan a predecir el momento en el que se producirán dichas emergencias y poder, de esta forma, optimizar el momento de control.

El éxito demográfico de *B. diandrus* radica en el alto porcentaje de supervivencia de plántulas y en su alta fecundidad, de acuerdo con la tasa de emergencia que ha tenido lugar en otoño e invierno (Riba y Recasens, 1997). No obstante, estos parámetros difieren según cohortes, reflejando la importancia del momento de emergencia sobre la presión que posteriormente pueda ejercer sobre el cultivo. Las cohortes que emergen inmediatamente después de la siembra del cultivo, representan la fuente principal de aporte de semillas al banco de semillas del suelo (Norris, 2007). Varios autores han realizado importantes aportaciones sobre la biología de *B. diandrus* y su influencia en el rendimiento de los cereales (Gill y Blacklow, 1984; Gill *et al.*, 1987; Kleeman y Gill, 2006; Kleeman y Gill, 2009), sin embargo, pocos estudios han analizado el efecto del momento de emergencia de una cohorte en su posterior fitness reproductora y especialmente en la variación demográfica que pueda haber, a corto plazo, cuando tiene lugar un retraso en la siembra del cultivo.

En los sistemas de no laboreo, la ausencia de remoción del suelo permite a las semillas permanecer cerca de la superficie del suelo, condición favorable para lograr su establecimiento. Por otra parte, muchas semillas de *B. diandrus* poseen cierta dormición (Gill y Corstairs, 1988; Kleeman y Gill, 2006; Kon y Blacklow, 1989), por lo que ese pequeño porcentaje que permanece en el suelo de una estación a otra puede dificultar los métodos de control. En este sentido, el retraso en la fecha de siembra del cultivo podría ser una estrategia de manejo que permitiría eliminar, con las operaciones de presiembra, las plantas que hayan emergido en otoño. Estudios previos han demostrado que el retraso de la siembra del cultivo provoca una disminución significativa de la competencia potencial de ciertas poblaciones de gramíneas y un control más eficaz de las nuevas plantas emergidas (Gill *et al.*, 1987; Powles y Matthews, 1996).

En una etapa muy temprana de la agricultura, el laboreo del suelo fue desarrollado como un medio para facilitar la eliminación de la vegetación presente -el control de las malas hierbas- y promover el desarrollo de los cultivos (Fernández-Quintanilla, 1997). Sin embargo, la implementación de los sistemas de laboreo de conservación, si bien han aportado beneficios económicos y medioambientales, han mostrado ciertas dificultades en el control de las malas hierbas. Entre los casos más conocidos sobresale *B. diandrus.* En los sistemas cerealistas del NE de España y en concreto en Cataluña, la implementación de las técnicas de siembra directa se inició hace más de 25 años. En ese periodo de tiempo *B. diandrus* ha protagonizado, en buena parte, los problemas producidos por las malas hierbas. La ausencia de herbicidas específicos para su control ha dificultado más la posibilidad de establecer estrategias de manejo. Sin embargo, dos hechos que han acaecido en los últimos años, permiten plantear un escenario distinto. Por un lado la aparición de herbicidas antigramíneos con eficacia sobre *B. diandrus* en trigo; por otro, el retraso de siembra del cultivo con el fin de eliminar las nascencias otoñales de esta especie y proceder a su eliminación con herbicidas no selectivos (principalmente glifosato). Precisamente, desde hace unos años, ciertos agricultores que llevan mucho tiempo implementando la siembra directa en sus campos de cereal constatan una menor presencia de *B. diandrus* en sus campos de cultivo y en algunos casos con densidades incluso inferiores a las que muestra en campos donde se continúan realizando labores del suelo mediante chisel o subsolador.

Esta constatación, conduce a plantearnos la posibilidad de desarrollar un programa de manejo integrado de *B. diandrus* de forma que puedan integrarse de forma eficaz métodos de tipo cultural y químico. Para ello resulta imprescindible conocer aspectos sobre su comportamiento biológico y su respuesta a factores que incidan en el comportamiento demográfico de la población.

Objetivos de la tesis

Los principales objetivos de esta tesis fueron:

1- Establecer un modelo de emergencia para *Bromus diandrus* en base a grados hidrotérmicos y validar dicho modelo en escenarios distintos.

2- Conocer la respuesta a medio plazo (tres años) del efecto combinado del retraso de la fecha de siembra del cultivo y la aplicación de un herbicida específico sobre la demografía poblacional de *B. diandrus*.

3- Analizar la fitness reproductiva de *Bromus diandrus*, de acuerdo con el momento de emergencia de las cohortes otoñales, y los posibles cambios que tengan lugar en la misma, en aquellas plantas que sobreviven al efecto de un herbicida antigramíneo.

4- Analizar el efecto acumulado (a largo plazo) de distintos tipos de manejo del suelo (no laboreo, chisel, subsolador y vertedera) sobre el patrón de emergencia y demografía de la población.

Estos objetivos se integran dentro de un marco de manejo integrado que se pretende establecer para esta especie.

Metodología y planteamiento experimental

El estudio fue llevado a cabo en la localidad de Agramunt, en la provincia de Lleida, durante las campañas 2008-09, 2009-10 y 2010-11. Se realizó en dos campos experimentales distintos (parcela 1 y parcela 2) que viene estableciendo desde hace años el grupo de Agronomía de la Universitat de Lleida.

La parcela 1, consistió en un campo experimental donde se estableció una rotación cebada (*Hordeum vulgare*, campaña 2008-09) y trigo (*Triticum aestivum*, campañas 2009-10 y 2010-11) bajo el sistema de siembra directa. Esta parcela tenía un diseño experimental en bloques completamente aleatorizados con tres repeticiones. El factor principal considerado fue la fecha de siembra del cultivo.

La parcela 2, consistió en un campo experimental en el que desde hace 22 años se vienen estableciendo distintos sistemas de manejo del suelo: siembra directa, chisel, subsolador y vertedera. Durante las tres campañas de ensayo se estableció una rotación trigo-cebada-cebada. La parcela tenía un diseño en bloques completamente aleatorizado con tres repeticiones. El factor principal considerado fue el sistema de manejo del suelo.

F1	Bloque 1
F2	
F3	
F1	Bloque 2
F3	
F2	
F2	Bloque 3
F1	
F3	

Parcela de ensayo 1. Diseño en bloques al azar con 3 repeticiones. F1, F2, F3: fechas de siembra

Arado de vertedera	Bloque 3
Subsolador	
Chisel	
Siembra directa	
Siembra directa	Bloque 2
Subsolador	
Chisel	
Arado de vertedera	
Arado de vertedera	Bloque 1
Chisel	
Subsolador	
Siembra directa	

Parcela de ensayo 2. Diseño en bloques al azar con 3 repeticiones

Objetivo 1: Con el propósito de elaborar un modelo que pudiese predecir las emergencias de *B. diandrus* basado en datos de temperatura del aire y humedad del suelo utilizando el software de Spokas y Forcella (2009), se elaboró un modelo hidrotérmico aplicable a diferentes fechas de siembra y localidad. Se procedió a validar el modelo en otras localidades y situaciones distintas (Capítulo 1).

Objetivo 2: El factor considerado fue el momento de siembra del cereal en otoño, con tres niveles (fechas de siembra): F1 mitad de octubre, F2 principios de noviembre y F3 principios de diciembre. Se estimó la emergencia mediante conteos destructivos semanales de plántulas de *B. diandrus* en cinco cuadros fijos de $0.1m^2$. La estimación de la densidad y la evaluación del efecto herbicida post-emergente se realizaron mediante conteos de densidad en momentos concretos a lo largo del ciclo del cultivo. Los resultados y discusión de este estudio corresponden al capítulo 2.

Objetivo 3: Cada año en el mes de junio, se recogieron plantas de *B. diandrus* correspondientes a tres cohortes (F1, F2 y F3) establecidas según las distintas fechas de siembra del cultivo. A partir de ellas se estimaron diferentes parámetros de la fitness vegetativa y reproductiva, peso de 1000 cariópsides y la diferente asignación de recursos a partes reproductoras según las posiciones de las cariópsides en la espiguilla, en función del momento de emergencia de la cohorte y de su respuesta al efecto del herbicida post-emergente. En cada una de estas parcelas se realizaron conteos para estimar la densidad a lo largo del ciclo del cultivo (Capítulo 3).

Objetivo 4: Para analizar el efecto acumulado a largo plazo (22 años) de diferentes tipos de manejo del suelo sobre la demografía de una población de *B. diandrus,* se compararon las emergencias registradas a lo largo del ciclo del cultivo en cuatro tipos de manejo del suelo: laboreo con chisel, subsolador, vertedera y siembra directa. Para determinar la eficacia del herbicida post-emergente se llevaron a cabo conteos de densidad en cada tipo de labor y se lo relacionó con el rendimiento del cultivo obtenido en cada caso. La densidad de *B. diandrus* según el tipo de labor también se relacionó con la fecundidad obtenida y la lluvia de semillas que esas poblaciones aportan a la campaña siguiente (Capítulo 4).

Bibliografía

Fernandez-Quintanilla, C. (1997). Agricultura de conservación. Fundamentos agronómicos, medioambientales económicos y económicos. Eds. García-Torres y González-Fernández. Capítulo 1 (1-12).

Forcella, F., Benech Arnold, R. L., Sánchez, R. and Ghersa, C. M. (2000). Modeling seedling emergence. *Field Crops Research* 67: 123-139.

García- Baudín, J. M. (1983). Weed grasses among grains (wheat and barley) in the Duero region. I. R. No. 9 SEA. Consejo General de Castilla y León. 18 p.

Gill, G. and Blacklow, W. (1984). Efect of great brome (Bromus diandrus Roth.) on the growth of wheat and great brome and their uptake of nitrogen and phosphorus. *Australian Journal of Agricultural Research* 35: 1-8.

Gill, G. S., Poole, M. L. and Holmes, J.E. (1987). Competition bewtween wheat and brome grass in Western Australia. *Australian Journal of Experimental* Agriculture 27: 291-294.

Gill, G. S. and Carstairs, S. A. (1988). Morphological, cytological and ecological discrimination of *Bromus rigidus* from *Bromus diandrus*. *Weed Research* 28: 399-405.

Kleemann, S. G. L. and Gill, G. S. (2006). Differences in the distribution and seed germination behaviour of populations of Bromus rigidus and Bromus diandrus in South Australia: Adaptations to habitat and implications for weed management. *Australian Journal of Agricultural Research* 57: 213-219.

Kleemann, S. G. L. and Gill, G. S. (2009). Population ecology and management of Rigid brome (*Bromus diandrus*) in Australian Cropping Systems. *Weed Science* 57: 202-207.

Kon, K. F. and Blacklow, W. M. (1989). Identification, distribution and population variability of great brome (*Bromus diandrus* Roth) and rigid brome (Bromus rigidus Roth). *Australian Journal of Agricultural Research* 39: 1039-1050.

Norris, R. F. (2007). Weed fecundity: current status and future needs. *Crop protection* 26: 182-188.

Powles S. B. and Matthew S. J. M. (1996). Integrated weed management for the control of herbicide resistant annual ryegrass (*Lolium rigidum*). Proc. II Intnl. Weed Control Congress (407-414). Copenhagen, Denmark, June 25-28.

Riba, F. Recasens, J. (1997). *Bromus diandrus* Roth en cereales de invierno. In: Sans, F. X. y Fernández-Quintanilla C. (editores). La biología de las malas hierbas de España. Ed. *Phytoma España-Sociedad Española de Malherbología*. Pp. 25–35.

Smith, P. M. (1980). *Bromus* L. En: Flora europea. Vol 5. Tutin, T. G., Heywood, V. H.; Bunger, N. A.; Moore, D. M.; Valentine, D. H.; Walters, S. M. and Weeb D. A. Ed. Cambridge University Press. Cambridge. Pp. 182–189.

Spokas, K. and Forcella, F. (2009). Software tools for weed seed germination modeling. *Weed Science* 57: 216-227.

Young, F. L. and Thorne, M. E. (2004). Weed species dynamics and management in no till and reduced till fallow cropping systems for the semi – arid agricultural region of the Pacific Northwest, USA. *Crop Protection* 23: 1097–1110.

CAPÍTULO 1

“Hydrothermal emergence model for *Bromus diandrus*”

El presente capítulo ha sido publicado en la revista Weed Science bajo el título: "Hydrothermal Emergence Model for Ripgut Brome (*Bromus diandrus*)" y cuyos autores son: Addy L. García, Jordi Recasens, Frank Forcella, Joel Torra y Aritz Royo-Esnal. *Weed Science* 2013 Vol 61 (1): 146-153.

Hydrothermal emergence model for *Bromus diandrus*

Introduction

Emergence is considered the most important event in the life of an annual species because it determines subsequent survival and success of the plant (Forcella *et al.*, 2000). The ability to predict weed emergence could enhance crop management, facilitating implementation of more effective strategies by optimizing the timing of weed control (Leblanc *et al.*, 2004; Myers *et al.,* 2004); this is becoming increasingly relevant for growers because of current pressure to reduce chemical input or to adopt nonchemical methods (Grundy *et al.,* 2000). Emergence of several weed species can be predicted using modeling techniques (Colbach *et al.,* 2005). A principal goal of emergence modeling for wild species is to predict germination timing under fluctuating field conditions (Meyer and Allen 2009). Seed germination and emergence are strongly influenced by soil temperature and water potential, and they can be predicted by using modeling techniques based on hydrothermal time (Bair *et al.*, 2006; Haj Seyed Hadi and Gonzalez-Andujar, 2009). Hydrothermal time mechanistically relates the weed seed bank to seedling emergence using soil microclimate simulations (Spokas and Forcella, 2009).

Temperature, when converted to thermal time, or growing degree days (GDD), has been used to predict seedling emergence. The use of average air or soil temperature above a specified threshold is accumulated over days until weed emergence (Royo-Esnal *et al.,* 2010a). Hydrothermal time is a GDD-like measurement that accumulates when daily average soil water potentials and temperatures are greater than threshold values below which seedling emergence cannot occur (Schutte *et al.*, 2008). According to Forcella *et al.,* (2000), hydrothermal time (HTT) models are frequently better for predicting emergence than GDD.

The modeling of emergence of winter weeds from arable land should be especially valuable for climatic conditions of Mediterranean-type environments, where initial weed emergence and crop sowing are governed by the timing of precipitation in autumn, and later emergence is likely to be regulated by soil temperature in addition to soil moisture (Kleemann and Gill, 2006).

Models, as those based on hydrothermal time, have been used to predict the emergence of several winter cereals weeds, oat (*Avena sterilis* ssp. *ludoviciana*) (Leguizamón *et al.,* 2005) and *Galium* species (Royo-Esnal *et al.,* 2010a), under the climatic conditions of dry-land agricultural systems of Spain. In the last decades, the adoption of continuous winter cereal production and the implementation of conservation agriculture techniques, such as direct drilling, have turned great brome (*Bromus diandrus* Roth) into one of the most important weeds in these cereal systems (Riba and Recasens, 1997). Although implementation of models that predict the emergence of *Bromus* species could have great implications for integrated weed management programs, no model has been developed yet.

In no-till systems the absence of soil disturbance permits the seeds to remain near the soil surface, which is a more favorable condition for seedling establishment of some species. Furthermore, some seeds of great brome may be dormant (Gill and Carstairs, 1988; Kleemann and Gill, 2006; Kon and Blacklow, 1989), and those low percentages that remain in the soil from one season to the next could hinder control methods. In this sense, chemical control of great brome is more restricted and difficult than for other weeds because herbicides effective against great brome usually damage the crop as well (Peeper, 1984).

Accordingly, in this scenario, new strategies are needed to manage great brome populations in reduced tillage systems that currently are being adopted in northeastern Spain. For example, delay of sowing date is one of the most practical methods that can be used by growers, as it effectively controls weeds that emerged in October and early November (Cirujeda *et al.,* 2008). However, its efficacy depends on the climatic conditions during autumn, mainly rainfall regimes and soil temperature, and on subsequent emergence of seedlings from the remaining soil seed bank.

To improve these strategies and obtain more effective management, models capable of providing information about the timing of emergence as functions of soil moisture and soil temperature may be useful. Consequently, the objectives of this research were to develop a hydrothermal time seedling emergence model for great brome using data derived from observations in rain fed winter cereals, and to validate and apply the model with independent data from other growing seasons.

Materials and Methods

Experimental site

Field experiments were conducted from autumn to spring 2008 to 2009, 2009 to 2010, and 2010 to 2011 in an experimental cereal field that was managed since 2006 to 2007 under no-tillage. The field was located in Agramunt, Lleida, in northeastern Spain (41°48′N, 1°07′E). The soil was a Fluventic Xerocrept (3.28 to 3.93 feet of deep), with 30.1 % sand, 51.9% silt, 17.9 % clay, 2.3 % organic matter, and pH of 8.5.

Experimental designs

Two experiments were used to first develop the model for the emergence of great brome and its validation, and second for the practical application with different field and soil management systems. The first experiment (trial 1) consisted in a randomized complete block design with three replications. Plot size was 6.56 by 54.68 yards. One factor was considered, the cereal sowing date. The first sowing date (F1) had been on October 20, 19, and 14; the second sowing date (F2) on November 7, 12, and 18; and the third sowing date (F3) on December 12, 3, and 13 in 2008, 2009, and 2010, respectively. Barley (*Hordeum vulgare* L.) cv. ‘Sunrise’ and ‘Hispanic’ were sown in 2008 and wheat (*Triticum aestivum* L.) cv. ‘Bokaro’ and ‘Artur Nick’ in 2009 and 2010. Each year, crops were sown at 180 kg·seed ha^{-1} (400 to 450 plants·m^{-2}). Sowing was performed with a no-till disc drill in rows 0.62 feet apart. Plots were sprayed with glyphosate (Roundup Plus) at 540 g ai ha^{-1} one to six days before each sowing date (October 14, 16, and 13 in F1; November 6, 4, and 12 in F2; and December 5, 2, and 9 in F3, in 2008, 2009, and 2010, respectively). In 2008 to 2009, a post-emergence tank mix of isoproturon plus diflufenican (1243 + 69 g·ha^{-1}) was applied in February. In 2009 to 2010 post-emergence weed control was accomplished by iodosulfuron-methyl sodium plus mesosulfuron-methyl-sodium (3 + 15 g ai·ha^{-1} plus wetting agent). In 2010 to 2011, broadleaf and grass weeds were controlled post-emergence by tribenuron-methyl plus metsulfuron-methyl (10 + 5 g·ha^{-1} plus wetting agent) in March. Iodosulfuron-methyl sodium plus mesosulfuron-methyl-sodium (3 + 15 g ai ha^{-1} plus wetting agent) was applied February 9 in F1 (tillering) and April 13 in F2 and F3 (2 to 5 leaves). Fertilizer was applied each year in February to March at 150 Kg N-32% ·ha^{-1}.

The second experiment (trial 2) also consisted of a randomized complete block with three replications. This experiment was designed to study three different soil management systems: subsoiler (SS), chisel plough (ChP), and moldboard plough (MbP). The sowing date in this experiment corresponds each year to the second sowing dates of trial 1. Crop type and sowing density were the same as in trial 1, except in 2009 to 10 in which was sown barley cv. ‘Hispanic’.

Weed emergence was estimated in each plot in ten permanent quadrats, each 0.1 m^2. After each sowing date, destructive counting of seedlings started and continued weekly until the end of May, except for the third season in trial 1, when counting of seedlings began in mid September (F0), before sowing, and ended in April.

Weather data

Daily rainfall and maximum and minimum air temperatures were obtained from a standard meteorological station located at the experimental fields.

Model development

The model was developed with data from F1 in seasons 2008 to 2009 and 2009 to 2010. Simulated soil temperatures (thermal time, TT) and water potentials (hydrotime, HT) were used to calculate hydrothermal time (HTT) based on the equation described by Roman *et al.*, (2000):

$$\mathrm{HTT} = \sum(\mathrm{HT\,X\,TT})$$

where HT = 1 when $\psi > \psi$b, otherwise HT = 0; and TT = $T - Tb$ when $T > Tb$, otherwise TT = 0. ψ is the daily average water potential in the soil layer from 0 to 5 cm; ψb is the base water potential for seedling emergence; T is the daily average soil temperature in the soil layer from 0 to 5 cm and Tb is the base temperature for seedling emergence (Martinson *et al.*, 2007; Royo-Esnal *et al.*, 2010a). With this formula, growing degree-days are accumulated only when the water potential and temperature conditions were higher than the base water potential and base temperature. The HTT was estimated using the Soil Temperature and Moisture Model (STM^2) (Spokas and Forcella, 2009). STM^2 requires as input daily maximum and minimum air temperatures and daily precipitation, along with information on the geographical location and soil texture and organic matter. HTT were accumulated over days beginning on the date when the main rainfall occurred prior to the first sowing date. The base water potential and base temperature were determined iteratively calculating HTT using a set of water potentials (−2.0 MPa to −0.5 MPa, at −0.1 MPa intervals) and temperatures (0 to 2 C at 1C intervals). Namely, the scale of HTT was changed by modifying the ψb and the Tb until the highest accuracy was obtained for the relationship between HTT and cumulative emergence of great brome. Typically, great brome emergence begins mid- to late summer, but because all emerged seedlings were killed before sowing, hydrothermal time was calculated from the first autumn rains each year.

The functional relationship between cumulative emergence and HTT was described by a sigmoid equation with the best fit. A Chapman equation was used,

$$y = K\left(1 - \left[\exp\{-bx\}\right]\right)^{a}$$

where y is the percentage of emergence, x is time expressed as HTT, and K, b, and a are empirically derived constants. K is the maximum percentage of emergence recorded, b is the rate of increase and a is a shape parameter. Fitting of the Chapman function for cumulative emergence was performed using SAS 9.1 (PROC NLIN; SAS Institute Inc., Cary, NC, USA). Model parameters were further adjusted by nonlinear least-squares regression and the goodness of curve fitting by contrast of joint hypothesis ($P < 0.05$).

Cumulative emergence model validation and readjustment

In the third season (2010 to 2011), emergence data of great brome were also taken before the first sowing date in trial 1 (described as F0). For this reason, the model developed for describing the emergence of great brome was validated with these data (F0), as well as with F1 in 2010 to 2011 and data from Cao *et al.*, (2011), obtained in two other localities of Huelva (South of Spain) in 2005 to 2006 and 2006 to 2007. Agreement between predicted and actual emergence values was determined with the root-mean-square error (RMSE):

$$RMSE = \sqrt{1/n\sum_{i=1}^{n}(x_i - y_i)^2}$$

where xi represents actual cumulative percent emergence, y_i is predicted cumulative percent emergence, and n is the number of observations (Mayer and Butler, 1993). RMSE provided a measurement of the typical difference between predicted and actual values in units of percentage seedling emergence. The RMSE ranges to evaluate the accuracy of the model are based on Royo-Esnal *et al.* (2010b): < 5, excellent prediction; 5 to 10, very good prediction; 10 to 15, good prediction; > 15, insufficient prediction.

When RMSE were not optimally described by these models (RMSE>15) the Chapman equation was modified by adding a lag-phase (z):

$$y = K(1 - [\exp\{-bx - z\}])^{a}$$

The lowest RMSE values indicated that the emergence model fit had been optimized.

Cumulative emergence practical model application

Different sowing dates (F2 and F3 in trial (1) and types of tillage (SS, ChP, and MbP in trial (2) of the three growing seasons were used to evaluate the practical application of the emergence model defined above.

Correction factors were calculated to adjust the cumulative emergence in F2 and F3. Both factors consider prior emergence during the F1. The corrections were 69% and 92% for F2 and F3, respectively, and they represent the percentages of seedling emergence that were eliminated with the delay of the sowing date through seedbed preparation. The correction factor 69% was also used in trial 2 as the crop was sown on the same date as in F2 in trial 1 each year.

Results

The three seasons differed considerably in terms of rainfall (Figure 1a), which represents an ideal situation for development of robust microclimate-based models, but not in temperature. Figure 1b represents the soil temperature and soil water potential in the first 5 cm of depth, calculated with the STM^2 using daily maximum and minimum air temperature (represented as mean air temperature in Figure 1a) and rainfall. Total rainfall from September to harvest (June) in 2008 to 2009 was 500 mm, while in 2009 to 2010 it was 637 mm, and in 2010 to 2011 only 190 mm. Besides the rainfall quantity, number of rainy days also differed between the three seasons (64 in 2008 to 2009, 77 in 2009 to 2010, and 27 in 2010 to 2011, Figure 1a), which is reflected in the soil water potential as long wet or dry periods (Figure 1b). The first season, the average of autumn-winter precipitation was 234 mm (October to February), which fell mainly in October (84 mm). Spring was rainy, with 155 mm between April and May (150 mm in April). In the second season, autumn-winter was wetter (357 mm), while spring was dryer than the previous season (85 mm). In these two seasons there had been short drought periods that are reflected in the soil water potential (Figure 1b). Finally, in 2010 to 2011 autumn-winter resulted extremely dry (13 mm), which decreased considerably the soil water potential, while spring was rainy (156 mm between March and June). For modeling purposes, such great natural variability in magnitudes of driving variables is highly desirable. In the three years, the average winter air temperature (December through February) was 4 C. Overall, the soil and air temperature did not vary significantly from each other as the depth at which soil temperature had been calculated (five cm) is highly influenced by air temperature.

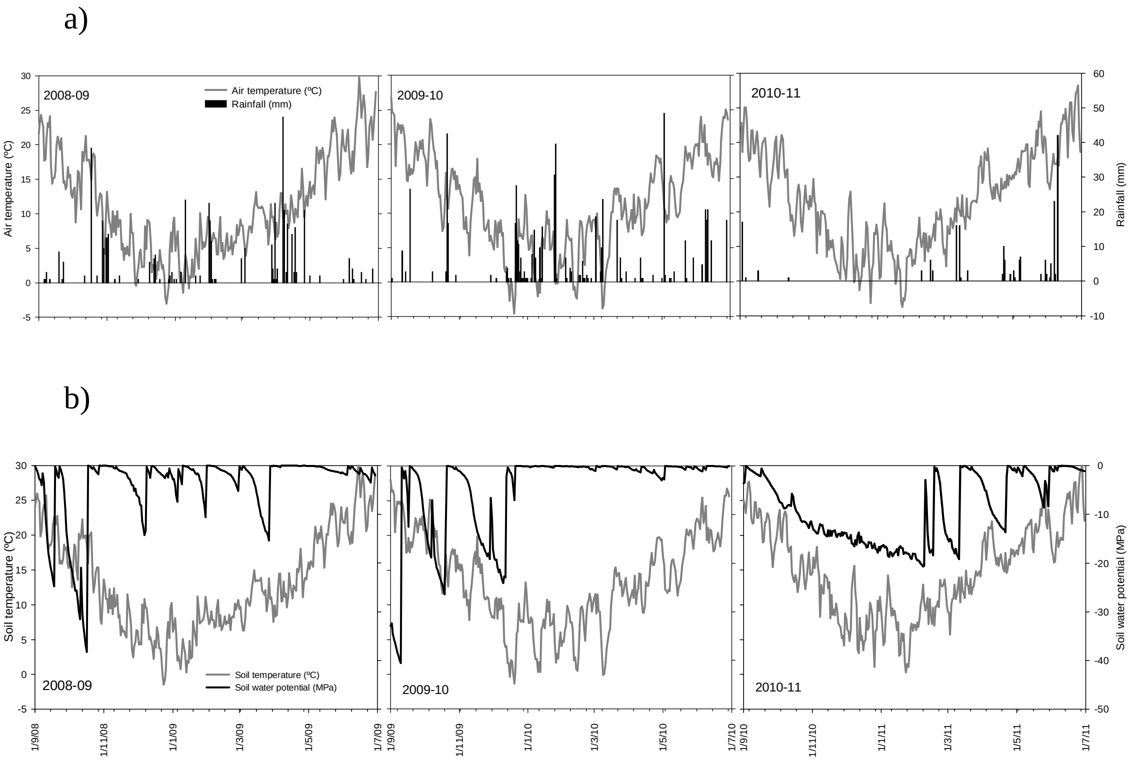

Figure 1a. Air temperature (ºC) and rainfall (mm), 1b. Soil temperature (ºC) and soil water potential (MPa) in the first five cm of depth for seasons 2008-09, 2009-10 and 2010-11.

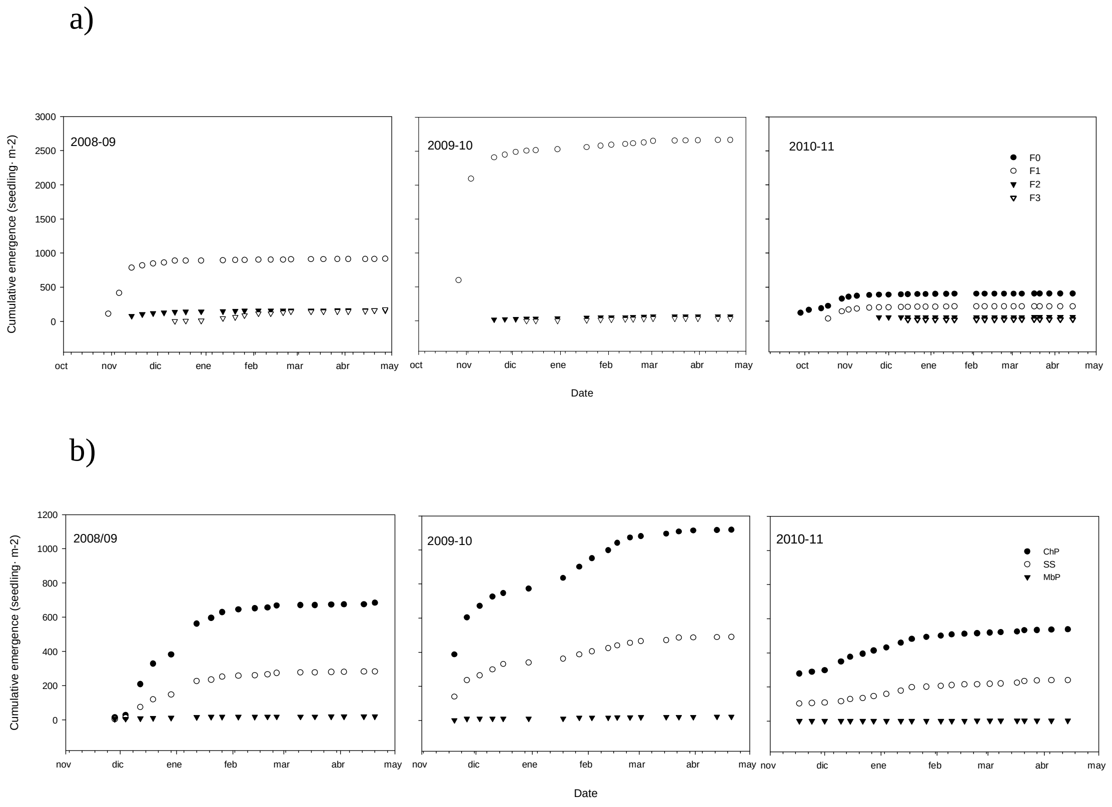

Figure 2. Cumulative emergence of great brome (seedling·m^{-2}) in a) three sowing dates (F0= previous to first sowing date, F1= first sowing date, F2= second sowing date and F3= third sowing date) and in b) three different soil managements throughout the three growing seasons (ChP= chisel plow, SS= subsoiler, and MbP= mouldboard plow).

The cumulative emergence in trial 1 was always higher in F1 than in F2 and F3. The beginning of emergence was coincident in 2008 to 2009 and 2009 to 2010 with rainfalls occurring in October. In 2010 to 2011 rainfalls in autumn only occurred in September. Each growing season shows a decreasing gradient from F1 to F3. In 2008 to 2009, the cumulative emergence of great brome differed according to the delay in sowing date (Figure 2a.). Delay of sowing from F1 to F2 entailed an 82% reduction in the cumulative emergence, and 81% reduction in F1 to F3. Between F2 and F3, percentage of cumulative emergence increased by 7%. In 2009 to 2010, the emergence of great brome in F1 was higher than the year before. The percentage of reduction from F1 to F2, F1 to F3, and F2 to F3 was of 98%, 99%, and 49%, respectively. In general, cumulative emergence in 2010 to 2011 was lower than in 2008 to 2009 and 2009 to 2010 for the three sowing dates, and rainfall was almost nil from October to January. Percentage reduction in cumulative emergence was 73%, 88%, and 56%, respectively, from F1 to F2, F1 to F3 and F2 to F3.

In trial 2, cumulative emergence in ChP was higher than SS and MbP in the three growing seasons and consistently lowest in MbP (Figure 2b). Cumulative emergence was higher in 2009 to 2010 than in 2008 to 2009 and 2010 to 2011. Considering that higher cumulative emergence occurred in ChP than in SS and MbP, a percentage of 100% was assigned to ChP. Accordingly, reductions in cumulative emergence were 59% in SS and 97% in MbP in 2008 to 09. In 2009 to 10 reductions reached 56% in SS and 98% in MbP, and in 2010-11 they were about 48% in SS and 99% in MbP.

Seedling emergence model development

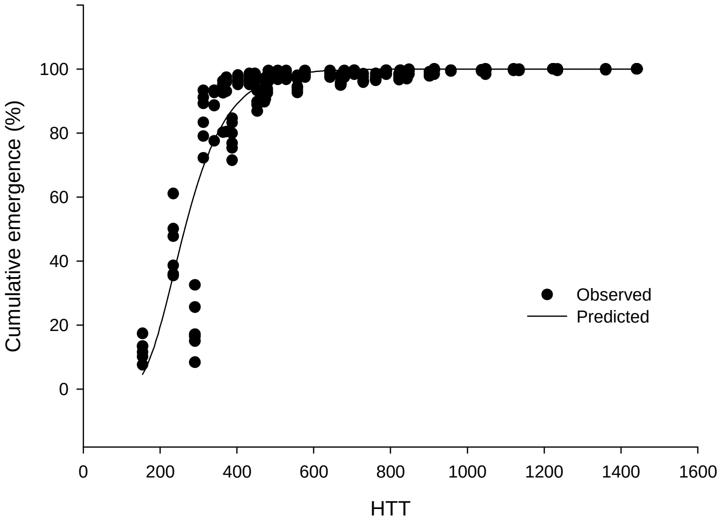

Figure. 3. Observed cumulative emergence of great brome in 2008-09 and 2009-10 and representation of the model developed with these data as a function of hydrothermal time (HTT). Emergence fitted using the Chapman function.

The emergence model (Chapman function) calculated using data from F1 in 2008 to 2009 and 2009 to 2010 is shown in Figure 3. In both seasons, emergence was characterized by a quick flush followed by a more gradual pattern. To optimize emergence model fit, a unique base temperature and base water potential was required. The base temperature and base water potential for HTT were estimated iteratively. The best fitting T_b was determined to be 0 C and the best fitting ψ_b was −1.35 MPa (R^2 = 0.80). Estimates of the variables *K*, *b*, z, and *a* fitted to HTT for great brome are 100, 0.013, ±55, and 21.4, respectively.

Seedling emergence model validation

Figure 4 shows observed and predicted emergence using the Chapman function (above), based on F0 and F1 during 2010 to 2011. Both descriptions showed good fit and reasonable accuracy with predicted emergence (RMSE of 11.4 and 10.9 respectively for F0 and F1). In both cases a lag phase (*z*) was determined by repeatedly testing RMSE, with a final fix at 55 HTT. The model was also validated with emergence data from two locations in Huelva province (Figure 4c).

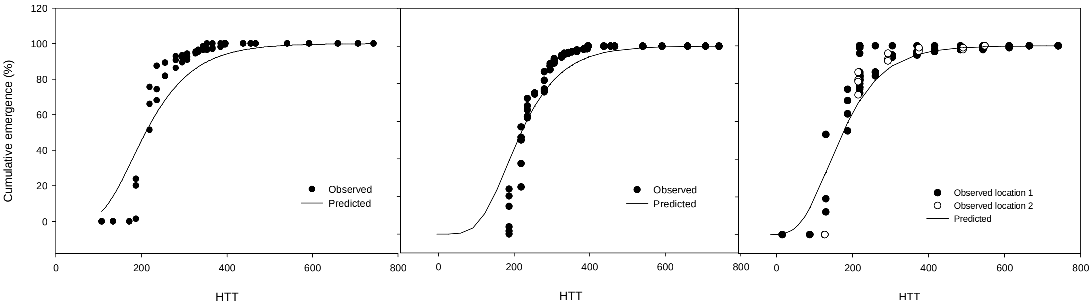

Figure 4. Model validation of cumulative seedling emergence of great brome as a function of hydrothermal time (HTT) in Agramunt (Spain). a) F0, cumulative emergence considered from September. b) F1, cumulative emergence considered from October (sowing date). c) Cumulative emergence using data obtained in Huelva (Cao *et al.*, 2011) L1=location 1 (closed circles), L2= location 2 (open circles). The line represents predicted emergence using the model parameters listed in the text. RMSE: Root Mean Square Error.

Practical application

The emergence model successfully predicted the emergence of F2 and F3 from trial 1 (Figure 5) and those from SS, ChP and MbP from trial 2 (Figure 6) during the three growing seasons.

In trial 1, according to the scale established for the RMSE values, out of six simulations, two were excellent (RMSE < 5), three were very good (RMSE 5 to 10), and one was good prediction (Figure 5). In season 2008 to 2009 and 2009 to 2010, values from F3 were better described (RMSE = 2.2 and 3.3, respectively) than those from F2 (RMSE = 5.3 and 10.1, respectively). In contrast, in season 2010 to 11, F2 showed a slightly better RMSE (5.6) than F3 (7.5). Finally, for F3 values, the 2008 to 2009 growing season (RMSE = 2.2) showed the best fit (Figure 5). Thus, the model described the emergence of F2 and F3 accurately, without adding any lag-phase, however, in some cases the use of a lag phase (established at 55 HTT) improves the fit, as in F2 and F3 in 2009 to 2010.

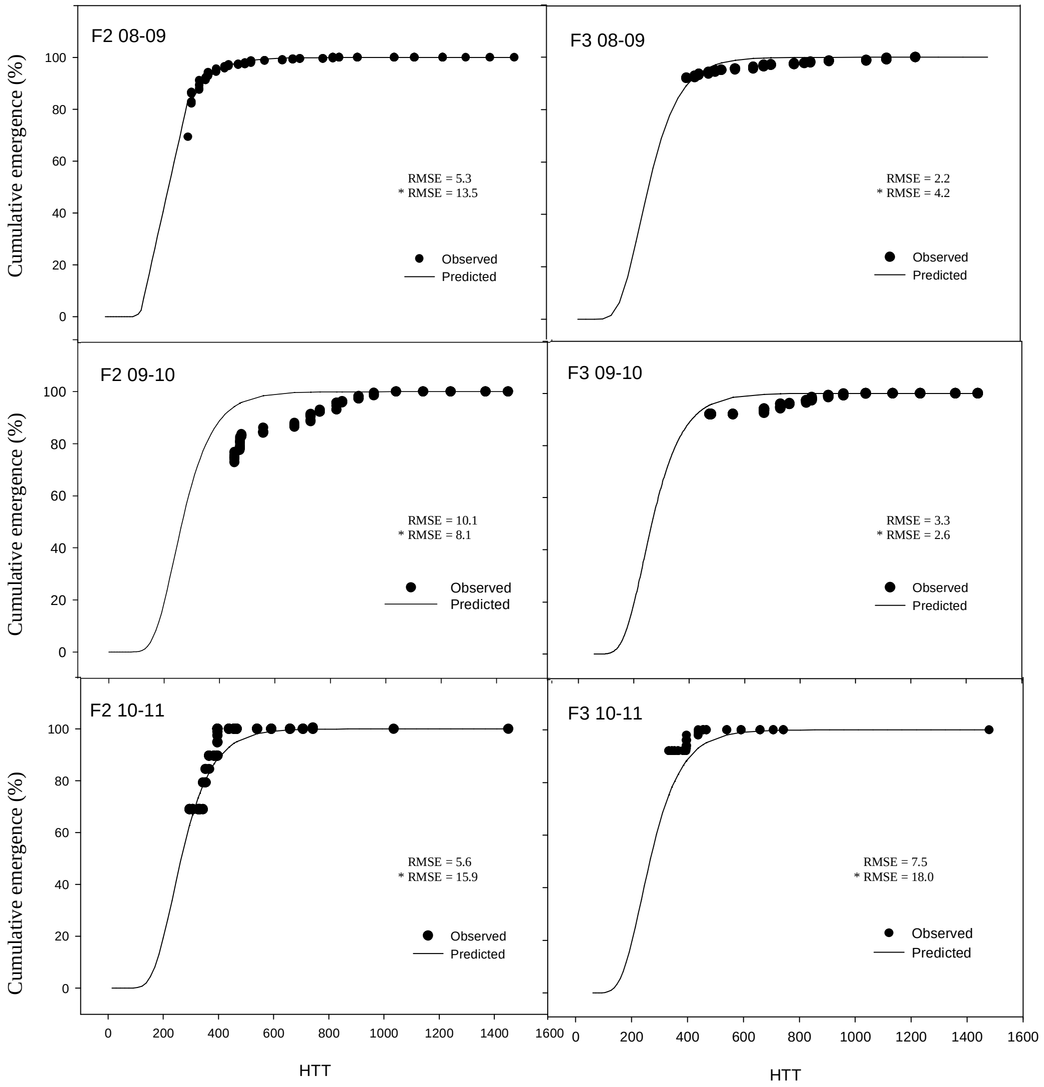

Figure 5. Hydrotermal seedling emergence model application for great brome with delay of the crop sowing date in no-tillage systems in Agramunt (Spain) for three growing seasons, 2008-09, 2009-10 and 2010-11. Root Mean Squarre Error is shown without (RMSE) and with the use of a lag phase of +55 HTT (*RMSE). F2, cumulative emergence (%) from November; and F3, cumulative emergence (%) from December. The line represents predicted emergence by the model developed without the lag phase. Symbols represent observed emergence.

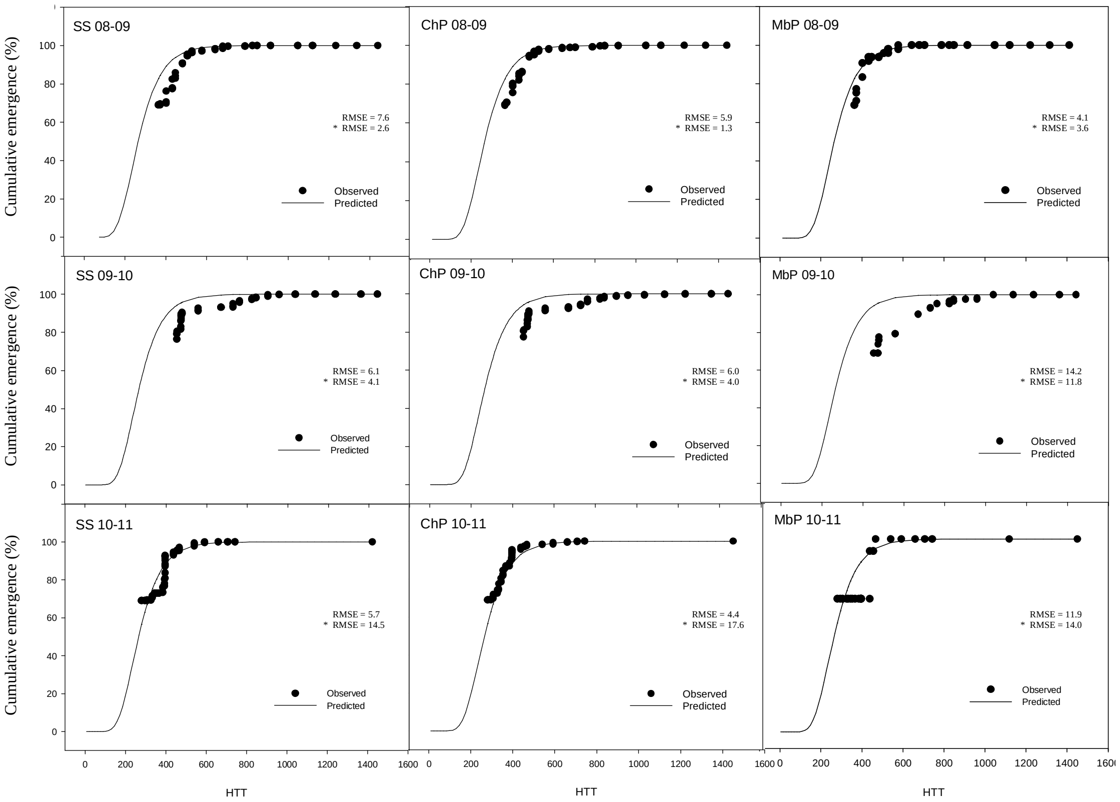

Figure 6. Hydrotermal seedling emergence model application for great brome in differents tillage systems (subsoiler, SS; chisel plow, ChP; and moldboard plow, MbP) in Agramunt (Spain) for three growing seasons 2008-09, 2009-10 and 2010-11. Root Mean Squarre Error is shown without (RMSE) and with lag phase of +55HTT (*RMSE). Lines represent predicted emergence without a lag phase. Symbols represent observed emergence.

Sowing date in the different soil management plots (trial 2) was coincident with F2 in trial 1; therefore the 69% factor correction, explained above, was applied to the emergence values. The model described emergence successfully in the three soil management systems during the three years with completely different weather situations (Figure 6). In the model application in F2 and F3 in trial 1, the use of a lag phase was not necessary because the fits were good. However, in trial 2, the use of a lag phase of 55 HTT, in 2008 to 2009 and 2009 to 2010 improved the fits. This did not happen in 2010 to 2011, when the exclusion of a lag phase was the best option for the description of emergence. The accuracy of this model developed for the emergence of great brome was excellent in two situations, very good in another five and good in the last two situations. The RMSE values of this experiment ranged from 4.4 to 14.2%. ChP was generally better described in the sequence of the three seasons (2008 to 2009, 2009 to 2010, and 2010 to 2011), with RMSE values of 5.9, 6.0, and 4.4, respectively; followed by SS, 7.6, 6.1, and 5.7, respectively; and MbP, 4.1, 14.1, and 11.9, respectively) (Figure 6).

Discussion

Germination and emergence are basic processes in the survival and success of a plant (Del Monte and Dorado, 2011) and the ability to predict weed emergence could enhance crop management by facilitating the implementation of more effective weed control strategies through the optimization of the timing of weed control (Leblanc *et al.*, 2004; Myers *et al.,* 2004). Cumulative emergence of great brome in trial 1 was higher in F1 than in F2 and F3 regardless of the season. According to some reports, the first cohort of seedlings contributes more to stand biomass and subsequent seed production as well as stronger competition with associated crops, thereby having the largest contribution to the next generation (Cao *et al.,* 2011). Total cumulative emergence was higher in 2009 to 2010 than in 2008 to 2009. The absence of a selective herbicide in barley, favored the growth and development of great brome and, therefore, its contribution to the soil seed bank was higher in the following year. The use of selective herbicides for great brome control in wheat provoked a reduction of fecundity (data not shown) in 2009 to 2010. For this same reason, together with the drought suffered in autumn 2010 to 2011, a reduction of total cumulative emergence occurred that season.

Kleemann and Gill (2006) showed rapid germination of seeds of great brome following initial autumn rains. In these experiments similar trends were observed, i.e., beginning of great brome emergence was coincident with rainfall periods. According to Riba (1993) germination and emergence could occur under a wide period of time, ranging from late summer to mid-winter, although it is concentrated in the autumn.

In trial 2 cumulative emergence was higher in chisel plow followed by the subsoiler and moldboard plow. An explanation for this order in soil management systems is that seeds may need only a superficial covering of soil to perceive darkness. As long as the embryo remains buried, it is likely to germinate, and this is facilitated by the way the seed falls to the ground and can be wedged into the soil (Del Monte and Dorado, 2011). Thus, the chisel plow deposits a thin layer of soil over the seeds, which allows germination. In contrast, in moldboard ploughed plots, which had the lowest cumulative emergence observed, soil inversion positioned seeds too deep to emerge. This also occurs in the related rigid brome (*Bromus rigidus* Roth) (Gleichsner and Appleby, 1989).

Hydrothermal time seedling emergence

Hydrothermal time emergence models that base predictions on field observations during previous growing seasons offer relatively robust predictions and with simple inputs and development (Forcella *et al.,* 2000). The model developed in this work seems to be strong enough, as it was developed with data from two completely different seasons in terms of rainfall, and it has been validated with a third season in the same field, as well as with independent data from the south of Spain (Huelva).

The water potential with which emergence of great brome was best explained was −1.35 MPa. In contrast, Del Monte and Dorado (2011) observed in a lab conditions that high germination percentages (above 75%) of great brome were obtained in darkness with water potentials ≥ −0.4 MPa. Germination in the lab was significantly lower, but still appreciable at −1.25 MPa. Thus, our field- and simulation-derived value of −1.35 MPa may be deduced as the base water potential while ≥ −0.4 MPa is the optimal water potential for the germination (and emergence) of this weed. To optimize emergence model fit, a unique base water potential is required (Schutte *et al.,* 2008). This base water potential may not be the best for any particular season, but it is the best overall for describing the three seasons with a robust model.

An advantage of the Chapman equation is the use of only three parameters that, in turn, makes it a simple model. The model predicted seedling emergence in different locations (Agramunt and Huelva) with reasonable accuracy. The RMSE values of this experiment calculated for model validation, (11.4 in F0, 10.9 in F1, and 12.6 and 14.0 in Huelva) were similar to RMSE values for model validation in other studies for common lambsquarters (*Chenopodium album*) (Roman *et al.,* 2000), tropic ageratum (*Ageratum conyzoides*) (Ekeleme *et al.,* 2005), and *Galium* spp. (Royo-Esnal *et al.,* 2010a).

Practical application

An interesting part of this model is that it could have been applied in other management systems (in the same locality where it was developed), which implies a wide range of situations where it probably can be used. All of the RMSE values obtained in the practical applications were below 15, indicating a very good predictive capability. The use of the lag phase in some cases further improved the fit of the model to the observed data.

The model applied to F2 and F3 in the three growing seasons showed slightly better accuracy for F3 than for F2. This could have happened because 92% of the population was destroyed by seedbed preparation and the correction factor left very low variation for K values (100%). The lack of need of a lag phase in these results is remarkable and gives a more robust basis to the model, which we believe is valid for rainfed cereal systems where sowing dates are often variable.

Great brome is a common weed present in many tillage systems, although it is associated with no-till (Kleemann and Gill, 2006). For this reason showing how the model predicted the emergence of great brome in other soil managements was important. Therefore, the model also was applied to chisel ploughed, subsoiled and moldboard ploughed areas. In fact, the RMSE values obtained from these comparisons strengthened the perceived value of the model, as all were below 15 (without use of a lag phase). In some cases, however, the use of a lag phase did improve the fit of the model to the observed data. This might imply that the description of the emergence could still be improved, maybe with the inclusion of other factors that have not been used here, such as remnant seed dormancy alleviation. Regarding differences in accuracy of the model among tillage systems, it was somewhat less accurate in MbP than in SS and ChP. This likely happened because of the much lower seedling densities in MbP than the other soil management systems, with a corresponding decrease in reliability of the MbP data.

To summarize, soil temperature and soil moisture seem to be the determinant factors driving emergence of great brome, as they are in other weeds (Forcella *et al.*, 2000; Roman *et al.*, 2000; Royo-Esnal *et al.*, 2010a). With these two factors, a model that describes the emergence of this weed was developed and demonstrated to be robust and reliable, as it was validated with four different data sets and put into practice in five management systems (two sowing delays and three soil tillage practices) over three years. The model can be used henceforth to improve control and management of great brome.

References

Bair, N. B., S. E. Meyer and P. S. Allen. (2006). A hydrothermal after-ripening time model for seed dormancy loss in *Bromus tectorum* L. *Seed Science Research* 16: 17–28.

Cao, R., M. Francisco-Fernandez, A. Anand, F. Bastida and J. L. Gonzalez-Andujar.

(2011). Computing statistical indices for hydrothermal times using weed emergence data. *Journal of Agriultural Science* 149: 701–712.

Cirujeda, A., Recasens, J., Torra, J. and Taberner, A. (2008). A germination study of herbicide-resistant field poppies in Spain. *Agronomy for Sustainable Development* 28: 207–220.

Colbach, N., C. Dürr, J. Roger-Estrade and J. Caneill. (2005). How to model the effects of farming practices on weed emergence. *Weed Research* 45: 2–17.

Del Monte, J. P. and J. Dorado. (2011). Effects of light conditions and after-ripening time on seed dormancy loss of *Bromus diandrus* Roth. *Weed Research* 51: 581–590.

Ekeleme, F., F. Forcella, D. W. Archer, I. O. Akobundu and D. Chikoye. (2005). Seedling emergence model for tropic ageratum (*Ageratum conyzoides*). *Weed Science* 53: 55–61.

Forcella, F., R. L. Benech Arnold, R. Sanchez and C. M. Ghersa. (2000). Modeling seedling emergence. *Field Crops Research* 67: 123–139.

Gill, G. S. and S. A. Carstairs. (1988). Morphological, cytological and ecological discrimination of *Bromus rigidus* from *Bromus diandrus*. *Weed Research* 28: 399–405.

Gleichsner, J. A. and A. P. Appleby. (1989). Effect of Depth and Duration of Seed Burial on Ripgut Brome (*Bromus rigidus*). *Weed Science* 37: 68–72.

Grundy, A. C., K. Phelps, R. J. Reader and S. Burston. (2000). Modeling the germination of *Stellaria media* using the concept of hydrothermal time. *New Phytology* 148: 433–444.

Haj Seyed Hadi, M. R. and J. L. Gonzalez-Andujar. (2009). Comparison of fitting weed seedling emergence models with nonlinear regression and genetic algorithm. *Computers and Electronics in Agriculture* 65: 19–25.

Kleemann, S. G. L. and G. S. Gill. (2006). Differences in the distribution and seed germination behaviour of populations of *Bromus rigidus* and *Bromus diandrus* in South Australia: Adaptations to habitat and implications for weed management. *Australian Journal of Agricultural Research* 57: 213–219.

Kon, K. F. and W. M. Blacklow. (1989). Identification, distribution and population variability of great brome (*Bromus diandrus* Roth) and rigid brome (*Bromus rigidus* Roth). *Australian Journal of Agricultural Research* 39: 1039–1050.

Leblanc, M. L., D. C. Cloutier, K. A. Stewart and C. Hamel. (2004). Calibration and validation of a common lambsquarters (*Chenopodium album*) seedling emergence model. *Weed Science* 52: 61–66.

Leguizamón, E. S., C. Fernandez-Quintanilla, J. Barroso and J. L. Gonzalez-Andujar. (2005). Using thermal and hydrothermal time to model seedling emergence of *Avena sterilis* ssp. *ludoviciana* in Spain. *Weed Research* 45: 149–156.

Martinson, K., B. Durgan, F. Forcella, J. Wiersma, K. Spokas and D. Archer. (2007). An emergence model for wild oat (*Avena fatua*). *Weed Science* 55: 584–591.

Mayer, D.G. and D.G. Butler. (1993). Statistical validation. *Ecological Modelling* 68: 21–32.

Meyer, S.E. and P.S. Allen. (2009). Predicting seed dormancy loss and germination timing for *Bromus tectorum* in a semi-arid environment using hydrothermal time models. *Seed Science Research* 19: 225–239.

Myers, M. W., W. S. Curran, M. J. VanGessel, D. D. Calvin, D. A. Mortensen, B. A. Majek, H. D. Karsten and G. W. Roth. (2004). Predicting weed emergence for eight annual species in the northeastern United States. *Weed Science* 52: 913–919.

Peeper, T. F. (1984). Chemical and biological control of downy brome (Bromus tectorum) in wheat and alfalfa in North America. *Weed Science* 32: 18–24.

Riba, F. (1993). *Demography and population dynamics of Bromus diandrus Roth in winter cereals.* PhD dissertation. University of Lleida. 117 p.

Riba, F., Recasens, J. (1997). *Bromus diandrus* Roth en cereals de invierno. In: Sans, F. X. y Fernández-Quintanilla C. (editores). *La biología de las malas hierbas de España.* Ed. Phytoma España-Sociedad Española de Malherbología. (25–35).

Roman, E. S., S. D. Murphy and C. J. Swanton. (2000). Simulation of *Chenopodium album* seedling emergence. *Weed Science* 48: 217–224.

Royo-Esnal, A., J. Torra, J. A. Conesa, F. Forcella and J. Recasens. (2010a). Modeling the emergence of three arable bedstraw (*Galium*) species. *Weed Science* 58: 10–15.

Royo-Esnal, A., J. Torra, J. A. Conesa and J. Recasens. (2010b). Characterization of emergence of autumn and spring cohorts of *Galium* spp. in winter cereals. *Weed Science* 50: 572–585.

Schutte, B. J., E. E. Regnier, S. K. Harrison, J. T. Schmoll, K. Spokas and F. Forcella. (2008). A hydrothermal seedling emergence model for giant ragweed (*Ambrosia trifida*). *Weed Science* 56: 555–560.

Spokas, K. and F. Forcella. (2009). Software tools for weed seed germination modeling. *Weed Science* 57: 216–227.

Weed Science 2013 61:146–153

Hydrothermal Emergence Model for Ripgut Brome (*Bromus diandrus*)

Addy L. García, Jordi Recasens, Frank Forcella, Joel Torra, and Aritz Royo-Esnal*

A model that describes the emergence of ripgut brome was developed using a two-season data set from a no-tilled field in northeastern Spain. The relationship between cumulative emergence and hydrothermal time (HTT) was described by a sigmoid growth function (Chapman). HTT was calculated with a set of water potentials and temperatures, iteratively used, to determine the base water potential and base temperature. Emergence of ripgut brome was well described with a Chapman function. The newly-developed function was validated with four sets of data, two of them belonging to a third season in the same field and the other two coming from independent data from Southern Spain. The model also successfully described the emergence in different field management and tillage systems. This model may be useful for predicting ripgut brome emergence in winter cereal fields of semiarid Mediterranean regions.

Nomenclature: Ripgut brome, *Bromus diandrus* Roth.
Key words: Chapman function, great brome, hydrothermal time, sowing delay, tillage systems.

Emergence is considered the most important event in the life of an annual species because it determines subsequent survival and success of the plant (Forcella et al. 2000). The ability to predict weed emergence could enhance crop management, facilitating implementation of more effective strategies by optimizing the timing of weed control (Leblanc et al. 2004; Myers et al. 2004); this is becoming increasingly relevant for growers because of current pressure to reduce chemical input or to adopt nonchemical methods (Grundy et al. 2000). Emergence of several weed species can be predicted using modeling techniques (Colbach et al. 2005). A principal goal of emergence modeling for wild species is to predict germination timing under fluctuating field conditions (Meyer and Allen 2009). Seed germination and emergence are strongly influenced by soil temperature and water potential, and they can be predicted by using modeling techniques based on hydrothermal time (Bair et al. 2006; Haj Seyed Hadi and Gonzalez-Andujar 2009). Hydrothermal time mechanistically relates the weed seed bank to seedling emergence using soil microclimate simulations (Spokas and Forcella 2009).

Temperature, when converted to thermal time, or growing degree days (GDD), has been used to predict seedling emergence. The use of average air or soil temperature above a specified threshold is accumulated over days until weed emergence (Royo-Esnal et al. 2010a). Hydrothermal time is a GDD-like measurement that accumulates when daily average soil water potentials and temperatures are greater than threshold values below which seedling emergence cannot occur (Schutte et al. 2008). According to Forcella et al. (2000), hydrothermal time (HTT) models are frequently better for predicting emergence than GDD.

The modeling of emergence of winter weeds from arable land should be especially valuable for climatic conditions of Mediterranean-type environments, where initial weed emergence and crop sowing are governed by the timing of precipitation in autumn, and later emergence is likely to be regulated by soil temperature in addition to soil moisture (Kleemann and Gill 2006).

Models, as those based on hydrothermal time, have been used to predict the emergence of several winter cereals weeds, oat (*Avena sterilis* ssp. *ludoviciana*) (Leguizamón et al. 2005) and *Galium* species (Royo-Esnal et al. 2010a), under the climatic conditions of dry-land agricultural systems of Spain. In the last decades, the adoption of continuous winter cereal production and the implementation of conservation agriculture techniques, such as direct drilling, have turned ripgut brome (*Bromus diandrus* Roth) into one of the most important weeds in these cereal systems (Riba and Recasens 1997). Although implementation of models that predict the emergence of *Bromus* species could have great implications for integrated weed management programs, no model has been developed yet.

In no-till systems the absence of soil disturbance permits the seeds to remain near the soil surface, which is a more favorable condition for seedling establishment of some species. Furthermore, some seeds of ripgut brome may be dormant (Gill and Carstairs 1988; Kleemann and Gill 2006; Kon and Blacklow 1989), and those low percentages that remain in the soil from one season to the next could hinder control methods. In this sense, chemical control of ripgut brome is more restricted and difficult than for other weeds because herbicides effective against ripgut brome usually damage the crop as well (Peeper 1984).

Accordingly, in this scenario, new strategies are needed to manage ripgut brome populations in reduced tillage systems that currently are being adopted in northeastern Spain. For example, delay of sowing date is one of the most practical methods that can be used by growers, as it effectively controls weeds that emerged in October and early November (Cirujeda et al. 2008). However, its efficacy depends on the climatic conditions during autumn, mainly rainfall regimes and soil temperature, and on subsequent emergence of seedlings from the remaining soil seed bank.

To improve these strategies and obtain more effective management, models capable of providing information about the timing of emergence as functions of soil moisture and soil temperature may be useful. Consequently, the objectives of this research were to develop a hydrothermal time seedling emergence model for ripgut brome using data derived from observations in rain fed winter cereals, and to validate and apply the model with independent data from other growing seasons.

Materials and Methods

Experimental Site. Field experiments were conducted from autumn to spring 2008 to 2009, 2009 to 2010, and 2010 to

---

DOI: 10.1614/WS-D-12-00023.1

* First, second and fifth authors, PhD Student, Professor, and Researcher, Dto Hortofruticultura, Botànica i Jardineria, ETSEA, Universitat de Lleida, Lleida, Spain; third author, Research Agronomist, USDA-ARS Lab, Morris, Minnesota, USA; fourth author, Researcher, Fundació Centre UdL-IRTA. Lleida. Spain. Corresponding author's Email: addylau@hbj.udl.cat

2011 in an experimental cereal field that was managed since 2006 to 2007 under no-tillage. The field was located in Agramunt, Lleida, in northeastern Spain (41°48′N, 1°07′E). The soil was a Fluventic Xerocrept (100 to 120 cm deep), with 30.1% sand, 51.9% silt, 17.9% clay, 2.3% organic matter, and pH of 8.5.

Experimental Designs. Two experiments were used to first develop the model for the emergence of ripgut brome and its validation, and second for the practical application with different field and soil management systems. The first experiment (trial 1) consisted in a randomized complete block design with three replications. Plot size was 6 by 50 m. One factor was considered, the cereal sowing date. The first sowing date (F1) had been on October 20, 19, and 14; the second sowing date (F2) on November 7, 12, and 18; and the third sowing date (F3) on December 12, 3, and 13 in 2008, 2009, and 2010, respectively. Barley (*Hordeum vulgare* L.) cv. 'Sunrise' and 'Hispanic' were sown in 2008 and wheat (*Triticum aestivum* L.) cv. 'Bokaro' and 'Artur Nick' in 2009 and 2010. Each year, crops were sown at 180 kg·seed ha^{-1} (400 to 450 plants·m^{-2}). Sowing was performed with a no-till disc drill in rows 19 cm apart. Plots were sprayed with glyphosate (Roundup Plus) at 540 g ai ha^{-1} one to six days before each sowing date (October 14, 16, and 13 in F1; November 6, 4, and 12 in F2; and December 5, 2, and 9 in F3, in 2008, 2009, and 2010, respectively). In 2008 to 2009, a POST tank mix of isoproturon plus diflufenican (1243 + 69 g·ha^{-1}) was applied in February. In 2009 to 2010 POST weed control was accomplished by iodosulfuron-methyl sodium plus mesosulfuron-methyl-sodium (3 + 15 g ai ha^{-1} plus wetting agent). In 2010 to 2011, broadleaf and grass weeds were controlled POST by tribenuron-methyl plus metsulfuron-methyl(10 + 5 g·ha^{-1} plus wetting agent) in March. Iodosulfuron-methyl sodium plus mesosulfuron-methyl-sodium (3 + 15 g ai ha^{-1} plus wetting agent) was applied February 9 in F1 (tillering) and April 13 in F2 and F3 (2 to 5 leaves). Fertilizer was applied each year in February to March at 150 kg N-32% ·ha^{-1}.

The second experiment (trial 2) also consisted of a randomized complete block with three replications. This experiment was designed to study three different soil management systems: subsoiler (SS), chisel plough (ChP), and moldboard plough (MbP). The sowing date in this experiment corresponds each year to the second sowing dates of trial 1. Crop type and sowing density were the same as in trial 1, except in 2009 to 10 in which was sown barley cv. 'Hispanic'.

Weed emergence was estimated in each plot in ten permanent quadrats, each 0.1 m^2. After each sowing date, destructive counting of seedlings started and continued weekly until the end of May, except for the third season in trial 1, when counting of seedlings began in mid September (F0), before sowing, and ended in April.

Weather Data. Daily rainfall and maximum and minimum air temperatures were obtained from a standard meteorological station located at the experimental fields.

Model Development. The model was developed with data from F1 in seasons 2008 to 2009 and 2009 to 2010. Simulated soil temperatures (thermal time, TT) and water potentials (hydrotime, HT) were used to calculate hydrothermal time (HTT) based on the equation described by Roman et al. (2000):

$$\mathrm{HTT} = \sum (\mathrm{HT} \times \mathrm{TT}) \qquad [1]$$

where HT = 1 when $\psi > \psi b$, otherwise HT = 0; and TT = $T - Tb$ when $T > Tb$, otherwise TT = 0. ψ is the daily average water potential in the soil layer from 0 to 5 cm; ψb is the base water potential for seedling emergence; T is the daily average soil temperature in the soil layer from 0 to 5 cm and Tb is the base temperature for seedling emergence (Martinson et al. 2007; Royo-Esnal et al. 2010a). With this formula, growing degree-days are accumulated only when the water potential and temperature conditions were higher than the base water potential and base temperature. The HTT was estimated using the Soil Temperature and Moisture Model (STM^2) (Spokas and Forcella 2009). STM^2 requires as input daily maximum and minimum air temperatures and daily precipitation, along with information on the geographical location and soil texture and organic matter. HTT were accumulated over days beginning on the date when the main rainfall occurred prior to the first sowing date. The base water potential and base temperature were determined iteratively calculating HTT using a set of water potentials (−2.0 MPa to −0.5 MPa, at −0.1 MPa intervals) and temperatures (0 to 2 C at 1C intervals). Namely, the scale of HTT was changed by modifying the ψb and the Tb until the highest accuracy was obtained for the relationship between HTT and cumulative emergence of ripgut brome. Typically, ripgut brome emergence begins mid- to late summer, but because all emerged seedlings were killed before sowing, hydrothermal time was calculated from the first autumn rains each year.

The functional relationship between cumulative emergence and HTT was described by a sigmoid equation with the best fit. A Chapman equation was used,

$$y = K(1 - [\exp\{-bx\}])^a \qquad [2]$$

where y is the percentage of emergence, x is time expressed as HTT, and K, b, and a are empirically derived constants. K is the maximum percentage of emergence recorded, b is the rate of increase and a is a shape parameter. Fitting of the Chapman function for cumulative emergence was performed using SAS 9.1 (PROC NLIN; SAS Institute Inc., Cary, NC, USA). Model parameters were further adjusted by nonlinear least-squares regression and the goodness of curve fitting by contrast of joint hypothesis ($P < 0.05$).

Cumulative Emergence Model Validation and Readjustment. In the third season (2010 to 2011), emergence data of ripgut brome were also taken before the first sowing date in trial 1 (described as F0). For this reason, the model developed for describing the emergence of ripgut brome was validated with these data (F0), as well as with F1 in 2010 to 2011 and data from Cao et al. (2011), obtained in two other localities of Huelva (South of Spain) in 2005 to 2006 and 2006 to 2007. Agreement between predicted and actual emergence values was determined with the root-mean-square error (RMSE):

$$RMSE = \sqrt{1/n \sum_{i=1}^{n} (x_i - y_i)^2} \qquad [3]$$

where x_i represents actual cumulative percent emergence, y_i is predicted cumulative percent emergence, and n is the number

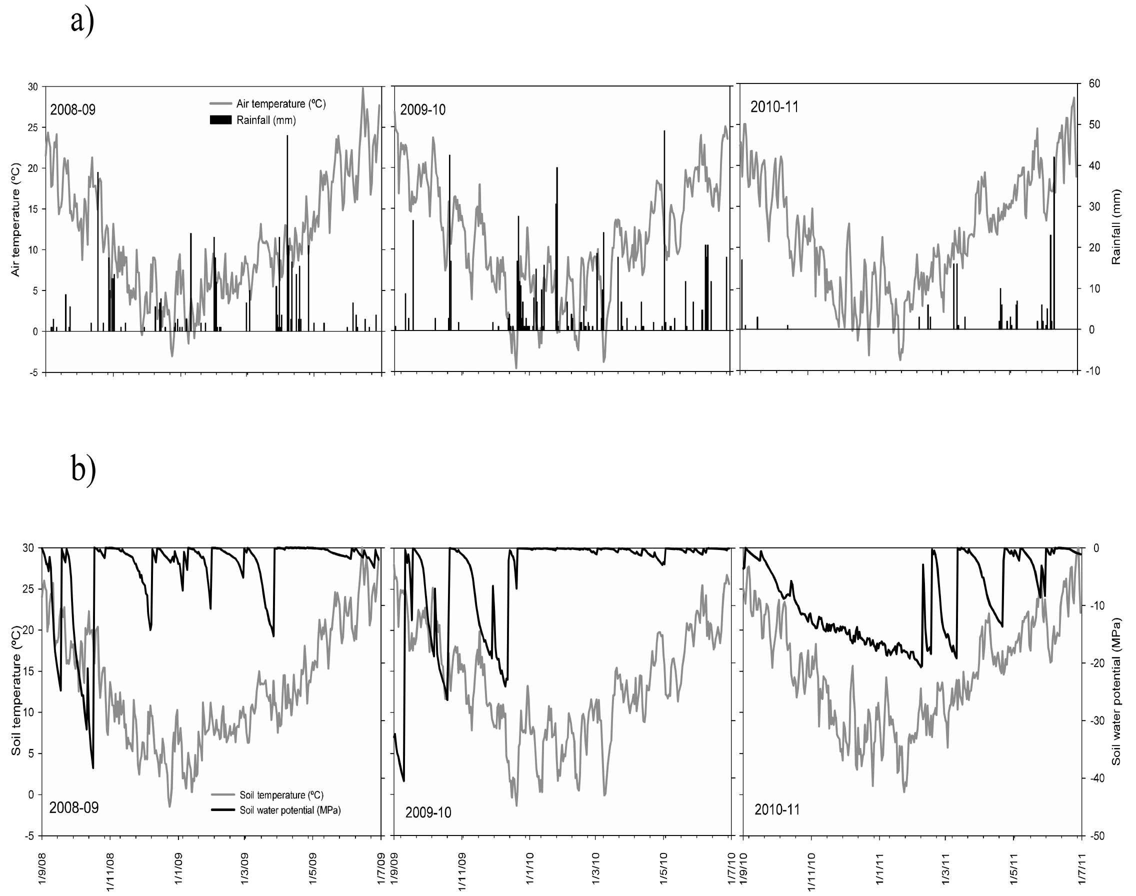

Figure 1. (a) Air temperature (C) and rainfall (mm). (b) Soil temperature (C) and soil water potential (MPa) in the first five cm of depth for seasons 2008 to 2009, 2009 to 2010 and 2010 to 2011.

of observations (Mayer and Butler 1993). RMSE provided a measurement of the typical difference between predicted and actual values in units of percentage seedling emergence. The RMSE ranges to evaluate the accuracy of the model are based on Royo-Esnal et al. (2010b): < 5, excellent prediction; 5 to 10, very good prediction; 10 to 15, good prediction; > 15, insufficient prediction. When RMSE were not optimally described by these models (RMSE>15) the Chapman equation was modified by adding a lag-phase (z):

$$y = K(1 - [\exp\{-bx - z\}])^a \qquad [4]$$

The lowest RMSE values indicated that the emergence model fit had been optimized.

Cumulative Emergence Practical Model Application. Different sowing dates (F2 and F3 in trial (1) and types of tillage (SS, ChP, and MbP in trial (2) of the three growing seasons were used to evaluate the practical application of the emergence model defined above.

Correction factors were calculated to adjust the cumulative emergence in F2 and F3. Both factors consider prior emergence during the F1. The corrections were 69% and 92% for F2 and F3, respectively, and they represent the percentages of seedling emergence that were eliminated with the delay of the sowing date through seedbed preparation. The correction factor 69% was also used in trial 2 as the crop was sown on the same date as in F2 in trial 1 each year.

Results

The three seasons differed considerably in terms of rainfall (Figure 1a), which represents an ideal situation for development of robust microclimate-based models, but not in temperature. Figure 1b represents the soil temperature and soil water potential in the first 5 cm of depth, calculated with the STM^2 using daily maximum and minimum air temperature (represented as mean air temperature in Figure 1a) and rainfall. Total rainfall from September to harvest (June) in 2008 to 2009 was 500 mm, while in 2009 to 2010 it was 637 mm, and in 2010 to 2011 only 190 mm. Besides the rainfall quantity, number of rainy days also differed between the three seasons (64 in 2008 to 2009, 77 in 2009 to 2010, and 27 in 2010 to 2011, Figure 1a), which is reflected in the soil water potential as long wet or dry periods (Figure 1b). The first season, the average of autumn-winter precipitation was 234 mm (October to February), which fell mainly in October (84 mm). Spring was rainy, with 155 mm between April and May (150 mm in April). In the second season, autumn-winter was wetter (357 mm), while spring was dryer than the previous season (85 mm). In these two seasons there had been short drought periods that are reflected in the soil water potential (Figure 1b). Finally, in 2010 to 2011 autumn-winter resulted extremely dry (13 mm), which decreased considerably the soil water potential, while spring was rainy (156 mm between March and June). For modeling purposes, such great natural variability in magnitudes

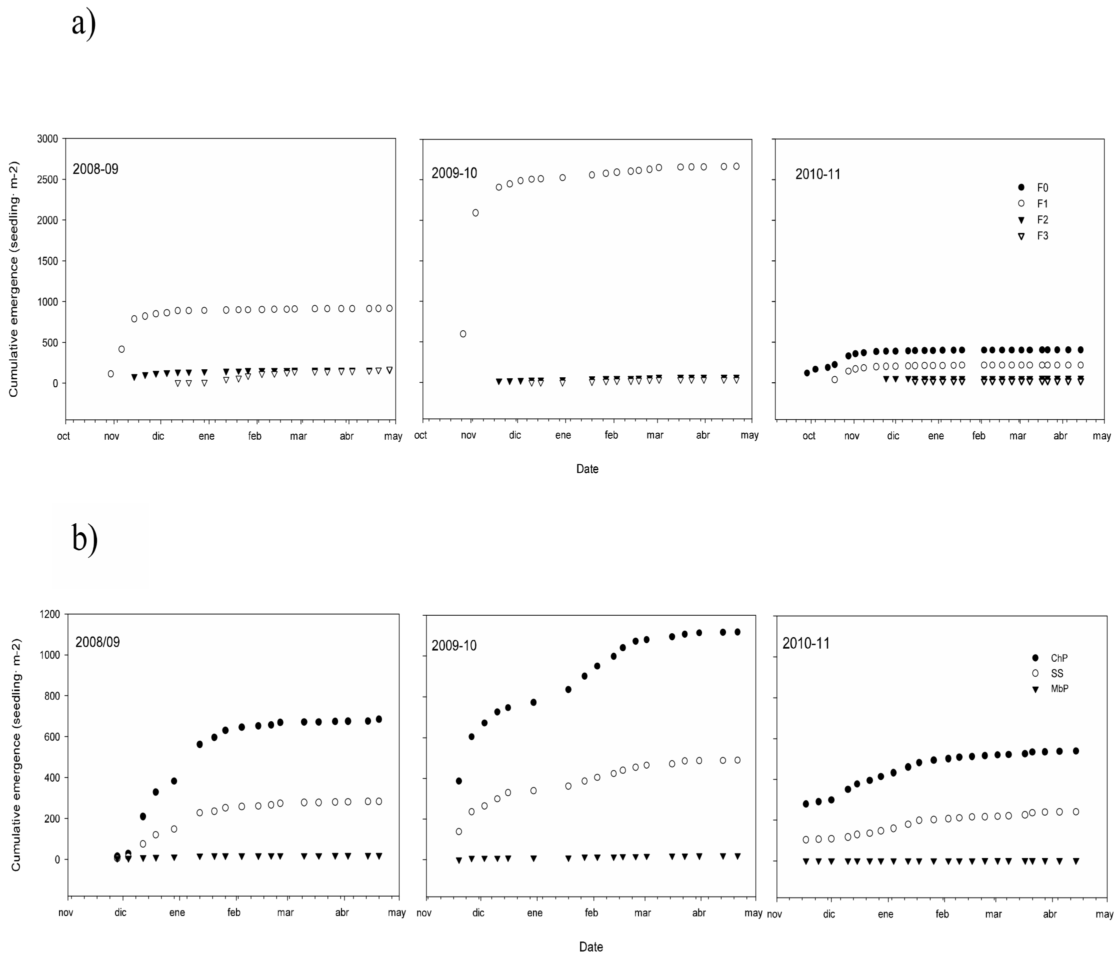

Figure 2. Cumulative emergence of ripgut brome (seedling·m^{-2}) in (a) three sowing dates (F0 = previous to first sowing date, F1 = first sowing date, F2 = second sowing date, and F3 = third sowing date) and in (b) three different soil managements throughout the three growing seasons (ChP = chisel plow, SS = subsoiler, and MbP = moldboard plow).

of driving variables is highly desirable. In the three years, the average winter air temperature (December through February) was 4 C. Overall, the soil and air temperature did not vary significantly from each other as the depth at which soil temperature had been calculated (five cm) is highly influenced by air temperature.

The cumulative emergence in trial 1 was always higher in F1 than in F2 and F3. The beginning of emergence was coincident in 2008 to 2009 and 2009 to 2010 with rainfalls occurring in October. In 2010 to 2011 rainfalls in autumn only occurred in September. Each growing season shows a decreasing gradient from F1 to F3. In 2008 to 2009, the cumulative emergence of ripgut brome differed according to the delay in sowing date (Figure 2a.). Delay of sowing from F1 to F2 entailed an 82% reduction in the cumulative emergence, and 81% reduction in F1 to F3. Between F2 and F3, percentage of cumulative emergence increased by 7%. In 2009 to 2010, the emergence of ripgut brome in F1 was higher than the year before. The percentage of reduction from F1 to F2, F1 to F3, and F2 to F3 was of 98%, 99%, and 49%, respectively. In general, cumulative emergence in 2010 to 2011 was lower than in 2008 to 2009 and 2009 to 2010 for the three sowing dates, and rainfall was almost nil from October to January. Percentage reduction in cumulative emergence was 73%, 88%, and 56%, respectively, from F1 to F2, F1 to F3 and F2 to F3.

In trial 2, cumulative emergence in ChP was higher than SS and MbP in the three growing seasons and consistently lowest in MbP (Figure 2b). Cumulative emergence was higher in 2009 to 2010 than in 2008 to 2009 and 2010 to 2011. Considering that higher cumulative emergence occurred in ChP than in SS and MbP, a percentage of 100% was assigned to ChP. Accordingly, reductions in cumulative emergence were 59% in SS and 97% in MbP in 2008 to 09. In 2009 to 10 reductions reached 56% in SS and 98% in MbP, and in 2010 to 2011 they were about 48% in SS and 99% in MbP.

Seedling Emergence Model Development. The emergence model (Chapman function) calculated using data from F1 in 2008 to 2009 and 2009 to 2010 is shown in Figure 3. In both seasons, emergence was characterized by a quick flush followed by a more gradual pattern. To optimize emergence model fit, a unique base temperature and base water potential was required. The base temperature and base water potential for HTT were estimated iteratively. The best fitting T_b was determined to be 0 C and the best fitting ψ_b was −1.35 MPa (R^2 = 0.80). Estimates of the variables *K*, *b*, *z*, and *a* fitted to HTT for ripgut brome are 100, 0.013, ±55, and 21.4, respectively.

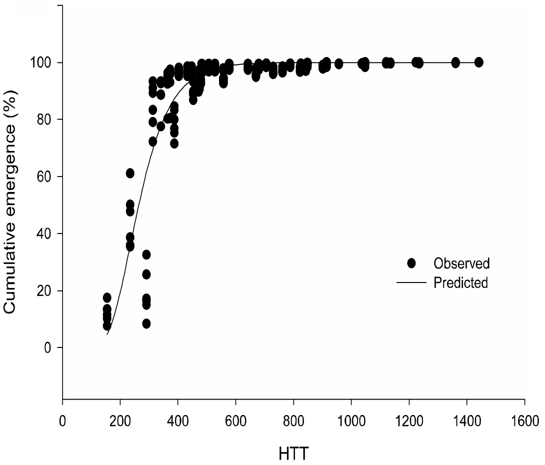

Figure 3. Observed cumulative emergence of ripgut brome in 2008 to 2009 and 2009 to 2010 and representation of the model developed with these data as a function of hydrothermal time (HTT). Emergence fitted using the Chapman function.

Seedling Emergence Model Validation. Figure 4 shows observed and predicted emergence using the Chapman function (above), based on F0 and F1 during 2010 to 2011. Both descriptions showed good fit and reasonable accuracy with predicted emergence (RMSE of 11.4 and 10.9 respectively for F0 and F1). In both cases a lag phase (*z*) was determined by repeatedly testing RMSE, with a final fix at 55 HTT. The model was also validated with emergence data from two locations in Huelva province (Figure 4c).

Practical Application. The emergence model successfully predicted the emergence of F2 and F3 from trial 1 (Figure 5) and those from SS, ChP and MbP from trial 2 (Figure 6) during the three growing seasons.

In trial 1, according to the scale established for the RMSE values, out of six simulations, two were excellent (RMSE < 5), three were very good (RMSE 5 to 10), and one was good prediction (Figure 5). In season 2008 to 2009 and 2009 to 2010, values from F3 were better described (RMSE = 2.2 and 3.3, respectively) than those from F2 (RMSE = 5.3 and 10.1, respectively). In contrast, in season 2010 to 11, F2 showed a slightly better RMSE (5.6) than F3 (7.5). Finally, for F3 values, the 2008 to 2009 growing season (RMSE = 2.2) showed the best fit (Figure 5). Thus, the model described the emergence of F2 and F3 accurately, without adding any lag-phase, however, in some cases the use of a lag phase (established at 55 HTT) improves the fit, as in F2 and F3 in 2009 to 2010.

Sowing date in the different soil management plots (trial 2) was coincident with F2 in trial 1; therefore the 69% factor correction, explained above, was applied to the emergence values. The model described emergence successfully in the three soil management systems during the three years with completely different weather situations (Figure 6). In the model application in F2 and F3 in trial 1, the use of a lag phase was not necessary because the fits were good. However, in trial 2, the use of a lag phase of 55 HTT, in 2008 to 2009 and 2009 to 2010 improved the fits. This did not happen in 2010 to 2011, when the exclusion of a lag phase was the best option for the description of emergence. The accuracy of this model developed for the emergence of ripgut brome was excellent in two situations, very good in another five and good in the last two situations. The RMSE values of this experiment ranged from 4.4 to 14.2%. ChP was generally better described in the sequence of the three seasons (2008 to 2009, 2009 to 2010, and 2010 to 2011), with RMSE values of 5.9, 6.0, and 4.4, respectively; followed by SS, 7.6, 6.1, and 5.7, respectively; and MbP, 4.1, 14.1, and 11.9, respectively) (Figure 6).

Discussion

Germination and emergence are basic processes in the survival and success of a plant (Del Monte and Dorado 2011) and the ability to predict weed emergence could enhance crop management by facilitating the implementation of more effective weed control strategies through the optimization of the timing of weed control (Leblanc et al. 2004; Myers et al. 2004). Cumulative emergence of ripgut brome in trial 1 was higher in F1 than in F2 and F3 regardless of the season. According to some reports, the first cohort of seedlings contributes more to stand biomass and subsequent seed production as well as stronger competition with associated crops, thereby having the largest contribution to the next generation (Cao et al. 2011). Total cumulative emergence was higher in 2009 to 2010 than in 2008 to 2009. The absence of a selective herbicide in barley, favored the growth and

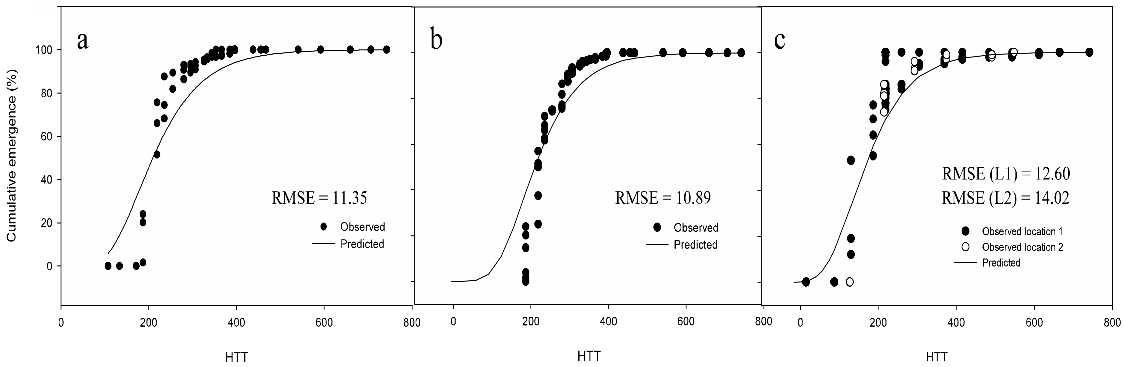

Figure 4. Model validation of cumulative seedling emergence of ripgut brome as a function of hydrothermal time (HTT) in Agramunt (Spain). (a) F0, cumulative emergence considered from September. (b) F1, cumulative emergence considered from October (sowing date). (c) Cumulative emergence using data obtained in Huelva (Cao et al. 2011) L1 = location 1 (closed circles), L2 = location 2 (open circles). The line represents predicted emergence using the model parameters listed in the text. RMSE: Root Mean Square Error.

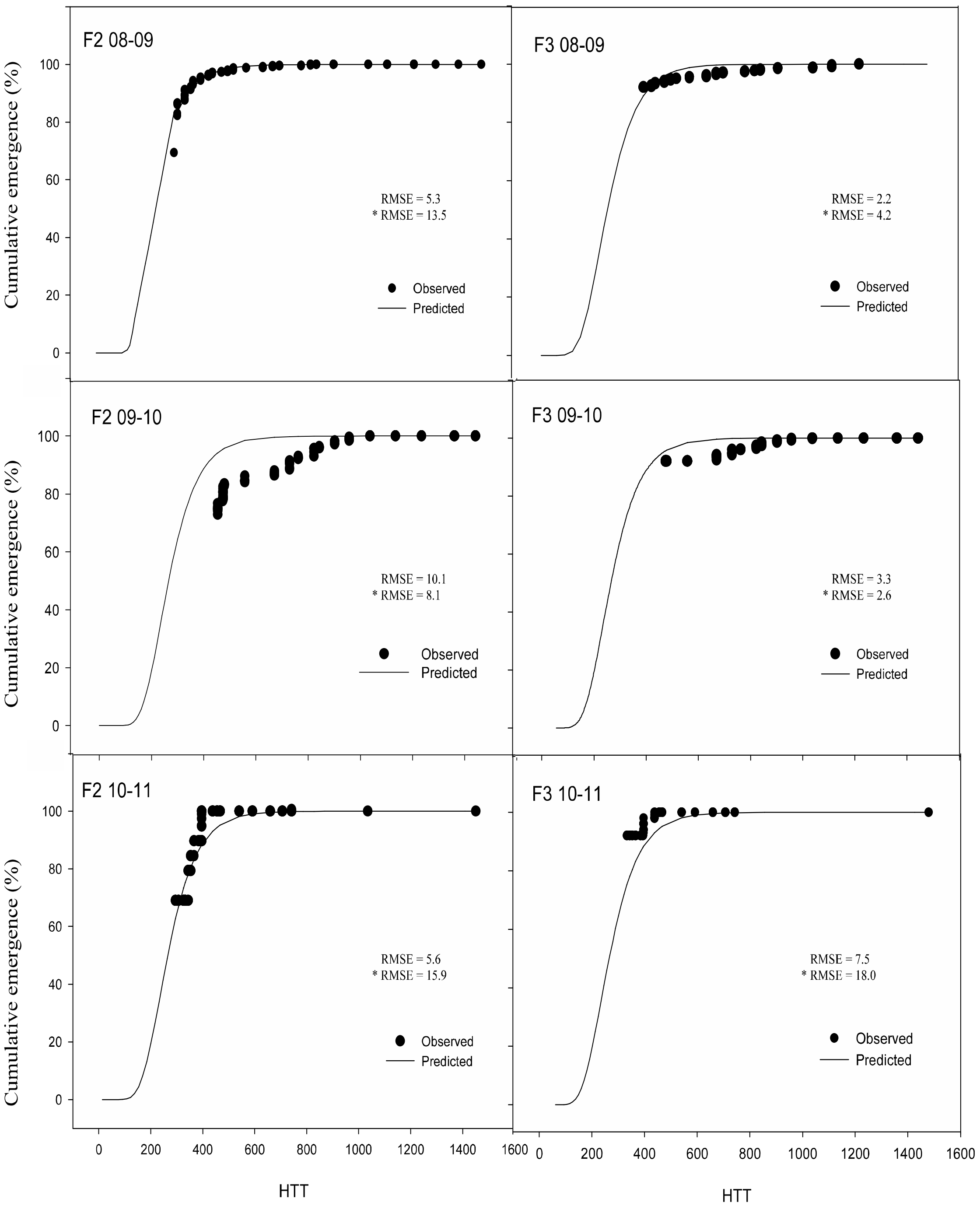

Figure 5. Hydrothermal seedling emergence model application for ripgut brome with delay of the crop sowing date in no-tillage systems in Agramunt (Spain) for three growing seasons, 2008 to 2009, 2009 to 2010, and 2010 to 2011. Root Mean Square Error is shown without (RMSE) and with the use of a lag phase of +55 HTT (*RMSE). F2, cumulative emergence (%) from November; and F3, cumulative emergence (%) from December. The line represents predicted emergence by the model developed without the lag phase. Symbols represent observed emergence.

development of ripgut brome and, therefore, its contribution to the soil seed bank was higher in the following year. The use of selective herbicides for ripgut brome control in wheat provoked a reduction of fecundity (data not shown) in 2009 to 2010. For this same reason, together with the drought suffered in autumn 2010 to 2011, a reduction of total cumulative emergence occurred that season.

Kleemann and Gill (2006) showed rapid germination of seeds of ripgut brome following initial autumn rains. In these experiments similar trends were observed, i.e., beginning of ripgut brome emergence was coincident with rainfall periods. According to Riba (1993) germination and emergence could occur under a wide period of time, ranging from late summer to mid-winter, although it is concentrated in the autumn.

In trial 2 cumulative emergence was higher in chisel plow followed by the subsoiler and moldboard plow. An explanation for this order in soil management systems is that seeds may need only a superficial covering of soil to perceive

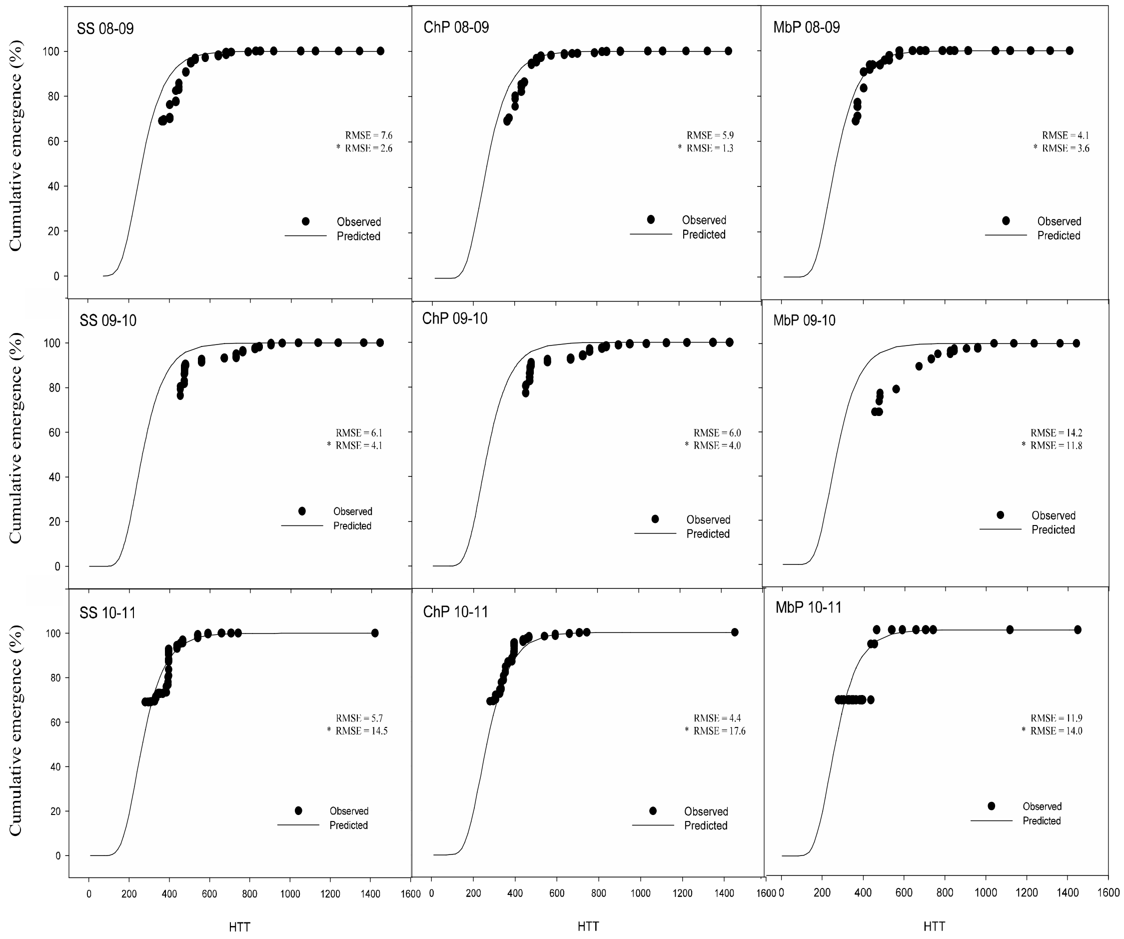

Figure 6. Hydrothermal seedling emergence model application for ripgut brome in different tillage systems (SS, ChP, MbP) in Agramunt (Spain) for three growing seasons 2008 to 2009, 2009 to 2010 and 2010 to 2011. Root Mean Square Error is shown without (RMSE) and with lag phase of +55HTT (*RMSE). Lines represent predicted emergence without a lag phase. Symbols represent observed emergence.

darkness. As long as the embryo remains buried, it is likely to germinate, and this is facilitated by the way the seed falls to the ground and can be wedged into the soil (Del Monte and Dorado 2011). Thus, the chisel plow deposits a thin layer of soil over the seeds, which allows germination. In contrast, in moldboard ploughed plots, which had the lowest cumulative emergence observed, soil inversion positioned seeds too deep to emerge. This also occurs in the related rigid brome (*Bromus rigidus* Roth) (Gleichsner and Appleby 1989).

Hydrothermal Time Seedling Emergence. Hydrothermal time emergence models that base predictions on field observations during previous growing seasons offer relatively robust predictions and with simple inputs and development (Forcella et al. 2000). The model developed in this work seems to be strong enough, as it was developed with data from two completely different seasons in terms of rainfall, and it has been validated with a third season in the same field, as well as with independent data from the south of Spain (Huelva).

The water potential with which emergence of ripgut brome was best explained was −1.35 MPa. In contrast, Del Monte and Dorado (2011) observed in a lab conditions that high germination percentages (above 75%) of ripgut brome were obtained in darkness with water potentials ≥ −0.4 MPa. Germination in the lab was significantly lower, but still appreciable at −1.25 MPa. Thus, our field- and simulation-derived value of −1.35 MPa may be deduced as the base water potential while ≥ −0.4 MPa is the optimal water potential for the germination (and emergence) of this weed. To optimize emergence model fit, a unique base water potential is required (Schutte et al. 2008). This base water potential may not be the best for any particular season, but it is the best overall for describing the three seasons with a robust model.

An advantage of the Chapman equation is the use of only three parameters that, in turn, makes it a simple model. The model predicted seedling emergence in different locations (Agramunt and Huelva) with reasonable accuracy. The RMSE values of this experiment calculated for model validation, (11.4 in F0, 10.9 in F1, and 12.6 and 14.0 in Huelva) were similar to RMSE values for model validation in other studies for common lambsquarters (*Chenopodium album*) (Roman et al. 2000), tropic ageratum (*Ageratum conyzoides* L.) (Ekeleme et al. 2005), and *Galium* spp. (Royo-Esnal et al. 2010a).

Practical Application. An interesting part of this model is that it could have been applied in other management systems (in the same locality where it was developed), which implies a wide range of situations where it probably can be used. All of the RMSE values obtained in the practical applications were below 15, indicating a very good predictive capability. The use of the lag phase in some cases further improved the fit of the model to the observed data.

The model applied to F2 and F3 in the three growing seasons showed slightly better accuracy for F3 than for F2. This could have happened because 92% of the population was destroyed by seedbed preparation and the correction factor left very low variation for K values (100%). The lack of need of a lag phase in these results is remarkable and gives a more robust basis to the model, which we believe is valid for rainfed cereal systems where sowing dates are often variable.

Ripgut brome is a common weed present in many tillage systems, although it is associated with no-till (Kleemann and Gill 2006). For this reason showing how the model predicted the emergence of ripgut brome in other soil managements was important. Therefore, the model also was applied to chisel ploughed, subsoiled and moldboard ploughed areas. In fact, the RMSE values obtained from these comparisons strengthened the perceived value of the model, as all were below 15 (without use of a lag phase). In some cases, however, the use of a lag phase did improve the fit of the model to the observed data. This might imply that the description of the emergence could still be improved, maybe with the inclusion of other factors that have not been used here, such as remnant seed dormancy alleviation. Regarding differences in accuracy of the model among tillage systems, it was somewhat less accurate in MbP than in SS and ChP. This likely happened because of the much lower seedling densities in MbP than the other soil management systems, with a corresponding decrease in reliability of the MbP data.

To summarize, soil temperature and soil moisture seem to be the determinant factors driving emergence of ripgut brome, as they are in other weeds (Forcella et al. 2000; Roman et al. 2000; Royo-Esnal et al. 2010a). With these two factors, a model that describes the emergence of this weed was developed and demonstrated to be robust and reliable, as it was validated with four different data sets and put into practice in five management systems (two sowing delays and three soil tillage practices) over three years. The model can be used henceforth to improve control and management of ripgut brome.

Acknowledgments

This work was supported by the Ministerio de Educación y Ciencia de España (AGL2007-60828 and AGL2010-22084-C02-01). It also was supported by a PhD student grant from the Universitat de Lleida. Special thanks to Cristina Maján, Noemí Pacheco Antón and Núria Moix for their help during the experimental work, and to Dr. Carlos Cantero and Carlos Cortés, from the Department of Crop and Forest Science at the University of Lleida. The first author thanks the Universitat de Lleida for the grant during the predoctoral stay in the U.S.A. The first author also thanks Valentina Atanackovic Xavier Solé-Senan and Alejandro Juárez for their help and constructive comments on the first version of abstract. Finally, we kindly thank Dean Peterson and Jim Eklund for their support and help during our stay in Morris, Minnesota.

Literature Cited

Bair, N. B., S. E. Meyer, and P. S. Allen. 2006. A hydrothermal after-ripening time model for seed dormancy loss in *Bromus tectorum* L. Seed Sci. Res. 16:17–28.

Cao, R., M. Francisco-Fernandez, A. Anand, F. Bastida, and J. L. Gonzalez-Andujar. 2011. Computing statistical indices for hydrothermal times using weed emergence data. J. of Agric. Sci. 149:701–712.

Cirujeda, A., J. Recasens, J. Torra, and A. Taberner. 2008. A germination study of herbicide-resistant field poppies in Spain. Agronomy for Sustainable Development 28:207–220.

Colbach, N., C. Dürr, J. Roger-Estrade, and J. Caneill. 2005. How to model the effects of farming practices on weed emergence. Weed Res. 45:2–17.

Del Monte, J. P. and J. Dorado. 2011. Effects of light conditions and after-ripening time on seed dormancy loss of *Bromus diandrus* Roth. Weed Res. 51:581–590.

Ekeleme, F., F. Forcella, D. W. Archer, I. O. Akobundu, and D. Chikoye. 2005. Seedling emergence model for tropic ageratum (*Ageratum conyzoides*). Weed Sci. 53:55–61.

Forcella, F., R. L. Benech Arnold, R. Sanchez, and C. M. Ghersa. 2000. Modeling seedling emergence. Field Crop. Res. 67:123–139.

Gill, G. S. and S. A. Carstairs. 1988. Morphological, cytological and ecological discrimination of *Bromus rigidus* from *Bromus diandrus*. Weed Res. 28:399–405.

Gleichsner, J. A. and A. P. Appleby. 1989. Effect of Depth and Duration of Seed Burial on Ripgut Brome (*Bromus rigidus*). Weed Sci. 37:68–72.

Grundy, A. C., K. Phelps, R. J. Reader, and S. Burston. 2000. Modeling the germination of *Stellaria media* using the concept of hydrothermal time. New Phytol. 148:433–444.

Haj Seyed Hadi, M. R. and J. L. Gonzalez-Andujar. 2009. Comparison of fitting weed seedling emergence models with nonlinear regression and genetic algorithm. Comput. Electron. Agri. 65:19–25.

Kleemann, S.G.L. and G. S. Gill. 2006. Differences in the distribution and seed germination behaviour of populations of *Bromus rigidus* and *Bromus diandrus* in South Australia: Adaptations to habitat and implications for weed management. Aust. J. Agr. Res. 57:213–219.

Kon, K. F. and W. M. Blacklow. 1989. Identification, distribution and population variability of great brome (*Bromus diandrus* Roth) and rigid brome (*Bromus rigidus* Roth). Australian J. Agric. Res. 39:1039–1050.

Leblanc, M. L., D. C. Cloutier, K. A. Stewart, and C. Hamel. 2004. Calibration and validation of a common lambsquarters (*Chenopodium album*) seedling emergence model. Weed Sci. 52:61–66.

Leguizamón, E. S., C. Fernandez-Quintanilla, J. Barroso, and J. L. Gonzalez-Andujar. 2005. Using thermal and hydrothermal time to model seedling emergence of *Avena sterilis* ssp. *ludoviciana* in Spain. Weed Res. 45:149–156.

Martinson, K., B. Durgan, F. Forcella, J. Wiersma, K. Spokas, and D. Archer. 2007. An emergence model for wild oat (*Avena fatua*). Weed Sci. 55:584–591.

Mayer, D. G. and D. G. Butler. 1993. Statistical validation. Ecol. Model. 68:21–32.

Meyer, S. E. and P. S. Allen. 2009. Predicting seed dormancy loss and germination timing for *Bromus tectorum* in a semi-arid environment using hydrothermal time models. Seed Sci. Res. 19:225–239.

Myers, M. W., W. S. Curran, M. J. VanGessel, D. D. Calvin, D. A. Mortensen, B. A. Majek, H. D. Karsten, and G. W. Roth. 2004. Predicting weed emergence for eight annual species in the northeastern United States. Weed Sci. 52:913–919.

Peeper, T. F. 1984. Chemical and biological control of downy brome (Bromus tectorum) in wheat and alfalfa in North America. Weed Sci. 32:18–24.

Riba, F. 1993. Demography and population dynamics of *Bromus diandrus* Roth in winter cereals. PhD dissertation. University of Lleida. 117 p.

Riba, F. and J. Recasens. 1997. *Bromus diandrus* Roth en cereals de invierno. In: Sans, F. X. y. Fernández-Quintanilla C. (editores). La biología de las malas hierbas de España. Ed. *Phytoma* España-Sociedad Española de Malherbología. (25–35).

Roman, E. S., S. D. Murphy, and C. J. Swanton. 2000. Simulation of *Chenopodium album* seedling emergence. Weed Sci. 48:217–224.

Royo-Esnal, A., J. Torra, J. A. Conesa, F. Forcella, and J. Recasens. 2010a. Modeling the emergence of three arable bedstraw (*Galium*) species. Weed Sci. 58:10–15.

Royo-Esnal, A., J. Torra, J. A. Conesa, and J. Recasens. 2010b. Characterization of emergence of autumn and spring cohorts of *Galium* spp. in winter cereals. Weed Sci. 50:572–585.

Schutte, B. J., E. E. Regnier, S. K. Harrison, J. T. Schmoll, K. Spokas, and F. Forcella. 2008. A hydrothermal seedling emergence model for giant ragweed (*Ambrosia trifida*). Weed Sci. 56:555–560.

Spokas, K. and F. Forcella. 2009. Software tools for weed seed germination modeling. Weed Sci. 57:216–227.

Received February 24, 2012, and approved May 17, 2012.

CAPÍTULO 2

“Options for an integrated management of *Bromus diandrus* in dry land cereal fields under no-till”

Options for an integrated management of *Bromus diandrus* in dry land cereal fields under no-till

Introduction

In the Ebro Valley region in north-eastern Spain, the introduction of conservation tillage systems more than 25 years ago induced significant and important changes in the management technology of winter cereals (Alvaro-Fuentes *et al.,* 2007). This transformation was crucial due to the agronomic and environmental benefits associated with zero or minimum tillage (Holland, 2004). Nevertheless, conservation tillage systems, and especially direct drilling, bring some difficulties in the control of certain weed species. Some evident cases have appeared in this area where the presence of species like *Bromus diandrus* Roth is large (Arrúe *et al.*, 2007; Riba and Recasens, 1997).

B. diandrus is an annual grass weed native to the Mediterranean region but has spread throughout the world. It has been suggested that the increased abundance of *B. diandrus* in field crops in southern Australia –where it is one of the most noxious weeds- is associated to cereal monocrop, widespread adoption of conservation tillage and to the absence of effective herbicides for its control in cereals (Kleeman and Gill, 2009a). In Spain, this species was first reported as a weed in cereal fields of the Duero Valley (García Baudín, 1983), and further, a significant increase of infestations have been observed in winter grains of other Spanish regions (Recasens *et al.*, 1996). Its biological behaviour in no tilled dry land cereal fields of Spain seems to be similar to those appointed in cereal crops in Australia. Only few reports on the biology and population ecology of this species and their responds to crop management in cereal systems in Spain are available (Riba, 1993; Riba and Recasens, 1997). However, due to the absence of effective herbicides for its control, there has not been developed any integrated weed management proposal.

In these dry land cereal systems of NE Spain yields are low and strongly dependant on the highly variable and erratic rainfall (Lampurlanés *et al.*, 2002; Cantero-Martínez *et al.*, 2003), and the adoption of conservation tillage strategies permits a long term higher soil water content. Nevertheless, the competitive effect of weeds as

B. diandrus can significantly reduce crop yields and the narrow range of economic benefits. Options of adopting alternative cultural strategies for weed control, like crop rotation, are limited due to climatic constrains. Therefore, in this no tilled cereal monocrop scenario, a nonselective herbicide is usually applied before sowing, mainly glyphosate, to eliminate emerged seedling; however this pre-sowing control might be limited because of light inhibition of germination of *B. diandrus* seeds (Gill and Blacklow, 1985; Harradine, 1986; Jauzein, 1989) leading to protracted seedling establishment and evasion of early control measures (Kleeman and Gill, 2006). Del Monte and Dorado (2011) have recently demonstrated that the dormancy dynamics of this species in Mediterranean climates is characterised by two distinct germination flushes (autumn and spring), coinciding with two not limiting soil humidity and temperature periods, confirming that new late emergences could take place several weeks after crop sowing.

The recent introduction of herbicides for the selective control of *B. diandrus* opens new options for an integrated management scenario. In wheat the herbicide mesosulfuron-methyl plus iodosulfuron-methyl-sodium, is proposed for the control of gramineous weeds, including *B. diandrus*, but in order to obtain acceptable efficacies the herbicide application must be before the three-leaf stage of the weed (Rapparini *et al.*, 2006; Kleeman and Gill, 2009b). In this sense, the option of delaying the crop sowing date permits the avoidance of the main autumn flushes of weed emergence and a better control of those late emerged cohorts. The decrease of the weight and the fewer contributions to seed bank of late emerged cohorts has been demonstrated in other grass weeds (Rice *et al.*, 2001; Conley *et al.*, 2002, Gallart *et al.*, 2010). On the other hand, a drawback to take into account when sowing is delayed is the possible reduction of the crop yield (Moss, 1985; Planes *et al.*, 1999; Anderson, 2007). However, Forcella *et al.*, (1993) found that the advantages of delayed sowing dates for weed control enhancement offset the lower crop yields. In this sense, it is supposed that in cereal fields infested by *B. diandrus* delaying crop sowing allows the control of the main autumn emergences and decrease the competitive effect of the weed. If the aim is to obtain greater density reductions of this species by delaying the crop sowing date, it must be taken into account its emergence behaviour according to temperature and soil moisture to adjust this decision to the optimal date. Recently, García *et al.* (2013) have developed and validated a model that predicts the field emergence of this species following the STM^2

program (Spokas and Forcella, 2009), and that should become a strategic tool in the implementation of an integrated management program.

Due to the absence of integrated weed management programs for this species in cereal systems in Spain, the results of that approach should have immediately practical application, especially in conservation tillage systems. With this aim a three-year field experiment in a cereal field under no tillage was established to study: 1) the emergence patterns of *B. diandrus* in function of crop sowing date according to a previously developed emergence model, 2) the effectiveness of different chemical control methods applied each season over *B. diandrus* cohorts according to their different stage of development, and 3) analyse the demographic changes in the *B. diandrus* population along the three growing seasons, integrating both cultural and chemical control methods.

Materials and Methods

Location and experimental design

Field trials were conducted from autumn to spring during the seasons 2008-09, 2009-10 and 2010-11 in an experimental cereal field that was managed since 2006-07 under no-tillage by the Agronomy Group of the University of Lleida. The field was located in Agramunt, Lleida, in north-eastern Spain (41º48`N, 1º07`E). The soil was a Fluventic Xerocrept (100-120 cm deep), with 30.1% sand, 51.9% silt and 17.9% clay, pH of 8.5 and organic matter content (OM) of 1.8% in the first 25 cm.

The experiment was set up in a complete randomized block design with three repetitions. Sowing date with three levels was the only considered factor: F1, mid-October (20, 19 and 14 October in 2008, 2009 and 2010, respectively); F2, mid-November (7, 12 and 18 November) and F3, early December (10, 3 and 13 December) (Table 1). Since season 2006-07, this trial was sowed with barley and it had been carried out with the same three sowing dates under zero tillage, but weed emergence was monitored since 2008-2009. In 2008-09, barley (*Hordeum vulgare* L.) was sown at a rate of 180 $Kg \cdot ha^{-1}$. In 2009-10 and 2010-11, winter wheat (*Triticum aestivum* L.) was sown in a similar density (Table 1). Fertilizer was applied each year in February to March at 150 Kg N-32%$\cdot$ ha^{-1}, according to yearly soil test recommendations.

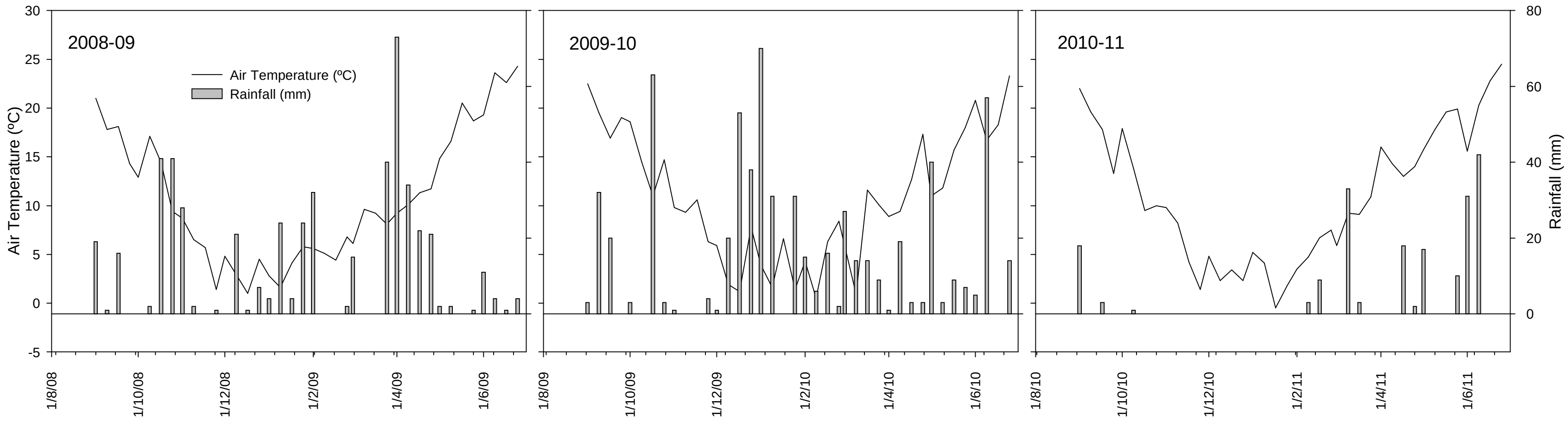

Figure 1. Daily mean temperature (ºC) and rainfall (mm) over the trial period, from September 2008 to July 2011 in a cereal field located in Agramunt, NE Spain.

Table 1. Crop sowing dates (F1, F2 and F3) and weed control methods performed in 2008-09, 2009-10 and 2010-11 seasons in the trial field.

Season	**Crop and sowing date**	**Postemergence herbicide treatment**	
2008-09	Crop: Barley cv. ‘Hispanic’	Isoproturon 1243 g a.i.·ha^{-1} plus diflufenican 69 g a.i.·ha^{-1}	2.4 D plus MCPA plus Dicamba (1.5 L·ha^{-1}) + Metribuzin (50 g a.i.·ha^{-1})
F1	20 October	19 February	19 February
F2	7 November	19 February	
F3	10 December	19 February	
2009-10	Crop: Wheat cv. ‘Bokaro’	Mesosulfuron-methyl plus iodosulfuron-methyl-sodium (15 and 3 g a.i.·ha-^{1})	
F1	19 October	5 March	
F2	12 November	5 March	
F3	3 December	5 March	
2010-11	Crop: Wheat cv. ‘Bokaro’	Mesosulfuron-methyl plus iodosulfuron-methyl-sodium (15 and 3 g a.i.·ha-^{1})	Tribenuron-methyl plus metsulfuron-methyl (10 and 5 g a.i.·ha-^{1})
F1	14 October	9 February	30 March
F2	18 November	13 April	30 March
F3	13 December	13 April	30 March

Each season a pre-sowing herbicide treatment (one to three days before) with glyphosate was applied in all plots, at a rate of 1,5 L·ha^{-1} and N- fertiliser was also applied in February-March 150 Kg·ha^{-1}.

Herbicide treatments

The plots were sprayed with glyphosate at a dose of 540 g a.i·ha^{-1} one to three days before each sowing date (Table 1). In 2008-09, post-emergence tank mix of isoproturon plus diflufenican (1243 + 69 g a.i·ha^{-1}) was applied 19 February. In F1, 2.4 D plus MCPA plus Dicamba (1.5 L·ha^{-1}) plus Metribuzin (50 g a.i.·ha^{-1}), was also applied in February. 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) 5 March. In 2010-11 broadleaf were controlled in post-emergence by tribenuron-methyl plus metsulfuron-methyl (10 + 5 g a.i·ha^{-1} plus wetting agent) in 30 March. Mesosulfuron-methyl plus iodosulfuron-methyl sodium (15 + 3 g a.i·ha^{-1} plus wetting agent) was applied 9 February in F1, 13 April in F2 and F3.

Parameters estimated

Each season destructive weekly counts of *B. diandrus* seedlings were started in each 6 x 50 m^2 plot, according to the different sowing dates, in five permanent quadrats (0.1 m^2) until the end of April. Furthermore, each season periodic samplings of weed density were collected with ten 0.1 m^2 quadrats thrown randomly along the plot.

Daily rainfall, maximum and minimum air temperatures were obtained from a standard meteorological station located at the experimental field.

The functional relationship between cumulative emergence (CE) and Hydrothermal Time (HTT) was obtained applying the sigmoid Chapman equation described by García *et al* (2013) for *B. diandrus*:

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

where y is the percentage of cumulative emergence after the first autumnal rains and x is time expressed as HTT. This model was based on the equation described by Roman *et al*. (2000) and HTT was estimated using the Soil Temperature and Moisture Model (STM^2) (Spokas and Forcella, 2009).

Post-emergence herbicide efficacy was estimated as the difference expressed in percentage between the density on the day of herbicide treatment and 60 days later. Fecundity was estimated each year in June, when surviving *B. diandrus* plants reached their complete development and fecundity. Twenty plants from each cohort (F1, F2 and F3) were collected and fecundity (caryopsides/plant) was estimated. Seed rain was calculated by multiplying final density of great brome at the end of the growing season by fecundity from each cohort.

Statistical analysis

According to the different crop sown and different treatments applied every year, data from each season were analyzed separately. All data were analysed through ANOVA using SAS 9.0 (PROC NLIN; SAS Institute Inc., Cary, NC, USA). When differences were detected between treatments, Tukey tests (P=0.05) was used for comparison of means. Previous to analyses, fecundity was transformed (log (x+1)) and percentage of weed emergence was transformed (arc sine (√x)) to satisfy the homogeneity of variance assumptions. Back-transformed data will be presented for clarity. The repeated statement option of SAS was used to compare weed densities between sampling dates for each sowing date. Sigma Plot program 11.0 was used for the density and emergence graphic representation.

Results

Weather characteristics of the growing seasons

Rainfall and temperature patterns are represented in Figure 1. The annual average temperature in the three growing seasons was below the long-term average temperature (10.9, 10.6 and 11.4 in 2008-09, 2009-10 and 2010-11 respectively vs. 11.7 ºC). The first and second growing seasons were above the long-term rainfall average (378 mm). Total rainfall from September to June (at harvest time) in 2008-09 was 500 mm, while in 2009-10 it was 637 mm, and in 2010-11 only 190 mm.

The first season (2008-09) the average of autumn-winter daily precipitation was 234 mm (October to February), which fell mainly in October (84 mm). Spring was rainy, with 155 mm between April and May (150 mm in April). In the second season (2009-10), autumn-winter was wetter (357 mm), while spring was dryer than the previous season (85 mm); and in the third season (2010-11) autumn-winter resulted extremely dry (13 mm), however spring was rainy (156 mm between March and June).

Weed emergence

During the experiment, the total CE of *B. diandrus* was each season higher in F1. The highest CE was observed in 2009-10 (2664 pl·m^{-2}). In 2008-09 and 2010-11, CE was 917 pl·m^{-2} and 217 pl·m^{-2} respectively (Table 3). Emergence was extended each year until the end of April. In 2008-09, the highest emergences observed for F1 (673 pl·m^{-2}) and F2 (80 pl·m^{-2}) were significantly different between them (Figure 2), but coincident in time (mid-November), one month and one week after their respective crop sowing dates. The maximum observed emergence in F3 (19 pl·m^{-2}) was lower than F1 and F2, and was reached in late April (Figure 2). No other significant differences on weekly emergences were obtained along the season between the three established crop sowing dates, with the only exception of the last observation in late April, due to new few spring emergences recorded on F3. In 2009-10, the highest emergence was also observed in F1 in mid-November (1809 pl·m^{-2}), one month after crop sowing. The highest observed emergences in F2 (18 pl·m^{-2}) and F3 (11 pl·m^{-2}) were lower than in the previous season, and their weekly values were significantly different from F1 until early January and also in early-mid March. In 2010-11, the highest values were observed in F1 (106 pl·m^{-2}) in late-October. In F2 and F3 the maximum emergences were very low (1 pl·m^{-2}) and observed in late-November and late-January, respectively. This season, only in early December, after the third crop sowing date, values of observed emergence in F1 were significantly different from those from F2 and F3.

In 2008-09, the CE of *B. diandrus* declined 82.1% from F1 to F2 (Table 3) and this decline was even higher in 2009-10 and 2010-11 (97.5% and 98.1% respectively). For all growing seasons, the reduction from F1 to F3 was very high, with values of 80.8%, 98.7% and 97.2%, respectively for 2008-09, 2009-10 and 2010-11. The decrease of the CE from F2 to F3 was only significant in 2009-10 (49.7%).

According to the crop sowing delay, a decrease on the percentage of plants emerged in autumn was observed each season (Table 3). For F1, autumn emergences represented more than 94% in each of the three seasons. For F2 percentages of autumnal emergence recorded are 86.6, 44.5 and 53.8% for each of the respective seasons. For F3 emergences recorded in autumn are practically negligible (between 0 and 11.7%).

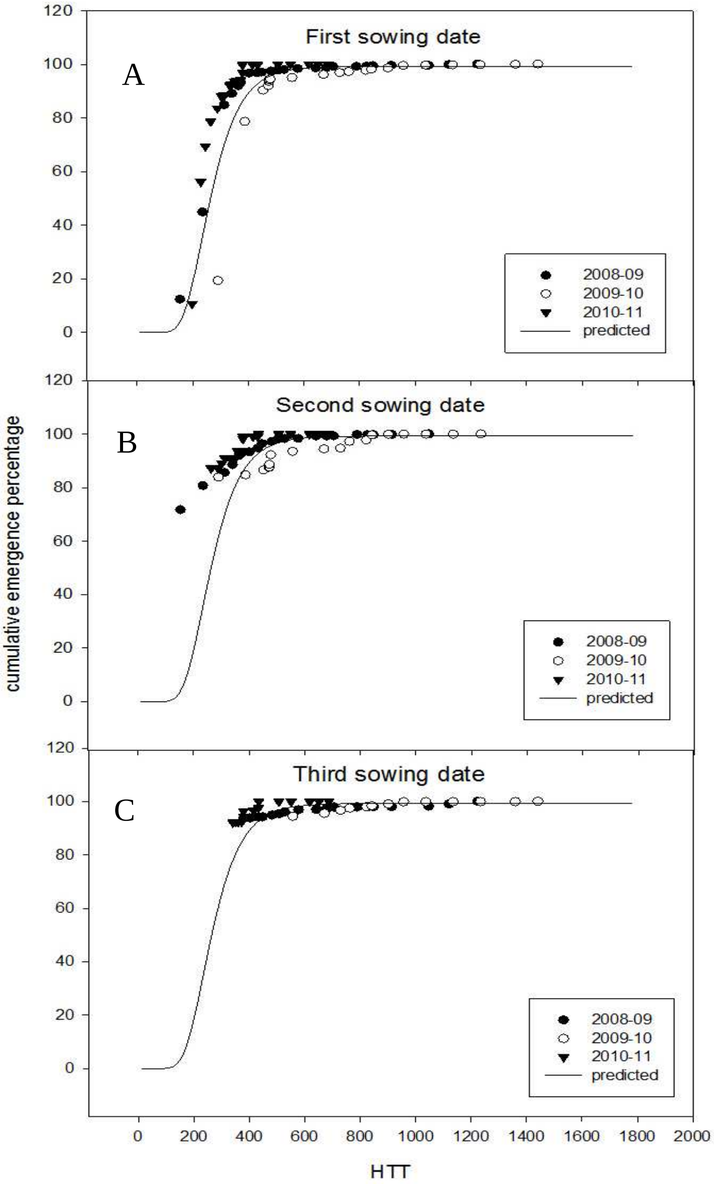

Figure 3. Hydrotermal seedling emergence predicted by the model from García *et al.* (2013) and observed CE of *B. diandrus* in three different crop sowing dates during the three studied seasons.

The hydrothermal seedling emergence model developed for *B. diandrus* in a previous work (García *et al.*, 2013) is represented separately for each crop sowing date (Figure 3). The model described emergence successfully for each crop sowing date averaging data from the three different growing seasons. The predicted model estimates a 50%, 75% and 90% of CE at 264, 329 and 406 HTT, respectively. According to this estimation, delaying crop sowing date permits a significant reduction of those emerged plants that represented over the regression line in the first crop sowing date (Figure 3A).

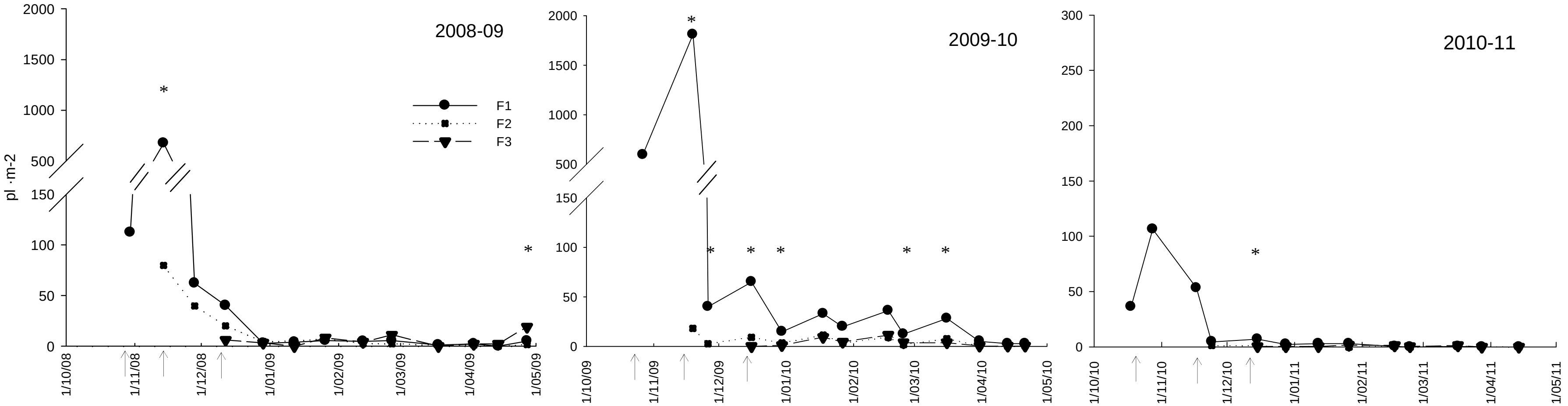

Figure 2. Observed emergence of *Bromus diandrus* in function of crop sowing date (D1: mid-October; D2: mid-November and D3: early December) during the three growing seasons. Arrows indicate the three crop sowing dates. Asterisks indicate significant differences between sowings dates for a specific date of observation (p<0.05).

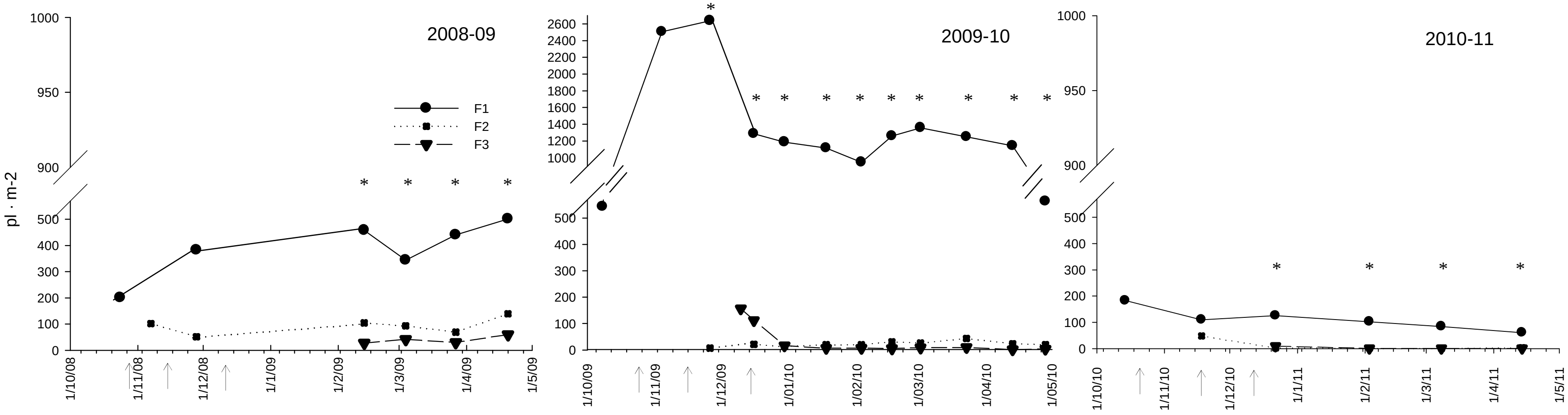

Figure 4. Density of *Bromus diandrus* in function of crop sowing date (D1: mid-October, D2: mid-November, D3: early December) during three growing seasons. Arrows indicate the crop sowing date. Asterisks indicate significant differences between sowings dates for a specific date of observation (p<0.05).

Weed density, herbicide effectiveness and crop yield

Figure 4 represents the evolution of the density of *B. diandrus* during the three growing seasons. Along each season, significant differences on density between different sowing dates were observed, with significantly higher values for F1. The initial density for F1 was 200.6, 542.6 and 183.1 pl·m^{-2} in 2008-09, 2009-10 and 2010-11, respectively. Initial density for F2 was higher in 2008-09 (101.8 pl·m^{-2}) than in 2009-10 (7.5 pl·m^{-2}) and 2010-11 (47.8 pl·m^{-2}). In 2009-10, the highest values of density for F1 were reached in late November (2637 pl·m^{-2}), whereas in 2008-09 and 2010-11 these maximums for this sowing date were reached in late April (500.5 pl·m^{-2}) and in mid-October (183.1 pl·m^{-2}), respectively. For F2 and F3, the highest densities observed in 2008-09 were 139 pl·m^{-2} and 60 pl·m^{-2}, respectively, in both cases in late-April; however, in 2009-10 for F2 the maximum density observed was 43.6 pl·m^{-2} in late-March and for F3 156.8 pl·m^{-2} in mid-December. In 2010-11, the highest densities observed for F2 and F3 were 47.8 pl·m^{-2} and 9.0 pl·m^{-2}, respectively, in mid-November and mid-December.

In 2008-09, isoproturon plus diflufenican was completely ineffective on *B. diandrus* in all crop sowing dates (Table 3). In 2009-10, the application of the herbicide mesosulfuron-methyl plus iodosulfuron-methyl-sodium did not provide a good control in F1 and F2, where the density reduction of barley reached 58.5 and 55.0%, respectively, but for F3 herbicide effect reached values of 84.2%. In 2010-11, the percentage of control in F1 was 58.4%, whereas in F2 and F3 the weed was completely controlled (100.0%).

Table 3. Values of cumulative emergence of *Bromus diandrus*, density when herbicide treatment, herbicide effect (at 60 days after treatment) and crop yield in function of crop sowing date (F1: mid-October; F2: mid-November; F3: early December) during three growing seasons.

2008-09 season

	Total cumulative emergence (pl·m^{-2})	Cumulative emergence decline (%) comparing sowing dates		% of plants emerged in autumn	Weed density (pl·m^{-2}) when herbicide treatment	Herbicide control effect (%)	Crop yield (Kg·ha^{-1})
		from F1	from F2				
F1	917 (a)	.	.	96.9 (a)	539.8 (a)	33.2	3152 (b)
F2	164 (b)	82.1	.	86.6 (a)	104.8 (b)	11.4	4687 (a)
F3	176 (b)	80.8	- 7	6.0 (b)	32.2 (c)	16.1	4498 (a)

2009-10 season

	Total cumulative emergence (pl·m^{-2})	Cumulative emergence decline (%) comparing sowing dates		% of plants emerged in autumn	Weed density (pl·m^{-2}) when herbicide treatment	Herbicide control effect (%)	Crop yield (Kg·ha^{-1})
		from F1	from F2				
F1	2664 (a)	.	.	94.2 (a)	1284.3 (a)	58.5	948 (b)
F2	68 (b)	97.5	.	44.5 (b)	26.7 (b)	55.0	2683 (a)
F3	34 (b)	98.7	49.7	0.0 (c)	8.8 (c)	84.2	3451 (a)

2010-11 season

	Total cumulative emergence (pl·m^{-2})	Cumulative emergence decline (%) comparing sowing dates		% of plants emerged in autumn	Weed density (pl·m^{-2}) when herbicide treatment	Herbicide control effect (%)	Crop yield (Kg·ha^{-1})
		from F1	from F2				
F1	217 (a)	.	.	96.8 (a)	102.3 (a)	58.4	1364 (a)
F2	4 (b)	98.1	.	53.8 (ab)	2.8 (b)	100.0	1265 (b)
F3	6 (b)	97.2	-30.7	11.7 (b)	1.0 (b)	100.0	924 (c)

Different letters between crop sowing dates within each season mean significant differences ($p< 0.05$).

In 2008-09 and 2009-10, crop yields obtained in F2 and F3 had been significantly higher than in F1, while in 2010-11 they had been significantly lower (Table 3). On average, the yields of the first season had been lower than in the two others. In 2008-09, maximum yields were observed in F2 (4687 $Kg \cdot ha^{-1}$) and F3 (4498 $Kg \cdot ha^{-1}$). In 2009-10 the maximum yield was obtained in F3 (3451 $Kg \cdot ha^{-1}$). On the contrary, yields in 2010-11 were very low, between 1364 $Kg \cdot ha^{-1}$ for F1 and 924 $Kg \cdot ha^{-1}$ for F3.

Weed fecundity and seed rain

Table 4 reflects values of weed density, fecundity and seed rain at the end of each growing season. In all seasons, the final density of *B. diandrus* was higher in F1 than in the two other crop sowing dates. In the third season (2010-11), a practical depletion of the final densitiy was obtained in F2 (0.7 $pl \cdot m^{-2}$) and F3 (0.1 $pl \cdot m^{-2}$), whereas in F1 a mean density of 42.6 $pl \cdot m^{-2}$ was estimated. On average, the fecundity of *B. diandrus* in the first season (2008-09) was higher than in 2009-10 and 2010-11, and it increased in function of the crop sowing date (F1<F2<F3). In 2008-09, the highest fecundity was observed in F3 (223.6 $seeds \cdot pl^{-1}$), but the highest seed rain was produced by F1 (27781.6 $seeds \cdot m^{-2}$) according to a higher weed density. On the contrary, the values of fecundity were very low in 2009-10 and 2010-11 (ranging from 14.7 to 29.8 $seeds \cdot pl^{-1}$), and with no significant differences between crop sowing dates. Both seasons (2009-10 and 2010-11), the highest seed rain was observed in F1 (7886 and 596 $seeds \cdot m^{-2}$, respectively) and the values for F3 were practically negligible (1.8 and 1.9 $seeds \cdot m^{-2}$, respectively).

Table 4. Final density, fecundity and seed rain for different cohorts of *Bromus diandrus* (F1, F2 and F3) during the three growing seasons. *B. diandrus* cohorts are established each season in function of crop sowing dates: F1: mid-October; F2: mid-November; F3: early December.

	Density ($pl \cdot m^{-2}$)	Fecundity ($seeds \cdot pl^{-1)}$	Seed rain ($seeds \cdot m^{-2}$)
2008-09 season			
F1	360.8 (a)	77.3 (c)	27781.6
F2	92.8 (b)	139.4 (b)	12903.8
F3	27.0 (c)	223.6 (a)	6021.0
2009-10 season			
F1	563.0 (a)	14.7 (b)	7886.7
F2	12.0 (b)	29.8 (a)	348.0
F3	0.1 (c)	18.3 (ab)	1.8
2010-11 season			
F1	42.6 (a)	14.9 (a)	596.4
F2	0.7 (b)	25.2 (a)	17.5
F3	0.1 (c)	19.2 (a)	1.9

Estimated data of densities were 20, 28 and 14 April in 2009, 2010 and 2011, respectively. Different letters between sowing dates for a same season mean significant differences ($p < 0.05$).

Discussion

Emergence patterns

The highest cumulative emergences of *B. diandrus* observed each season when crop was sowing in mid-October (Figure 2) are according to the low level of seed dormancy and rapid flush of autumn emergences appointed for this species by other authors (Kleeman and Gill, 2006, 2009a; Gill and Castairs, 1988; Riba and Recasens, 1996). In a recent study carried out with Australian populations of *B. diandrus*, Kleeman and Gill (2013) found a requirement of a short cold stratification to allow it to germinate due to stimulatory effect of chilly on GA synthesis within the seeds, and appointed a possible adaptative mechanism of dormancy that delays germination and seedling emergence until late autumn and early winter when temperature drop below 4ºC. This observation is according with the results obtained in our experiment, where the main flushes of emergences were observed after chilling temperatures are registered in late autumn (early or mid-November) (Figure 1 and Figure 2). Furthermore, Del Monte and Dorado (2011) recently demonstrated a photo-inhibition of the germination in seeds of *B. diandrus* populations collected in cereal fields of Central Spain, and suggest that this main flush of emergences in no-tillage systems take place by seeds remaining on the soil surface, where they only need a superficial coverage (i.e. shaded by field stubble) to perceive darkness and avoid light inhibition of germination. On the contrary, if seeds remain exposed to light, dormancy could be prolonged over two months, and possibly four months. In our study, the protracted seedling emergences observed during winter and spring represent only < 6% for F1 (overall the three seasons), when the crop was sown in mid-October (Table 3). These results indicate that the remaining seeds on the soil in no-tilled fields, such as this of our study, find favourable conditions to germinate with the first autumn rains. The highest observed flushes of emergences in the two first seasons coincide with high rainfalls recorded in October (84 and 69 mm, respectively). Del Monte and Dorado (2011) also appointed that in non photo-inhibition conditions, only a severe drought or low temperatures at the end of autumn could limit the germination. These conditions were recorded in our experiment in 2010-11 and could explain the observed low percentage of emergences.

The hydrotermal model developed by García *et al.*, (2013) predicts 50%, 75% and 90% of CE of *B. diandrus* at 264, 329 and 406 HTT after the first rains in autumn, independently of the season. The application of this HTT models allows a more accurate establishment of the date for pre-sowing control measures.

Effect of the crop sowing delay

Delaying the crop sowing date implies both a notable reduction of the emerged weed population and a delayed development of the seedlings. This reduction on CE ranged between 80.8% and 98.7% (Table 3). No data is available on the competitive effect of *B. diandrus* on barley in Spanish cereal systems, but data from an Australian research (Gill *et al.*, 1987) confirm that this species can reduce yields of wheat to 50% because of early competition. Our results confirm the efficacy of this cultural strategy in reducing competition of *B. diandrus* in cereal systems. For other grass weeds, Melander (1995) and Rasmussen (2004) also observed an effect of crop sowing time reducing the weed pressure and improving crop growth relative to weed growth. Furthermore, in similar cereal field conditions to our experiment, Cirujeda and Taberner (2009) observed a significant decrease (50%) of *Lolium rigidum* emergences delaying 20 days the crop sowing date.

However, one constrain of delaying crop sowing date is the potential reduction of the yield (Moss, 1985). In our experiment, when barley was harvested in our field trial the first season, significantly higher yields were obtained when crop was sown in mid-

November and early December as a clear consequence of the lower competitive effect of *B. diandrus* densities (Table 3). Sing *et al*. (1995) also observed a higher increase on wheat yield due to the avoidance of *Avena sterilis* competition when crop sowing was delayed 20 days in November. Furthermore, despite the lower weed control obtained with herbicides, it is remarkable to note the higher yields obtained overall in barley the first season, than in wheat the next two. This could indicate more limited conditions for the growth of several wheat varieties in the region, in agreement with exposed by Anderson and Impiglia (2002), where barley's productivity and stability is higher than in wheat. In 2008-09, the more regular rainfall recorded allowed a better crop establishment, tillering and grain filling. On the contrary, 2009-10 was dry during spring, affecting reproductive biomass and mainly grain filling, and 2010-11 showed a severe drought during all the growing period.

Analysing intrinsically the *B. diandrus* demography behaviour, a clear intraespecific density dependent effect was detected the first season. The lower weed densities obtained delaying crop sowing date was reflected on higher fecundities (Table 4). In this sense, the final balance expressed as seed rain was higher for F1. Consequently, the high seed recruitment occurred in the soil were followed by a huge seedling emergence in F1 the next season (2009-10) and by the highest density values observed during all the experiment. On the other hand, seedling density was significantly reduced when the crop sowing was delayed (97.7% for F2 and 98.7% for F3), which reflects the great efficiency of this cultural method when huge densities of *B. diandrus* are present.

Herbicide effect

It is well known that the chemical control of this species in barley is not successful (Gill *et al.*, 1987; Kleemann and Gill, 2009a). Furthermore, in 2009-10 when wheat was sown, the herbicide mesosulfuron-methyl plus iodosulfuron-methyl sodium had an unequal effect on the control of *B. diandrus* depending on the crop sowing date (Table 3). It could be assumed that this low control level in F1 was caused by the high densities registered (>1000 pl·m^{-2}), making it difficult the herbicide absorption because of leave stratification. However, despite the lower weed density in F2 (26.7 pl·m^{-2}), the herbicide effectiveness was also very low (55.0%). These low control effects seem to have been influenced by the advanced development stage (tillering) of plants. Similar results were observed in 2010-11 in F1, where the herbicide effectiveness was only

58.4%. Furthermore, in all these cases, the new emergences occurred during spring masked the values of herbicide control.

A lower fecundity was also noticed in those herbicide surviving plants or emerging after herbicide application (<30 seed·plant^{-1}) (Table 4). Similar decreasing results on fecundity were obtained by Kleeman and Gill (2009b) for Australian populations of this species treated with this same herbicide. These authors also observed a limited and variable control of *B. rigidus* (11-67%) with this herbicide on wheat, however, other authors obtained good control (90%), when this herbicide was applied between three-leaf stage and beginning of tillering (Rapparini *et al.*, 2006). Our study detects only an acceptable or good control effect on *B. diandrus* in F2 (84.2%) in 2009-10 and in F2 and F3 (100%) in 2010-11, when the herbicide was applied over low weed densities and little developed seedlings.

Options for an integrated management program

The very low *B. diandrus* densities observed at the end of the three years indicate the effectiveness of the integrated management carried out. When visited the field trials in May 2012, where the same herbicide was applied in wheat following the same gradient of crop sowing dates, the density in F1 averaged 34 plants·m^{-2} whereas null density of *B. diandrus* was confirmed in F2 and F3 (data not shown).

Results of this study allow assessing three fundamental aspects when establishing an integrated management for *B. diandrus* in dry-land winter cereals fields under no-till: First, the importance of barley-wheat rotation that allows the use of other herbicides; second, the importance of integrating the delay of the sowing date in this kind of management, which allows a significant reduction of in-crop emergence of *B. diandrus*, both in barley and wheat, according to the data obtained from the hydrothermal time model; and third, the importance of performing a selective herbicide treatment in the correct leaf-stage of the weed to reduce the final density, limiting significantly the fecundity of surviving plants and avoiding as much as possible the seed soil recruitment. In our study, this approach allowed a practical elimination of brome infestation.

References

Alvaro-Fuentes, J., Cantero-Martinez, C., Lopez, M. V. and Arrue, J. L. (2007). Soil carbon dioxide fluxes following tillage in semiarid Mediterranean agroecosystems. *Soil and Tillage Research* 96: 331-341.

Anderson, R. L. (2007). Managing weeds with a dualistic approach of prevention and control. A review. *Agronomy for Sustainable Development* 27: 13-18.

Anderson, W. K., Impliglia, A. (2002). Management of dryland wheat. In: Curtis, B. C., Rajaram, S., Gómez Macpherson, H. (Eds.). Wheat: Improvement and production. Plant Production and Protection Series, No 30. FAO, Rome, p.567.

Arrue, J. L., Cantero-Martínez, C., López, M. V., Moreno, F., Murillo, J. M., Pérez de Ciriza, J. J., Sombrero, A., Tenorio, J. L. and Zambrana, E. (2007): Conservation agriculture research in Spain. KASSA project, Mediterranean platform, deliverable 1.2, appendix A1.

Cantero-Martínez, C., Angás, P. and Lampurlanés, J. (2003) Growth, yield and water productivity of barley (*Hordeum vulgare* L.) affected by tillage and N fertilization in Mediterranean semiarid, rainfed conditions in Spain. *Field Crops Research* 84: 341-357.

Cheam, A. H. (1986). Patterns of change in seed dormancy and persistence of *Bromus diandrus* Roth (great brome) in the field. *Australian Journal of Agricultural Research* 37: 471-481.

Cirujeda, A., and Taberner, A. (2009). Cultural control of herbicide-resistant *Lolium rigidum* Gaud. populations in winter cereal in Northeastern Spain. *Spanish Journal of Agricultural Research* 7: 146-154.

Conley, S. P., Binning, L. K., Boerboom, C. M. and Stoltenboom, D. E. (2002). Estimating giant foxtail cohort productivity in soybean based on weed density, leaf area or volume. *Weed Science* 50: 72-78.

Del Monte J. P. and Dorado J. (2011). Effect of light conditions and after ripening time on seed dormancy loss of *Bromus diandrus*. *Weed Research* 51: 581-590.

Forcella, F., Eradatoskoui, K. and Wagner, S. W. (1993). Application of weed seedbank ecology to low-input crop management. *Ecological Applications* 3: 74-83.

Gallart, M., Mas, M. T., and Verdu, A. M. C. (2010). Demography of *Digitaria sanguinalis*: Effect of the emergence time on survival, reproduction, and biomass. *Weed Biology and Management* 10: 132-140.

García-Baudín, J. M. (1983). Malas hierbas gramíneas en los cereales (trigo y cebada) de la región del Duero. Servicio de Extensión Agraria. Consejo General de Castilla y León. 17 p.

García, A. L., Recasens, J., Forcella, F., Torra, J. and Royo-Esnal, A. (2013) Hydrothermal emergence model for *Bromus diandrus*. *Weed Science* 61: 146:153.

Gill, G. S., and Blacklow, W. M. (1985). Variations in seed dormancy and rates of development of great brome, *Bromus diandrus* Roth., as adaptations to the climates of southern Australia and implications for weed control. *Australian Journal of Agricultural Research* 36: 295-304.

Gill, G. S. and Carstairs S. A. (1988). Morphological, cytological and ecological discrimination of *Bromus rigidus* from *Bromus diandrus*. *Weed Research* 28: 399-405.

Gill, G. S.; Poole, M. L. and Holmes, J. E. (1987). Competition between wheat and brome grass in Western Australia. *Australian Journal of Experimental Agriculture* 27: 291-294.

Harradine, A. R. (1986). Seed longevity and seedling establishment of *Bromus diandrus* Roth. *Weed Research* 26: 173-180.

Holland, J. M. (2004). The environemntal consequences of adopting conservation tillage in Europe: reviewing the evidence. *Agriculture, Ecosystems and Environment* 103: 1-25.

Jauzein, P. (1989). Photosensibilite des bromes annuels (*Bromus* L. spp.). *Weed Research* 29: 53-63.

Kleemann, S. G. L., and Gill, G. S. (2006). Differences in the distribution and seed germination behaviour of populations of *Bromus rigidus* and *Bromus diandrus* in South Australia: Adaptations to habitat and implications for weed management. *Australian Journal of Agricultural Research* 57: 213-219.

Kleemann, S. G. L., and Gill, G. S. (2009a). Population Ecology and Management of Rigid Brome (*Bromus rigidus*) in Australian Cropping Systems. *Weed Science* 57: 202-207.

Kleemann, S. G. L. and Gill, G. (2009b). The role of imidazolinone herbicides for the control of *Bromus diandrus* (rigid bromue) in wheat in southern Australia. *Crop Protection* 28: 913-916.

Kleemann, S. G. L. and Gill, G. (2013) Seed dormancy and seedling emergence in ripgut brome (*Bromus diandrus* Roth) populations in southern Australia. *Weed Science* In-Press. **doi:** http://dx.doi.org/10.1614/WS-D-12-00083.1

Lampurlanés J., Angás, P. and Cantero-Martínez, C. (2002) Tillage effects on water storage during fallow, and on barley root growth and yield in two contrasting soils of the semi-arid Segarra region in Spain. *Soil and Tillage Research* 69: 27-40.

Melander, B. (1995). Impact of drilling date on *Apera spica-venti* L. and *Alopecurus myosuroides* Huds. in winter cereals. *Weed Research* 35: 157-166.

Moss, S.R. (1985a). The effect of drilling date, pre-drilling cultivations and herbicides on Alopecurus myosuroides (black-grass) population in winter cereals. *Aspects of Applied Biology* 9: 31-39

Planes, J., Briceño, R. and Recasens, J. (1999) ¿Influye la fecha de siembra en el control de poblaciones de *Lolium rigidum* resistentes a herbicidas?. *VII Congreso de la Sociedad Española de Malherbología* Logroño. Proceedings: 387- 393

Rapparini, G., Campagna, G. and Geminiani, E. (2006) Graminacee del grano, evoluzione della lotta. *Informatore Agrario* 62: 73-75.

Rasmussen, I. A. (2004). The effect of sowing date, stale seedbed, row width and mechanical weed control on weeds and yields of organic winter wheat. *Weed Research* 44: 12-20.

Recasens, J., Riba, F., Izquierdo, J., Forn, R. and Taberner, A. (1996). Gramíneas infestantes de los cereales de invierno de Cataluña. ITEA 92 (2): 116-130.

Riba, F. (1993). Demografia i dinàmica de poblacions de *Bromus diandrus* Roth en cereals d`hivern. PhD thesis, Universitat de Lleida. 117 p.

Riba, F. and Recasens, J. (1997). *Bromus diandrus* Roth en cereales de invierno. In: Sans, F. X. y Fernández-Quintanilla, C. (editores). La biología de las malas hierbas de España. Ed. *Phytoma España-Sociedad Española de Malherbología*. Pp: 25–35.

Rice, K. J. and Dyer, A. R. (2001). Seed aging, delayed germination and reduced competitive ability in *Bromus tectorum*. *Plant Ecology* 155: 237-243.

Roman, E. S., Murphy, S. D. and Swanton, C. J. (2000). Simulation of *Chenopodium album* seedling emergence. *Weed Science* 48: 217-224.

Sing, S., Malik, R. K., Panwar, R. S. and Balyan, R. S. (1995). Influence of sowing time on winter wild oat (*Avena ludoviciana*) control in wheat (*Triticum aestivum*) with isoproturon. *Weed Science* 43: 370-374.

Spokas, K. and Forcella, F. (2009). Software tools for weed seed germination modelling. *Weed Science* 57: 216-227.

CAPÍTULO 3

“Fitness in *Bromus diandrus* in response to cohort effect and herbicide stress”

Fitness in *Bromus diandrus* in response to cohort effect and herbicide stress

Introduction

Direct drilling exhibits difficulties in the control of certain weed species. Some evident cases have appeared in the dry-land cereal systems in north eastern Spain, where species like *Bromus diandrus* Roth are widespread (Riba and Recasens, 1997; Arrúe *et al.*, 2007). This species was a very common weed on road and field margins, and has proliferated in cereal crops due to the absence of effective herbicides and to the introduction, over the past twenty years, of conservation tillage (Young and Thorne, 2004, Kleeman and Gill, 2006).

Cultivation is a useful strategy to control weeds in pre-sowing, but the adoption of no-tillage systems obligated to replace cultivation with broad-spectrum herbicides before sowing (mainly glyphosate) (Kleeman and Gill, 2009a). However, pre-sowing control of *Bromus* species may be limited because of light inhibition of germination (Del Monte and Dorado, 2011) leading to protracted seedling establishment and evasion of early control measures (Kleeman and Gill, 2006). Furthermore, chemical control of *B. diandrus* in post emergence is usually non effective and surviving plants could restore, maintain or even increase the infestations. The recent introduction of herbicides like mesosulfuron-methyl offered an efficient control of *B. diandrus* (Rapparini *et al.*, 2006; Couloume and Adrien, 2005), but they are selective only in wheat, not in barley, which is the main crop in the region. In addition, its efficacy depends on the growing stage of the weed, not being effective when it is more advanced than three-leaf stage (Kleeman and Gill, 2009a). All these constraints are restricting the effectiveness of control strategies against *B. diandrus* in cereal crops where conservation agriculture (specially no tillage) is implemented. In the dry-land cereal systems in NE Spain it is difficult to adopt alternative strategies for weed control like crop rotation due to limited rainfall, allowing only the growth of winter cereals with limited profits depending on the season. This situation draws a scenario where very limited options can be incorporated to control noxious weeds like *B. diandrus*. In this sense, delaying crop sowing date could be an additional management strategy. Previous studies demonstrate that crop sowing delay causes a significant decrease on the potential competition of autumn grass weed populations and a more efficient control of new emerged plants (Gills *et al.*, 1987; Powles and Matthews, 1996).

The demographic success of *B. diandrus* depends on seedling survival and on fecundity according to the rate of emergence in autumn (Riba and Recasens, 1997). For other grass weeds it is confirmed that the emergence time has an important effect on fitness; cohorts that emerged earlier weighted more and contributed more to the seed bank than those emerged later (Rice *et al.*, 2001; Conley *et al.*, 2002; Gallart *et al.*, 2010). These studies indicated that percentage of seedling emergence, growth rate and fecundity differed among emerged cohorts, showing the importance of emergence time and crop competition on weed demography. Cohorts emerging immediately after crop sowing will represent the main source of recruitment from the weed population and seed bank (Norris, 2007).

Several studies have reported the biology of *B. diandrus* and its influence on cereal yields (Gill and Blacklow, 1984; Gill and Holmes, 1987; Kleeman and Gill 2006; Kleeman and Gill 2009a); however, few studies have analysed the effect of cohort emergence on fitness and the demographic response when crop sowing is delayed. Furthermore, the restricted use of the specific herbicide mesosulfuron-methyl when wheat is growing, suggests a study of the fitness response of survival plants after this herbicide application. Potential changes on fitness and their influence to reduce the population demography could have an interesting implication on *B. diandrus* management strategy integrating cultural and chemical techniques.

We hypothesize that the date of crop sowing has a significant influence on *B. diandrus* fitness and furthermore, on the effectiveness of post-emergence chemical control in a cereal monocrop system. The specific objectives of this research were to determine, along three continuous seasons, the effect of different crop sowing dates on the fitness parameters and resource allocation patterns in *B. diandrus*, first in the most frequent situation, on barley, when the post emergence herbicides applied are not efficient, and second when a specific chemical control is applied on wheat.

Materials and Methods

Study site

Experimental plots were established in a field trial in Agramunt (41º48’N and 1º07’E) (Lleida, Spain). The field is located 330 m above the sea level and has a semiarid continental Mediterranean climate by the influence of Ebro Valley. The soil was a Fluventic Xerocrept (100-120 cm deep), with 30.1 % sand, 51.9% silt and 17.9 % clay, 2.3 % organic matter and pH of 8.5. Rainfall received at the site during the study period as well the long-term average are presented in Table 1.

Table 1. Monthly rainfall for 2008-09 to 2010-11 and monthly mean long-term rainfall (1975 to 2011) in Agramunt, Catalonia (NE Spain)

	Season			Long-term mean[a]
Month	2008-09	2009-10	2010-11	1975- 2011
	Rainfall (mm)			
October	84	69	1	50
November	31	5	0	36
December	29	112	0	30
January	56	132	0	31
February	34	39	12	18
March	55	64	36	30
April	150	26	20	48
May	5	59	27	54
June	20	76	73	38
Total Oct-June	464	582	169	378

[a] Rainfall details averaged from 1975 to 2011

Agronomic management

Trials were conducted over three consecutive growing seasons (2008-09, 2009-10 and 2010-11) in an experimental cereal field under zero tillage. The site had been under no-till production for two seasons prior to the initiation of the study. The experiment was arranged as a randomized complete block design with three replications. Each plot was 6 x 30 m and the main factor considered was the cereal sowing date: first sowing date (*B. diandrus* cohort F1), 20, 19 and 14 October 2008, 2009 and 2010, respectively; second sowing date (cohort F2), 7, 12 and 18 November 2008, 2009 and 2010, respectively; and third sowing date (cohort F3), 10, 3 and 13 December 2008, 2009 and 2010, respectively. Barley cv. ‘Hispanic’ was sown in 2008 and wheat cv. ‘Bokaro’ in 2009 and 2010. Each year cereals were sown at 180 kg seed·ha^{-1} (400-450 plants·m^{-2}). Crop sowing was performed with a no-till disc drill in rows 19 cm apart.

Plots were sprayed with glyphosate at 540 g a.i.·ha^{-1} one to six days before each sowing date (14, 16 and 13 October in F1; 6, 4 and 12 November in F2; and 5, 2 and 9 December in F3, in 2008, 2009 and 2010, respectively). In 2008-09 a post-emergence tank mix of isoproturon plus diflufenican (1243 + 69 g a.i.·ha^{-1}) was applied in February. In 2009-10 the post-emergence weed control (in 2-5 leaves) was accomplished by mesosulfuron-methyl plus iodosulfuron-methyl sodium (15 + 3 g a.i.·ha^{-1} plus wetting agent) applied in December for F1 and in March for F2 and F3. In 2010-11 broadleaf were controlled in post-emergence by tribenuron-methyl plus metsulfuron-methyl (10 + 5 g a.i.·ha^{-1} plus wetting agent) in March. Mesosulfuron-methyl plus iodosulfuron-methyl sodium (15 + 3 g a.i.·ha^{-1} plus wetting agent) was applied in February in F1 (tillering) and in April in F2 and F3 (2-5 leaves). Fertilizer was applied each year in February to March at 150 Kg N-32%·ha^{-1}, according to yearly soil test recommendations.

Weed density

Each season densities of *B. diandrus* were estimated in each plot 60 days after herbicide applications within a 0.10 m^2 quadrate at ten random locations.

Vegetative and reproductive fitness

Each year in June, when *B. diandrus* reached their complete development and fecundity, 20 plants from plots belonging to each cohort (F1, F2 and F3) were collected and the following parameters were estimated: number of stems per plant, number of spikelets per stem, fecundity (caryopsides per plant) and number of caryopsides per spikelet. Aerial vegetative and reproductive biomasses per plant were also estimated. For this purpose, plants were cut at ground level, placed in a tray, separated in aerial vegetative biomass (VB) and reproductive biomass (RB) and oven dried at 65ºC for 24 hours. Reproductive effort was calculated per plant from the latter two parameters (ER = RB/VB).

Thousand grain weight

For each different cohort and from different plants, many inflorescences (panicles) were collected and from them separated the caryopsides. From 100 caryopsides the weights of thousand grains for each cohort were estimated after three replications.

Allocation gradient within the panicle

Before crop harvest, for each *B. diandrus* cohort twenty panicles were collected from different plants (with three replications). In each panicle, two different position of spikelets -apical (*A*) and basal (*B*)- and two positions of caryopsides in the spikelet -apical (*a*) and basal (*b*)- were considered, thus obtaining four different positions of caryopsides in the panicle: *Aa*, *Ab*, *Ba* and *Bb*. The weight of twenty caryopsides situated in the same position and for each cohort was estimated every season. Weights are expressed per caryopsis.

Statistical analysis

In order to find possible differences between cohorts, different ANOVA analyses were performed using SAS (SAS Institute INC., Cary, NC, USA). Because different cereals were sown and different weed managements were applied each year, results have been analyzed separately for each growing season. In those cases where ANOVA analysis were significant, LSD post-hoc tests at p=0.05 were done. Before analysis, all parameters were transformed to satisfy the homogeneity of variance assumptions [log (x+1)], while the reproductive effort was √ (x + 0.5) transformed. Linear regressions analyses were performed between biological parameters (vegetative biomass vs. reproductive biomass and fecundity) with Sigma Plot program 11.0. Previously, parameters were log (x+1) transformed.

Results

Table 2. Means and standard errors of plant density (60 days after post-emergence herbicide treatment) and fitness parameters for three different cohorts of *Bromus diandrus* in a cereal field, during the growing seasons 2008-09, 2009-10 and 2010-11.

Season	Cohort	Density (pl/m^2)	Nº stem/pl.	Nº spikelets/pl.	Nº spikelets/stem	Nº caryopsides/pl.	Nº caryopsy-des/spikelet
2008/09	F1	500.5 ± 108.6 (a)	2.9 ± 0.4 (a)	18.1 ± 1.8 (a)	6.9 ± 0.3 (a)	77.3 ± 8.1 (a)	4.3 ± 0.1 (a)
	F2	141.3 ± 30.7 (b)	3.9 ± 0.3 (b)	33.2 ± 3.1 (b)	8.5 ± 0.4 (b)	139.4 ± 10.9 (b)	4.2 ± 0.1 (a)
	F3	60.0 ± 26.8 (c)	5.5 ± 0.7(c)	49.3 ± 7.7 (c)	8.6 ± 0.3 (b)	223.6 ± 32.3 (c)	4.5 ± 0.1 (a)
2009/10	F1	563.3 ± 76.5 (a)	2.9 ± 0.3 (a)	6.9 ± 0.7 (a)	2.8 ± 0.1 (a)	13.7 ± 2.2 (a)	2.0 ± 0.2 (ab)
	F2	21.0 ± 11.1 (b)	2.9 ± 0.3 (a)	13.7 ± 1.9 (b)	5.3 ± 0.3 (b)	28.8 ± 5.2 (b)	2.1 ± 0.2 (a)
	F3	3.8 ± 2.5 (c)	2.2 ± 0.3 (a)	10.0 ± 3.2 (ab)	4.0 ± 0.6 (c)	18.3 ± 7.3 (ab)	1.4 ± 0.1 (b)
2010/11	F1	60.5 ± 19.3 (a)	6.4± 0.7 (a)	18.3 ± 2.0 (a)	3.5 ± 0.1 (a)	14.7 ± 2.4 (a)	0.8 ± 0.2 (a)
	F2	2.8 ± 0.9 (b)	4.4 ± 0.3 (b)	22.5 ± 2.7 (a)	4.8 ± 0.2 (b)	25.2 ± 2.0 (a)	1.1 ± 0.1 (a)
	F3	1.0 ± 0.6 (b)	4.0 ± 0.4 (b)	18.7 ± 1.9 (a)	4.6 ± 0.2 (b)	19.2 ± 3.8 (a)	1.1 ± 0.2 (a)

Cohorts established each season in function of crop sowing date. F1: middle October, F2: middle November, F3: early December. Fitness parameters estimated in June before crop harvest. Different letters between cohorts for the same season mean significant differences (p< 0.05).

Weed density

Crop sowing date had relevance for the density of *B. diandrus* (Table 2). The first two seasons, 2008-09 and 2009-10, F1 had densities of 500.5 pl·m^{-2} and 563.3 pl·m^{-2}, respectively, whereas the third season (2010-11) its density was lower (60.5 pl·m^{-2}). Each season, densities decreased significantly between cohorts. In 2008-09, this decrease represented 71.8% between F1 and F2, 88.0% between F1 and F3 and 57.6% between F2 and F3. In 2009-10, the percentages of density reduction were 96.2% between F1 and F2, 99.3% between F1 and F3 and 81.8% between F2 and F3. In 2010-11, the percentages of reduction were 95.4% between F1 and F2, and 98.3% between F1 and F3. No significant differences on weed density were observed this season between F2 and F3.

Vegetative and reproductive fitness

The number of stems per plant increased significantly from early to late cohorts in season 2008-09. However, in 2009-10 there were not significant differences. In 2010-11 significant higher values were observed for F1 (6.4 stems per plant) in comparison with F2 (4.4) and F3 (4.0) (Table 2).

Overall, higher number of spikelets, both per plant and stem, were observed in 2008-09 compared to 2009-10 and 2010-11 (Table 2). The first two seasons significant differences between cohorts were observed, for both parameters, with lower values registered in F1. In 2010-11 the number of spikelets per stem showed differences between cohorts with the same pattern.

Fecundity (nº caryopsides per plant) showed greater values in 2008-09 than in the next two seasons (Table 2). When comparing cohorts, the maximum value observed (223.6) was for F3 in 2008-09; in contrast, the maximum values were for F2 the following seasons (28.8 and 25.2, in 2009-10 and 2010-11, respectively). Considering the three cohorts together, the reduction on fecundity was close to 80% in 2009-10 and 2010-11 compared to 2008-09. Moreover, in 2008-09 a significant increasing gradient of fecundity between cohorts was observed. In 2009-10, only the fecundity for F1 was significantly lower than F2. No differences on fecundity between cohorts were observed in 2010-11.

Despite the significant increase of fecundity observed between cohorts in 2008-09, the number of caryopsides per spikelet was statistically similar between them (from 4.2 to 4.5) (Table 2). Nevertheless, this parameter showed lower values in the next two seasons. In 2009-10, the number of caryopsides per spikelet for F2 (2.1) was significantly higher than F3 (1.4). In 2010-11, no significant differences between cohorts were observed (ranging from 0.8 and 1.1 caryopsides per spikelet).

Table 3. Means and standard errors of vegetative biomass, reproductive biomass and reproductive effort per plant for different *Bromus diandrus* cohorts at the end of three cropping seasons.

Season	Cohort	Vegetative biomass (mg)	Reproductive biomass (mg)	Reproductive effort
2008-09	F1	41.5 ± 4.5 (a)	30.5 ± 3.0 (a)	0.77 ± 0.02 (a)
	F2	77.0 ± 6.0 (b)	45.0 ± 3.0 (b)	0.62 ± 0.02 (b)
	F3	121.5 ± 23.0 (c)	64.0 ± 10.0 (c)	0.57 ± 0.02 (b)
2009-10	F1	6.5 ± 1.0 (a)	10.0 ± 1.0 (a)	1.63 ± 0.14 (a)
	F2	14.0 ± 2.5 (b)	20.5 ± 3.0 (b)	1.51 ± 010 (a)
	F3	8.5 ± 1.5 (ab)	13.0 ± 4.0 (ab)	1.45 ± 0.15 (b)
2010-11	F1	11.5 ± 1.5 (a)	22.5 ± 2.5 (a)	2.30 ± 0.27 (a)
	F2	16.0 ± 2.0 (a)	41.0 ± 5.0 (b)	2.62 ± 0.16 (ab)
	F3	11.5 ± 1.0 (a)	29.5 ± 2.5 (ab)	4.14 ± 0.87 (b)

Cohorts established each season in function of crop sowing date. F1: middle October, F2: middle November, F3: early December. Different letters between cohorts for the same season mean significant differences ($p < 0.05$). Parameters estimated in June before crop harvest.

Overall, higher values of vegetative and reproductive biomass were observed in plants in 2008-09 than in the two next seasons (Table 3). For vegetative biomass this reduction represents an 88% in 2009-10 and an 84% in 2010-11. For reproductive biomass, overall, the percentage of decrease in 2009-10 and 2010-11 were 69% and 34%, respectively. In 2008-09, vegetative biomass significantly increased from cohort F1 to F3 (from 41.5 to 121.5 mg). In 2009-10, vegetative biomass only resulted significantly higher in F2 (14.0 mg). Not significant differences were found between cohorts in 2010-11 with a maximum value observed for F2 (16.0 mg).

Averaging three cohorts, the higher value of reproductive biomass were observed in plants from 2008-09 season, with a significant increase from early to late cohorts (from 30.5 for F1 to 64.0 mg for F3). In the next two seasons, reproductive biomass resulted significantly higher in F2 than F1 (Table 3).

The reproductive effort across cohorts averaged different depending on the cropping season: 0.68 in 2008-09, 1.53 in 2009-10 and 3.60 in 2010-11. Furthermore, there was a clear significant decreasing gradient in the reproductive effort in 2008-09 in function of cohorts. On the contrary, in 2010-11 significant lower values were only observed for F1, whereas values of F2 and F3 were the highest observed during the three seasons.

Relationship between fitness parameters

Figure 1 shows a positive linear relationship between vegetative and reproductive biomass. Adjustments were good the three seasons (R^2 ranging from 0.68 to 0.98). In 2008-09, the plants were bigger and the relationship comprised greater rang values of vegetative and reproductive biomass than in 2009-10 and 2010-11. However, the slope was more pronounced in 2009-10 and 2010-11, where plants were constricted to produce a minimum effective reproductive biomass from a lower vegetative biomass.

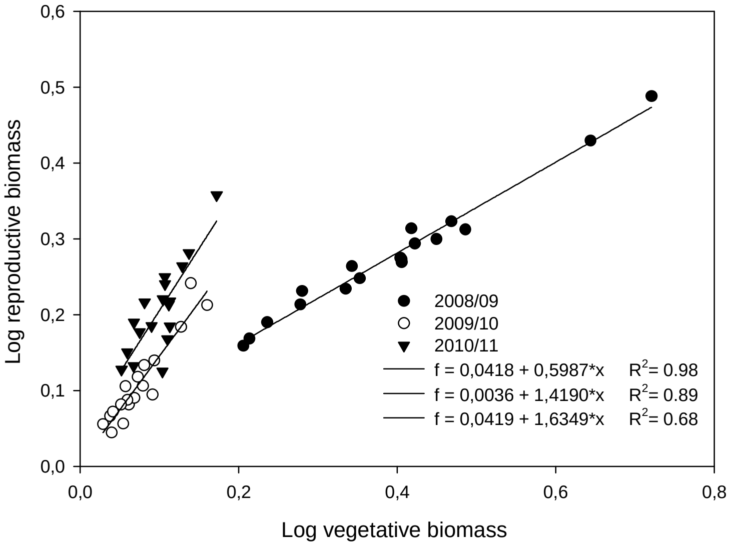

Figure 1. Linear regressions between vegetative and reproductive biomass of *Bromus diandrus* for three different cropping seasons: 2008-09, 2009-10 and 2010-11.

Significant positive regressions between vegetative biomass and fecundity (Figure 2) were obtained for the three seasons (R^2 ranging from 0.43 to 0.94). A greater rang of values was obtained in 2008-09 corresponding to plants with higher vegetative biomass and fecundity. However, in 2009-10 and 2010-11 the more pronounced slopes are according with lower range of values of both parameters.

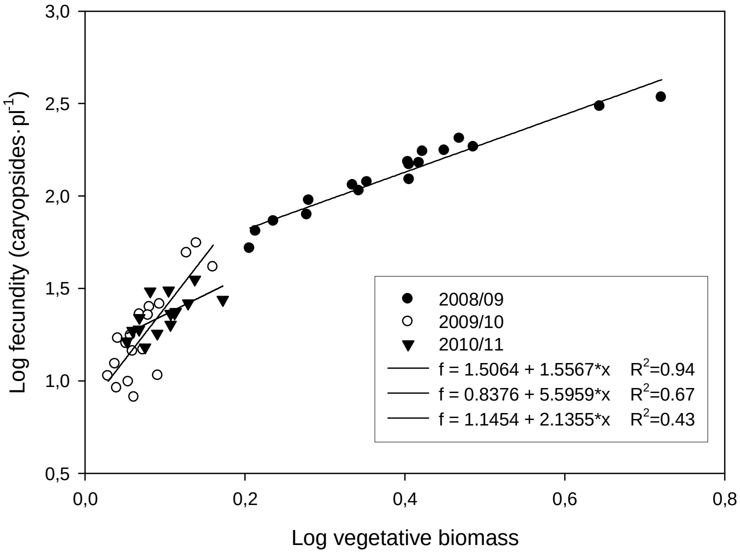

Figure 2. Linear regressions between vegetative biomass and fecundity of *Bromus diandrus* for three different cropping seasons: 2008-09, 2009-10 and 2010-11.

Weight of 1000 grains

Overall, in 2008-09 values of weight of 1000 grains were 24.2% higher than in 2009-10 and 31.3% higher than in 2010-11. In 2008-09 a significant decreasing gradient from F1 (17.62 g) to F3 (14.87 g) was observed, while in 2009-10 these significant differences did not follow a gradient in function of the cohort establishment, where highest values were observed in F2 (13.76 g) and lowest in F1 (10.86 g). There were no significant differences between cohorts in 2010-11 and, on average, the seed weight of the three cohorts were lower than the two previous seasons.

Table 4. Weight (g) and standard errors of 1000 caryopses of different cohorts of *Bromus diandrus*, for three different cropping seasons: 2008-09, 2009-10 and 2010-11. Parameters estimated when plants where completely developed.

Season	2008-09	2009-10	2010-11
F1	17.62 ± 0.27 (a)	10.86 ± 0.13 (a)	11.97 ± 0.80 (a)
F2	15.96 ± 0.19 (b)	13.76 ± 0.30 (c)	10.98 ± 0.15 (a)
F3	14.87 ± 0.15 (c)	12.09 ± 0.03 (b)	10.32 ± 0.32 (a)

Cohorts established each season in function of crop sowing date. F1: middle October, F2: middle November, F3: early December. Different letters between cohorts for the same season mean significant differences (p< 0.05%).

Allocation within the panicle

In general, a clear decreasing gradient of weight of caryopsides were observed according to seasons (Table 5). Considering all positions and the three cohorts together the mean weights of the caryopsides were 15.90 mg, 11.02 mg and 10.64 mg, respectively, for 2008-09, 2009-10 and 2010-11 (data not shown). A cohort effect was only observed in 2008-09 for all the positions considered, with greater values for F1 than F2 or F3. On the contrary, no significant differences were found between cohorts for any position in 2009-10 and 2010-11. In 2008-09 and 2009-10, a position effect was observed within each cohort –with the exception of cohort F1 in 2009-10–, while in 2010-11 no significant differences were found between the four positions considered. In 2008-09 a similar pattern of allocation were observed in the three cohorts. The heaviest caryopsides were those from the bottom spikelets situated in apical position in the panicle (*Ab*), followed by those coming from basal position in spikelets situated in basal position in the panicle (*Bb*), whereas the weight of caryopsides coming from apical position in both, apical (*Aa*) and basal position (*Ba*) of spikelet in the panicle were lower and in most cases significantly different from *Ab*.

Table 5. Mean weight (mg) of one caryopsis according to the position apical (*a*) or basal (*b*) of caryopsis in the spikelet and the position apical (*A*) or basal (*B*) of spikelet in the inflorescence of different cohorts of *Bromus diandrus* for three growing seasons. Parameters estimated when plants where completely developed.

Season	Cohort	Caryopsis position			
		Ab	*Bb*	*Aa*	*Ba*
2008-09	F1 *	20.33 ± 0.14 (a)	19.04 ± 0.56 (ab)	18.33 ± 0.41 (ab)	16.94 ± 0.40 (b)
	F2 **	17.65 ± 1.20 (a)	16.24 ± 0.36 (ab)	13.86 ± 0.48 (bc)	11.95 ± 0.58 (c)
	F3 **	17.16 ± 0.84 (a)	14.86 ± 0.12 (ab)	13.00 ± 0.67 (bc)	11.39 ± 0.36 (c)
2009-10	F1	13.27 ± 1.41 (a)	11.51 ± 0.05 (a)	10.96 ± 0.58 (a)	8.53 ± 0.22 (a)
	F2	14.60 ± 0.04 (a)	12.66 ± 1.40 (ab)	9.22 ± 0.84 (b)	8.18 ± 0.42 (b)
	F3	13.73 ± 0.47 (a)	12.47 ± 0.05 (ab)	8.78 ± 1.92 (ab)	8.32 ± 1.09 (b)
2010-11	F1	12.26 ± 1.53 (a)	10.73 ± 1.72 (a)	11.71 ± 1.93 (a)	11.15 ± 1.64 (a)
	F2	9.86 ± 0.81 (a)	11.13 ± 0.29 (a)	9.76 ± 0.27 (a)	9.87 ± 0.62 (a)
	F3	10.54 ± 0.29 (a)	10.51 ± 1.06 (a)	9.83 ± 0.89 (a)	10.38 ± 1.03 (a)

Cohorts established each season in function of crop sowing date. F1: middle October, F2: middle November, F3: early December. Different letters between caryopsides positions for a same cohort mean significant differences ($p < 0.05$). Asterisks indicate that values from cohort F1 in season 2008-09 are significantly different ($p < 0.05$) of values from other cohorts (F2 and F3) for any of the caryopsis position considered.

Discussion

Weed density

The significant decreasing gradient on *B. diandrus* density in function of the crop sowing date observed during the three growing seasons (Table 2) responds to a gradient on seedling emergence according to the loss of seed dormancy occurred during autumn. Germination and emergence in *B. diandrus* can occur under a prolonged period of time, ranging from late summer to mid-winter (Riba, 1993), although it is mainly concentrated in autumn, following initial rains (Kleemann and Gill, 2006). The delay of the crop sowing date caused a diminution of the emergences and reduced the weed density that competed with the crop. The densities estimated 60 days after herbicide treatment were different in function of the seasons. The first season (2008-09), no post-emergence effect against *B. diandrus* was observed with isoproturon plus diflufenican in barley and the depletion on weed density (71.8% between F1 - F2) can be attributed exclusively to the crop sowing delay. In 2009-10, after the herbicide treatment, F1 showed an even higher density than F1 from the previous season, but the lower densities of F2 and F3 cohorts (96.2% and 99.3% of reduction, respectively) reflect the effect of the sowing delay and the efficiency of the chemical control by mesosulfuron-methyl plus iodosulfuron-methyl sodium. No data was available about densities when the herbicide was applied, but it is supposed have been major difficulty for the herbicide absorption in leaves in F1 in 2009-10 due to the high *B. diandrus* density. In 2010-11, a clear reduction of density was observed in all cohorts. This season the absence of rainfalls since crop sowing until February affected the emergence of *B. diandrus*, however, a similar pattern of decreasing density was observed between cohorts after herbicide application, with a reduction of 95.4% from F1 to F2 and 98.3% from F1 to F3. These results demonstrate that in direct drilling the control of this species only with a pre-seeding application of glyphosate is limited, but the weed density can be reduced with a several week delay of the sowing date in combination with a post-emergence application of a specific herbicide. After three years, a practically depletion of *B. diandrus* population was achieved in F2 and F3 with plant density values as low as 2.8 and 1 pl·m^{-2}, respectively. This decreasing tendency was verified visiting the field trial in spring 2012 (after the herbicide application of mesosulfuron-methyl plus iodosulfuron-methyl sodium) and a null density of *B. diandrus* was confirmed in F2 and F3 plots whereas the density for F1 plots averaged 34 pl·m^{-2} (data not shown).

Vegetative and reproductive fitness

The delay of the crop sowing date implied clear differences in intraespecific competition and also in fitness response differences in *B. diandrus*. In 2008-09, none herbicide effect was detected on plants without distinction of cohorts, but a clear density effect was observed in the first cohort, causing a significant lower development of the plants, which were smaller and produced a significant lower number of stems per plant, lower number of spikelets per plant and stem, and significant lower fecundity than the second and the third cohorts (Table 2). This season, the cohort effect on fitness increased as consequence of lower intraespecific competition. However, despite the increasing fitness across cohort emergence, a final reduction of seed rain (seeds·m^{-2}) was obtained as a consequence of density reduction: 38678 for F1; 19700 for F2 and 13414 for F3.

In our study, the number of caryopses per spikelet for the three cohorts were similar in 2008-09 (average of 4.35), demonstrating that this parameter does not seem to be affected by plant competition. Similarly, Torra and Recasens (2008) observed stable values of the number of seeds per capsule in *Papaver rhoeas* despite of the decreasing performance and reproductive fitness in function of cohort emergence and crop competition. These results suggest that despite the changes on fitness parameters according to competition, the plant keeps a regulation mechanism that guarantees a minimal fecundity. Dyer *et al.* (2012), analysing the growth response of *Bromus tectorum* to interspecific competition, observed that the allocation of components for reproduction was maintained even when interspecific competition had a large negative effect on target plant growth. In this sense, it can be feasible to assume a similar modulating response in an intraspecific competition scenario.

A different fitness gradient between cohorts was observed the next two seasons. In 2009-10, overall, plants surviving specific herbicide application were smaller than in 2008-09, with lower values for the majority of fitness parameters. For F1, a complementary effect of mesosulfuron-methyl plus iodosulfuron-methyl sodium herbicide was added to the intraspecific competition stress produced by plant density. This can be confirmed comparing the fitness parameters for F1 from the first to the second season, when there was a similar plant density. Furthermore, the pattern of an increasing fitness response across cohort emergence observed the first season was not confirmed in 2009-10. Unequal lower values of fitness parameters were observed between cohorts, reflecting that in those surviving plants, allocation pattern is more consequence of herbicide stress than density dependent. In 2010-11 a similar tendency is observed across cohort emergence. This season, plants that survived the specific herbicide application showed lower values than in 2008-09, for most fitness parameters estimated. However, the higher number of stem per plant observed in F1 and F2 than those observed the two previous seasons, could be attributed to other causes than to a within species competition. As it is well established for other grass weeds (Cousens *et al.*, 1988; Medd *et al.*, 1985; Izquierdo *et al*, 1993), the strongest crop competition takes place early in the growing seasons, affecting weed tillering. The stress occurred due to lack of rain in 2010-11 until February reduced the competitive effect of the crop, and despite the lower size of plants, permitted a major weed tillering.

In 2008-09, the increasing fecundity of *B. diandrus* across cohorts showed a clear density dependent response. The values of F1 are in correspondence with those observed by Riba (1993) in this species from plants collected in relatively similar cereal fields. On the contrary, in 2009-10 and 2010-11, when the specific herbicide was applied, fecundities were smaller. Similar decreasing results on fecundity were obtained by Kleemann and Gill (2009b) for Australian populations of this species, recording fecundities of 71 and 22 caryopsides per plant in non treated and treated populations with mesosulfuron-methyl herbicide, respectively. This decreasing fecundity observed in our study in plants treated with this herbicide is related with the different production of caryopsides per spikelet, ranging on average (three cohorts pooled) from 4.35 in 2008-09 to 1.03 in 2010-11. Despite this, this parameter was stable between cohorts in 2008-09, and seems to be the more sensitive to the disruption caused when the specific herbicide is applied.

Increasing values of vegetative and reproductive biomass were obtained in function of cohort emergence the first season (Table 3) which resulted in a decreasing reproductive effort. A similar relationship was confirmed by Riba (1993) comparing summer and winter cohorts of this species. However, performance of plants that survived the specific herbicide application in 2009-10 and 2010-11, showed higher values of reproductive effort -irrespective of cohort- than in 2008-09. This parameter reflects the reproductive penalty produced by herbicides obligating the surviving plants to a greater effort to produce seeds. In this sense, the linear relationship between vegetative and both reproductive biomass (Figure 1) and fecundity (Figure 2) differed between seasons, with greater slopes and lower and narrower rang of values when the plants are affected by the herbicide. These linear relationships allows to predict the seed production based on the weed biomass (Thompson *et al.*, 1991, Norris, 2007), and in our case it has interesting implications in studies of weed population dynamics and also when a bioeconomic model is constructing using data from surviving plants after herbicide application.

Weight of 1000 grains

In 2008-09, the decreasing gradient on seed weight in function of cohort establishment is related with the increasing fecundity observed, and simultaneously with the plant density of each cohort. Riba (1993) also observed lower seed weight when fecundity was higher in *B. diandrus*. However, this correlation was not observed the next two seasons (2009-10 and 2010-11) when the fecundity in general was much lower. No data is available on seed weight of plants treated with the herbicide mesosulfuron-methyl plus iodosulfuron-methyl sodium but a decreasing expression of this parameter could be feasible. Moreover, a complementary expression of the decreasing fitness should be obtained through further analysis of the seed dormancy and viability from plants survival to herbicide treatments. No records are available yet, but must be of practical interest in studies of integrated weed management (IWM) programs of *B. diandrus*.

Allocation within panicle

Without a specific herbicide (2008-09), a clear and significant gradient on resources allocation in function of position of caryopses in the panicle was observed for each cohort. Caryopsides from apical spikelets showed heavier weight, regardless of their position within them. This could be interpreted as a result of the different moment when the spikelets started to develop and the inflorescence was still inside the plant: spikelet production follows a downward direction, starting the development from the highest (apical) positions of the inflorescence, when vegetative apex is transformed into reproductive apex, as is defined for several grasses (Pujol, 1998). Moreover, for other grasses, González-Rabanal *et al.* (1994) and Recasens *et al.* (2007) confirmed that these differences on seed position in the panicle resulted in further differences on seed dormancy. During development, seeds in different positions may experience different temperatures and/or water contents, as well as in resource partitioning, which could influence their dormancy status. This further assessment in *B. diandrus* could provide new knowledge on how the position of caryopsis on the panicle promotes changes on dormancy others than environmental factors.

Furthermore, the first season it was also observed a decreasing gradient of weight of caryopses inside the spikelet from the basal to apical position. These differences are according to the sequential process of floral development within the spikelet. In rice, these differences in grain weight within the spikelet are attributed to an intra-spikelet competition for assimilates pre- and post anthesis (Calderini and Reynolds, 2000). The absence of these differences in *B. diandrus* when the specific herbicide was applied (2009-10 and 2010-11), could be explained by a disruption of the source-sink balance during the period of grain filling. The high number of spikelets without filled grains observed in plants that survived the herbicide (data not show) evidences this process.

Implications for management

The delay of crop sowing date not only permits to reduce the density of *B. diandrus* and the weed pressure on crop, but also the recruitment of new seeds to the seed bank. In the absence of a specific herbicide, plants from late cohorts showed higher fecundity, a decrease on the reproductive effort and a decrease on the weight of 1000 grains, but their contribution to the final seed recruitment is lower than those observed for earlier cohorts with higher densities. The delay on crop sowing date (i.e. middle November) should be considered as an efficient management tool to control this species in a cereal monocrop in no tillage systems. The application of a specific herbicide like mesosulfuron-methyl plus iodosulfuron-methyl sodium when wheat sowing is delayed, apart from increasing efficiency due to delayed plant phenology and reduction of weed density, also reduces the fitness of survival plants. After three growing seasons it was possible to practically deplete the *B. diandrus* population in the field. The implementation of these both cultural and chemical strategies in no tillage systems permits to improve those IWM programs established in dryland arable fields where the options to grow alternative crops to cereals are very limited.

References

Arrue, J. L., Cantero–Martinez, C., Lopez, M. V., Moreno, F., Murillo, J. M., Perez De Ciriza, J. J., Sombrero, A., Tenorio, J. L. and Zambrana, E. (2007). *Conservation* *agricultura research in Spain*. In: Knowledge Assessment and Sharing on Sustainable Agriculture (KASSA). Ed Cirad.

Calderini, D. F., and Reynolds, M. P. (2000). Changes in grain weight as a consequence of de-graining treatments at pre- and post-anthesis in synthetic hexaploid lines of wheat (*Triticum durum* x *T. tauschii*). *Australian Journal of Plant Physiology* 27: 183-191.

Conley, S. P., Binning, L. K., Boerboom, C. M. and Stoltenboom, D. E. (2002). Estimating giant foxtail cohort productivity in soybean based on weed density, leaf area or volume. *Weed Science*. 50: 72-78.

Couloume, B. and Adrien, M. (2005). Atlantis WG, a new product for postemergence weed control in cereals – experiences in France. Pflanzenschutz-Nachrichten Bayer: 58: 261-268.

Cousens, R. D., Firbank L. G., Mortimer, A. M. and Smith G. R. (1988) Variability in the relationship between crop yield and weed density for winter wheat and *Bromus sterilis*. *Journal Applied Ecology* 25: 1033-1044.

Del Monte, J. P. and Dorado, J. (2011). Effect of light conditions and after ripening time on seed dormancy loss of *Bromus diandrus*. *Weed Research* 51: 581-590.

Dyer, A. R., Hardison, J. L. and Rice, K. J. (2012). Phenology constrains opportunistic growth response in *Bromus tectorum* L. *Plant Ecology* 213: 103-112.

Gallart, M., Mas, M. T. and Verdú, A. M. C. (2010). Demography of *Digitaria sanguinalis*: Effect of the emergence time on survival, reproduction, and biomass. *Weed Biology and Management* 10: 132-140.

Gill, G. and Blacklow, W. (1984). Efect of great brome (*Bromus diandrus* Roth.) on the growth of wheat and great brome and their uptake of nitrogen and phosphorus. *Australian Journal of Agricultural Research* 35: 1-8.

Gill, G. S., Poole, M. L. and Holmes, J. E. (1987). Competition between wheat and brome grass in Western Australia. *Australuan Journal of Experimental Agriculture* 27: 291-294.

González Rabanal, F., Casal, M. and Trabaud, L. (1994). Effects of high temperaturas, ash and seed position in the inflorescence on the germination of three Spanish grasses. *Journal of Vegetation Science* 5: 289-294.

Izquierdo, J., Recasens, J., Fernández-Quintanilla, C. and Gill, G. (2003). Effects of crop and weed densities on the interactions between barley and *Lolium rigidum* in several Mediterranean locations. *Agronomie* 23: 529-536.

Kleemann, S. G. L. and Gill, G. S. (2006). Differences in the distribution and seed germination behaviour of populations of *Bromus rigidus* and *Bromus diandrus* in South Australia: Adaptations to habitat and implications for weed management. *Australian Journal of Agricultural Research* 57: 213-219.

Kleeman, S. G. L. and Gill, G. S. (2009a) Population ecology and management of *Rigid brome* (*Bromus diandrus*) in Australian Cropping Systems. *Weed Science* 57: 202-207.

Kleemann, S. G. L. and Gill, G. S. (2009b). The role of imidazolinone herbicides for the control of *Bromus diandrus* (rigid bromus) in wheat in southern Australia. *Crop Protection* 28: 913-916.

Medd R. W., Auld, B. A., Kemp D. R. and Murison, R. D. (1985) The influence of wheat density and spatial arrangement on annual ryegrass, *Lolium rigidum* Gaudin, competition. *Australian Journal of Agricultural Research* 36: 361-371.

Norris, R. F. (2007) Weed fecundity: current status and future needs. *Crop Protection* 26: 182-188.

Powles, S. B. and Matthew, S. J. M., (1996) Integrated weed management for the control of herbicide resistant annual ryegrass (*Lolium rigidum*). Proc. II Intnl. Weed Control Congress. Copenhagen, Denmark, June 25-28. (407-414).

Pujol, M. (1998) Gramíneas, aplicaciones agronómicas. Ed. UPC. Barcelona 219 p.

Rapparini, G., Campagna, G., Geminiani, E. (2006) Graminacee del grano, evoluzione della lotta. *Informatore Agrario* 62: 73-75.

Recasens, J., Caimons, O., Torra, J. and Taberner, A. (2007). Variation in seed germiation and early growth between and within acetolacetate synthase herbicide resistant and susceptible *Lolium rigidum* accessions. *Seed Science and Technology* 35: 32-47.

Riba, F.; Recasens, J. (1997). *Bromus diandrus* Roth en cereals de invierno. In: Sans, F. X. y Fernández-Quintanilla C. (editores). La biología de las malas hierbas de España. Ed. *Phytoma* España-Sociedad Española de Malherbología. Pp: 25–35.

Riba, F. (1993). Demografia i dinàmica de poblacions de *Bromus diandrus* Roth en cereals d`hivern. Tesis doctoral. Universitat de Lleida. 117 p.

Rice, K. J. and Dyer, A. R. (2001). Seed aging, delayed germination and reduced competitive ability in *Bromus tectorum*. *Plant Ecology* 155: 237-243.

Thompson, B. K., Weiner, J. and Warwick, S. I. (1991). Size dependent reproductive output in agricultural weeds. *Canadian Journal of Botany* 69: 442-446

Torra, J. and Recasens, J. (2008). Demography of corn poppy (*Papaver rhoeas*) in relation to emergence time and crop competition. *Weed Science* 56: 826-833.

Young, F. L. and Thorne, M. E. (2004) Weed-species dynamics and management in no-till and reduced-till fallow cropping systems for the semi-arid agricultural region of the Pacific Northwest, USA. *Crop Protection* 23: 1097-1110.

CAPÍTULO 4

“Long-term effect of different tillage systems on the emergence and demography of *Bromus diandrus* in rainfed cereals in north-eastern Spain”

Long-term effect of different tillage systems on the emergence and demography of *Bromus diandrus* in rainfed cereals in north-eastern Spain

Introduction

The adoption of conservation tillage systems is increasing in semiarid areas because of environmental benefits and savings in time and economic inputs (Holland, 2004; Sánchez-Girón *et al.*, 2007). Nevertheless, these conservation tillage systems, and especially direct drilling, bring some difficulties in weed control of certain species. Some evident cases have appeared in NE of Spain where the presence of species like *Bromus diandrus* Roth is large (García-Baudín, 1983; Riba and Recasens, 1997; Arrúe *et al.*, 2007). This situation took place several years after the adoption of these soil management systems. Simultaneously, different reports confirmed that *B. diandrus* is favoured by reduced tillage or no tillage in Australian fields (Cheam, 1986; Gill and Blacklow, 1985; Gill and Blacklow, 1984) and the limited control options of this species favoured its competitive effect on crop yield (Gill *et al.*, 1987; Kon and Blacklow, 1988). However, several farmers from Catalonia (NE Spain) which began direct drilling more than 20 years ago recently appointed that after a continuous conservation tillage, the problems caused by *B. diandrus* are less important than years before, and in some cases the densities are lower than those observed in fields were chisel plough is still being applied. Nevertheless, no experimental data are available to confirm these observations.

The effect of different tillage practices on weed population dynamics is well documented and is mostly reflected in the different weed seed distribution in the soil profile (Buhler *et al.*, 1997; Dorado *et al.*, 1999; Ball, 1992; Dorado and López Fando, 2006; Murphy *et al.*, 2006; Mas and Verdú, 2003). However, very few information is available on the long term effects of different tillage systems on weed population dynamics. Bàrberi and Lo Cascio (2001) comparing four different tillage systems, observed greater weed seed bank in no-tillage (NT) after 12 years of similar crop management. Similarly, Carter and Ivany (2006) also observed higher weed diversity in the upper 0-10 cm of the soil in no-till plots compared with different tilled plots after 14 years of management. Nevertheless, in a long-term study of 25 years of cereal-leguminous rotation system in Spain, Hernández-Plaza *et al.* (2011) found no differences on weed richness comparing no-tillage, minimum tillage and conventional tillage.

Germination of *Bromus diandrus* and other related species is considered to be inhibited by light (Froud-Williams, 1981; Hilton, 1984; Ellis *et al.*, 1986; Jauzein, 1989), and according to these dormancy seeds in the soil surface in NT can show a protracted seedling emergence owing evasion of early control measures in cereal crops (Kleemann and Gill, 2006). 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 dark and seeds can find in NT more favourable conditions for germination once photosensitiviy has been lost. These authors appointed the possibility that seeds on the soil may need only a superficial coverage to perceive darkness. According to them, the darkness level offered to seeds by stubble residues or straw, could favour germination. However, no data is available to confirm this hypothesis.

Until few years ago, and limited by the absence of post-emergence effective herbicides, the control of *B. diandrus* was only performed by non-selective herbicides application (mainly glyphosate) previous to crop sowing. This continuous weed control method together with an early cereal sowing in the area the first years of no-till implementation promoted high infetations of *B. diandrus* as was observed in other studies (García *et al*., 2013) because prompted a selection of biotypes more adapted to emerge early in the autumn. In a recent work, Kleemann and Gill (2013) suggest that the presence of photoinhibition in *B. diandrus* could have an adaptive value, and the increased dormancy observed in some populations could be associated to cold stratification requirements. Fleet and Gill (2012) observed polymorphism of seed dormancy in *Hordeum murinum*, and they suggest that increased selection pressure from cropping systems could have selected mechanisms that increase the expression of seed dormancy.

Information on emergence patterns, final fecundity and seed rain in different long-term tillage systems in our field crops could confirm if *B. diandrus* really can show adaptive behaviour depending on the conservation tillage system applied. With this idea, an experimental cereal field trial initiated 22 years ago, where different tillage systems were continuously implemented during this period of time, was monitored during three growing seasons.

Materials and Methods

Study site

The experiment was conducted over three seasons (2008-09, 2009-10 and 2010-11) in Agramunt (41º 48´N, 1º 07´E) (Lleida, Spain) in a dry-land field managed for more than 22 years by the Agronomy Research Group from University of Lleida. The field is 330 m.a.s.l. and has a continental Mediterranean climate. The soil at this location is *Xerocrept tipic*, 100-120 cm deep, with 30.1% sand, 51.9% silt and 17.9% clay, 2.3% organic matter and pH of 8.5. Daily rainfall, maximum and minimum air temperatures were obtained from a standard meteorological station located at the experimental field during the study period. Mean monthly temperature and total rainfall recorded at the site as well the long term averages are presented in Table 1.

Table 1. Mean temperature and monthly rainfall for Agramunt during 2008-09, 2009-10 and 2010-11 seasons, and long term averages.

	Mean monthly temperature ºC			Long-term mean[a]	Rainfall (mm)			Long-term mean[a]
	2008/2009	2009/2010	2010/2011	1975-2011	2008/2009	2009/2010	2010/2011	1975-2011
September	18	19	19	20	36	55	21	43
October	14	15	13	14	84	69	1	50
November	6	9	6	8	31	5	0	36
December	3	4	3	4	29	112	0	30
January	4	3	3	4	56	132	0	31
February	5	4	6	6	34	39	12	18
March	8	7	9	9	55	64	36	30
April	11	12	15	13	150	26	20	48
May	18	14	19	17	5	59	27	54
June	22	19	21	22	20	76	73	38

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

Site, tillage and cropping systems

Since 1986 different soil managements were continuously implemented in this field trial: chisel plough (ChP), subsoiler (SS), mouldboard plough (MbP) and no-tillage (NT). ChP treatment consisted to a depth of 20 cm before sowing. SS consisted of three 4 cm wide shank spaced 35 cm apart past to a depth of 20-25 cm. The MbP consisted of three bottoms of 0.50 m width and performed an operation to a depth of 25-30 cm plus one or two cultivator passes (15 cm depth). To break clods and promote the germination, a roller was used for tilled systems before sowing. In the no-tillage treatment (NT) sowing was performed with a no-till disc drill. Plots were arranged in complete randomized block design with three replicates. Plots sizes were 50 x 9 m. When the monitoring was started, each plots were under the same tillage treatments for 22 years. The cropping system consisted of a barley-wheat-barley rotation and tillages were implemented in November. Barley (*Hordeum vulgare* L.) was sown 15 November 2008 and 11 November 2010 seasons, whereas wheat (*Triticum aestivum* L.) was sown 12 November 2009. The sowing rate was always 180 $\mathrm{Kg \cdot ha^{-1}}$ in rows spaced 17 cm apart. Sowing was done after spraying with herbicide (1.5 $\mathrm{L \cdot ha^{-1}}$ 36% glyphosate [N-(phosphono-methyl)-glycine] to keep soil free of weeds. The post-emergence herbicide used in 2008-09 was isoproturon plus diflufenican (1743 + 69 $\mathrm{g \cdot ha^{-1}}$) and was applied in 19 February 2009. In 2009-10, post-emergence weed control was accomplished by mesosulfuron-methyl plus iodosulfuron-methyl sodium (15 + 3 g $\mathrm{a.i. \cdot ha^{-1}}$ plus wetting agent) applied 6 March. In 2010-11 broadleaf were controlled in post-emergence, respectively, by tribenuron-methyl plus metsulfuron-methyl (10 + 5 $\mathrm{g \cdot ha^{-1}}$ plus wetting agent) in 30 March. Each season in March, fertilization was performed with N-32% at 150 $\mathrm{Kg \cdot ha^{-1}}$.

Parameters estimated

In each plot destructive weekly counts of emerged weed seedlings were started at 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. Periodic samplings of weed densities were collected with ten 0.1 m^2 quadrats randomly thrown along the plot. Estimation of densities started before crop sowing.

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

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

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 estimated HTT using the Soil Temperature and Moisture Model ($\mathrm{SMT^2}$) 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 reached their complete development and maturity. Twenty plants from each plot were collected and the number of caryopsis per plant was estimated. Seed rain in each treatment was estimated multiplying fecundity by final density.

Statistical analysis

Because of the different crops and different treatments applied in each season, data from each growing season were analyzed separately. All data were analysed through ANOVA using SAS 9.0 (PROC NLIN; SAS Institute Inc., Cary, NC, USA). When differences were detected between treatments, LSD test ($P<0.05$) was used for comparison of means. Previous to analyses, weed emergence and weed density were transformed ($\log(x+1)$) to satisfy the homogeneity of variance assumptions. Back-transformed data will be presented for clarity. The repeated statement option of SAS was used to compare weed densities and cumulative emergences 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 11.4 ºC the three seasons vs. 11.71 ºC). The first and the second growing seasons were above the long-term rainfall average (378 mm). Total rainfall from September to June (at harvest time) in 2008-09 was 500 mm, while in 2009-10 it was 637 mm and in 2010-11 only 190 mm (Table 1).

In 2008-09 the average of autumn-winter precipitation was 234 mm (October to February), which fell mainly in October (84 mm). Spring was rainy, with 155 mm between April and May (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 resulted extremely dry (13 mm), however spring was rainy (156 mm between March and June).

Weed emergence patterns

During the experiment CE of *B. diandrus* differed between treatments (Table 2) and followed, each season, a similar and decreasing gradient ChP > SS > NT > MbP. Values observed each season in ChP are significantly different from those observed in NT and MbP, and values from SS are significantly different from 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 registered in 2010-11.

Table 2. Total cumulative emergence of *Bromus diandrus* (pl·m^{-2}) in different tillage systems along three different growing seasons.

Tyllage system	Season 2008-09	Season 2009-10	Season 2010-11
Chisel plough (ChP)	684 (a)	1117 (a)	259 (a)
Subsoiler (SS)	282 (ab)	489 (ab)	138 (ab)
Mouldboard plough (MbP)	20 (c)	21 (c)	2 (c)
No-tillage (NT)	73 (bc)	50 (bc)	13 (bc)

Different letters indicate significant differences between soil management ($p < 0.05$).

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

The hydrothermal seedling emergence model developed for *B. diandrus* in a previous work (García *et al.*, 2013) is represented separately for each tillage system (Figure 2). Considering that higher CE occurred in ChP than in SS, NT and MbP, a percentage of 100% was assigned to ChP. Accordingly, reductions in CE were between 48 and 59% in SS, 89 and 95% in NT and 97 and 99% in MbP along the three seasons. For all situations, the model predicts 50%, 75% and 90% of CE at 264, 329 and 406 HTT after the first autumn rainfalls.

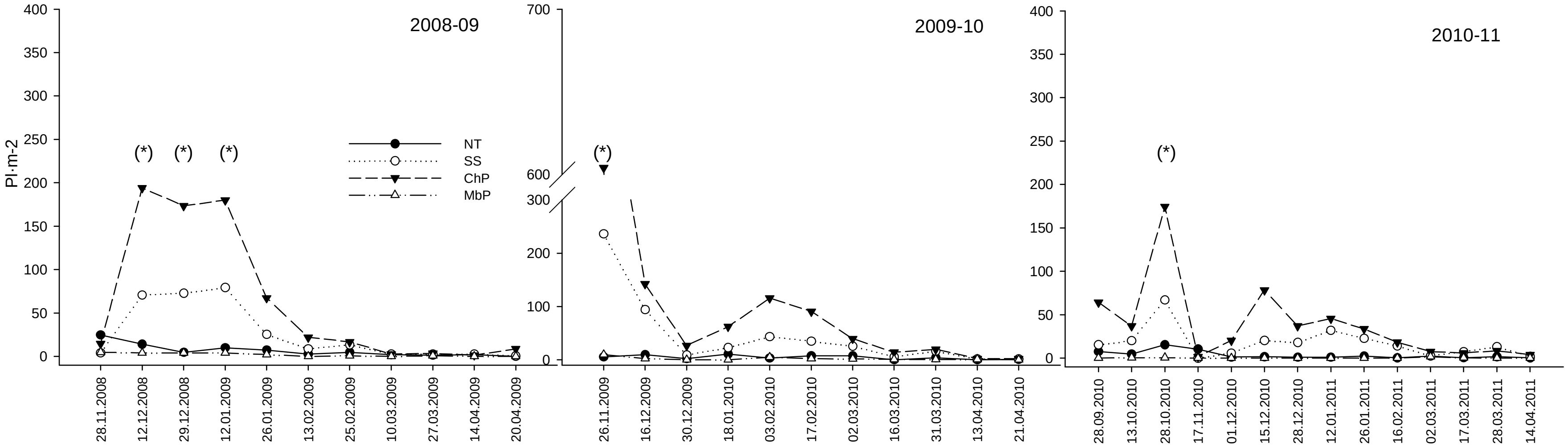

Figure 1. Observed emergence of *Bromus diandrus* in function of soil management, chisel plow (ChP), subsoiler (SS), mouldboard plow (MbP) and no-tillage (NT) during three growing seasons. Asterisks indicate significant differences between soil managements ($p < 0.05$).

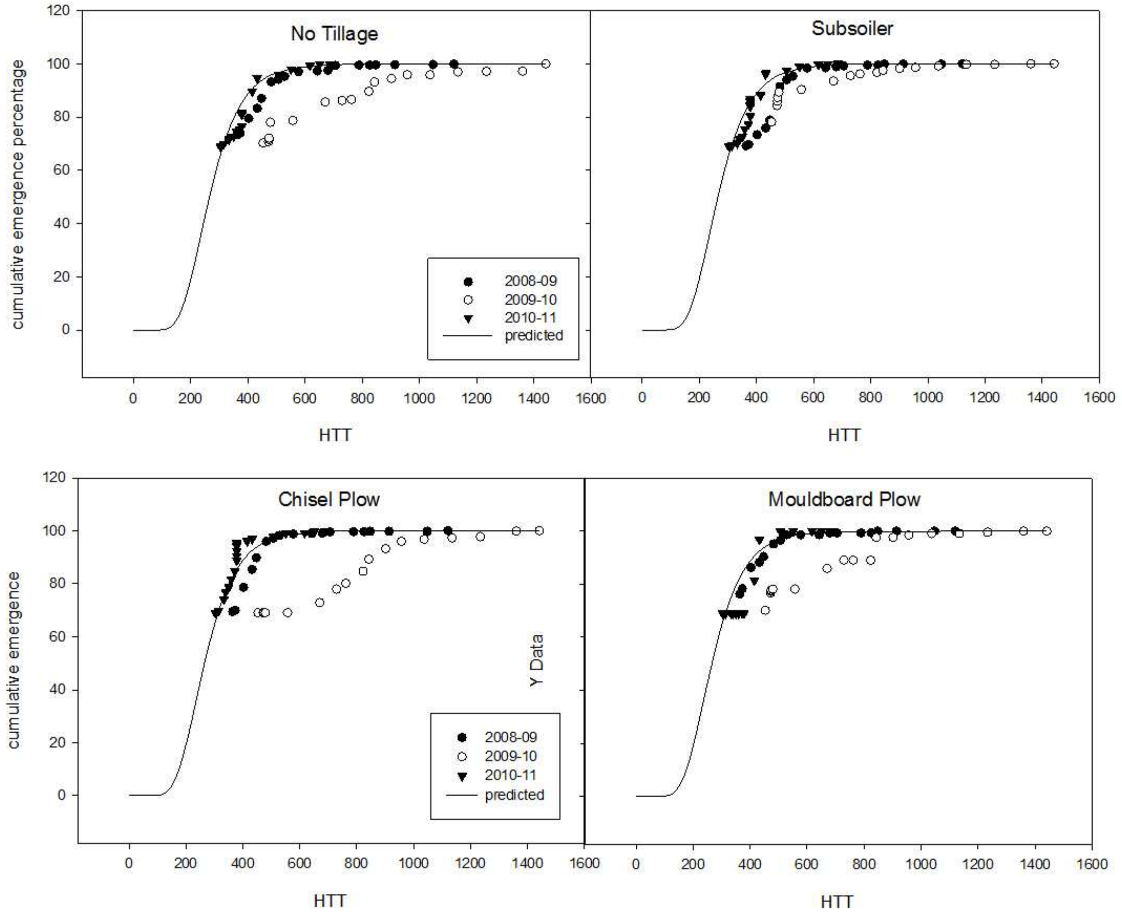

Figure 2. Hydrotermal seedling emergence model application for *B. diandrus* (García *et al.*, 2013) in the four different tillage systems (line) together with percentage of cumulative emergence from three different growing seasons (dots and triangles).

Weed density

In 2008-09 significant differences on density were detected between the tillage systems. ChP values were significantly higher than in SS, and simultaneously values of both systems were also significantly higher than in MbP and NT in mid February, early March and mid-April. This season also stood out the high density observed in mid-April in ChP and SS, with values higher than 200 pl·m^{-2}. In 2009-10 a similar tendency was observed with significantly higher values of density in ChP and SS during all the growing period (with maximum of 593 and 298 pl·m^{-2}, respectively). This season, observations made in mid-October and early November permited to detect in NT the fast increase of density previous to the crop sowing and their depletion after the pre-sowing herbicide application. In 2010-11 density values were low in all till systems, and only those observed in ChP were significantly higher from mid-December until mid-April.

Table 3. Density (at the end of the season), fecundity and seed rain of *B. diandrus* and crop yield for different soil management during three cropping seasons.

2008-09 season	Density ($pl \cdot m^{-2}$)	Fecundity ($seeds \cdot pl^{-1}$)	Seed rain ($seeds \cdot m^{-2}$)	Crop yield ($Kg \cdot ha^{-1}$)
Chisel Plow (ChP)	266.0 (a)			3690.7 (b)
Subsoiler (SS)	207.7 (ab)			4698.0 (ab)
Mouldboard Plow (MbP)	6.3 (b)			5228.4 (a)
No-tillage (NT)	45.3 (ab)			5354.6 (a)
2009-10 season				
Chisel Plow (ChP)	241.3 (a)	22.5 (a)	5434.1	3239.7 (b)
Subsoiler (SS)	134.7 (a)	30.9 (a)	4162	3983.4 (a)
Mouldboard Plow (MbP)	6.0 (b)	11.2 (a)	67.5	4279.1 (a)
No-tillage (NT)	2.7 (b)	12.1 (a)	32.7	4379.2 (a)
2010-11 season				
Chisel Plow (ChP)	74.7 (a)	56.1 (a)	4190.7	1946.5 (ab)
Subsoiler (SS)	40.7 (ab)	41.5 (a)	1690.3	1962.7 (ab)
Mouldboard Plow (MbP)	0.3 (c)	50.5 (a)	15.2	1675.7 (b)
No-tillage (NT)	7.7 (bc)	55.2 (a)	425.2	2895.8 (a)

Different letters indicate significant differences between soil management ($p < 0.05$).

Weed demographic behaviour and crop yield

Table 3 shows the different values of density and fecundity at the end of each growing season according to the applied different tillage systems. Each season a decreasing gradient on final the density, ChP > SS > NT > MbP, was observed. 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. Significantly 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 pl·m^{-2}), NT (3 pl·m^{-2}) and MbP (0.3 pl·m^{-2}) in 2008-09, 2009-10 and 2010-11 seasons, respectively.

The herbicide application offered an unequal control depending on the tillage system and season (data not show). Only mesosulfuron-methyl plus iodosulfuron-methyl sodium in 2009-10 showed a good control in NT (93%) whereas for other tillage systems the protracted emergence of seedlings during spring masked the control effect. Furthermore, the effectiveness of the herbicide applied on barley the seasons 2008-09 and 2010-11 was not successful for *B. diandrus*.

No fecundity data was available for the first season, but this parameter range 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 levels and fecundity, the estimated seed rain the second and the third seasons were highest in ChP (5434 and 4191 seeds·m^{-2}, respectively) and lowest in NT (33 seeds·m^{-2}) in 2009-10 and in MbP (15 seeds·m^{-2}) in 2010-11.

Each season, crop yields obtained were different depending on the tillage system. Overall, higher crop yields were obtained the first season than the two others. In 2008-09, when barley was grown, significantly higher yields were obtained in in MbP (5228 Kg·ha^{-1}) or in NT (5354 Kg·ha^{-1}) than in ChP (3690 Kg·ha^{-1}). In 2009-10, wheat yields were significantly higher in MbP (4279 Kg·ha^{-1}) and in NT (4379 Kg·ha^{-1}) than in ChP (3240 Kg·ha^{-1}). In 2010-11, significantly higher barley yields were obtained in NT (2896 Kg·ha^{-1}) than in MbP (1676 Kg·ha^{-1}).

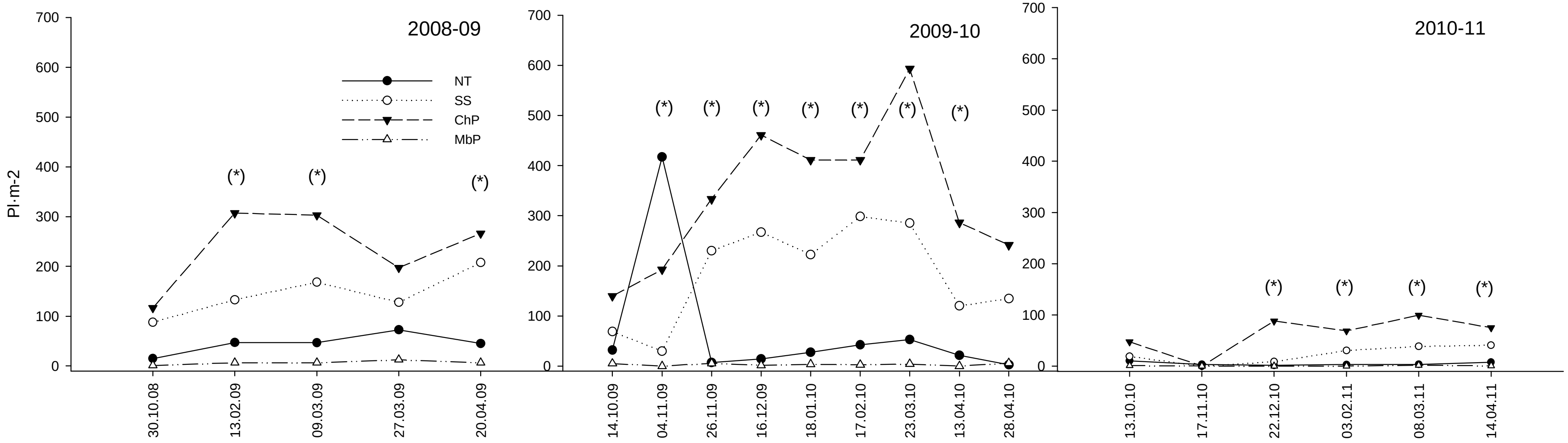

Figure 3. Density of *Bromus diandrus* in the four soil management systems, chisel plow (ChP), subsoiler (SS), mouldboard plow (MbP) and no-tillage (NT) during three growing seasons. Asterisks indicate significant differences between soil management ($p < 0.05$).

Discussion

In the present work the CE of *B. diandrus* observed each season in a long-term management experiment (22 years) in a cereal field follows the next decreasing gradient: ChP > SS > NT > MbP (Table 2). These results contradict previous works where highest emergences and densities of *B. diandrus* (or related species form the same genus) were observed in NT compared to other soil tillage systems (Gill and Blacklow, 1985; Kon and Blacklow 1988; Riba and Recasens, 1997; Kleeman and Gill, 2006). Higher total emergences and densities were found in those tillage systems (ChP and SS) where seeds are superficially buried in the soil. These differences could be explained by the conditions created in the soil surface after the same long-term management and in the possible changes on seed dormancy. No data are available of the possible long term effects of field management on *B. diandrus* and very few works report information in this sense. In a long-term study of 25 years of cereal-leguminous rotation system in Spain, Hernández-Plaza *et al.* (2011), found lower densities of *B. diandrus* in NT (0.09 pl·m^{-2}) than in minimum tillage (0.14 pl·m^{-2}), and this species was considered one of the less important observed in NT. Furthermore, Bàrberi and Lo Cascio (2001) noted that the seed bank density of *B. diandrus* was not between the 12 major weed species observed in different tillage systems (including NT) and two crop rotations after 12 years of similar crop management.

It is well known that the germination of many weed seeds can be promoted by light, in the sense that buried seeds perceive the light signal mainly during soil disturbance (Juroszek and Gerhards, 2004). Nevertheless, the species of 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 *Anisanta*, to which belongs *B. diandrus* (Jauzein, 1989). In *Bromus* species, the phytochrome is operating just in the opposite direction to what is found in the vast majority of photoblastic seeds, and Pfr (active form of phytochrome) inhibits its germination (Benech-Arnold *et al.*, 2000). It is difficult to determine the level of light present in the soil surface in NT systems in contrast with those in the upper soil level after soil tillage. A possible cover effect of straw could be considered as determinant for *B. diandrus* seeds situated on NT soil surface, facilitating the dormancy break and their earlier emergence. Dyer (1995) and Benech-Arnold *et al.* (2000)

appointed that, in general, higher levels of residues in soil surface decrease the soil thermal amplitude and prevent from light penetration. However, Jensen (2009), observed in a ploughed field that the persistence of *B. sterilis* and *B. hordeaceus* seeds in the soil was very short irrespective of the depth or whether they were covered or not by chopped straw.

Del Monte and Dorado (2011) appointed that in no-tillage sowing techniques, as those applied in cereals in Central Spain, seeds of *B. diandrus* that remain in the soil surface need only 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 to the ground and can be wedged into the soil. In long-term conditions of NT as those of the present work, it could be feasible to assume that the perception of darkness by seeds should be easier with field stubble or straw cover. In this situation, full ripened seeds of *B. diandrus* can germinate fast in autumn if temperature and water availability are not limiting.

Kon and Blacklow (1988) appointed that there is a high heritable variation within Australian populations of *B. diandrus* that would allow further adaptations to new or changing environments. Kleemann and Gill (2013) also observed large differences in germination patterns between *B. diandrus* populations and appointed a possible selection for greater seed dormancy according to crop management practices. The authors proposed that the presence of photoinhibition in *B. diandrus* could have adaptive value under no till systems and seeds would be able to germinate after burial caused by the sowing operations. In our study, different levels of emergences of *B. diandrus* were observed previous to crop sowing date in all tillage systems, but several months after crop sowing (February and March) these values were significantly greater in ChP and SS (Figure 2 and Figure 3). The burial effect caused by ChP and SS in our study is more tangible than those that can produce sowing operations.

For Australian populations, Kleemann and Gill (2013) confirm that dormancy of *B. diandrus* seeds should be overcame by cold stratification and such populations are expected to germinate much later in the growing season when temperatures will have declined. On the contrary, Del Monte and Dorado (2011) suggest that low temperatures (< 10º C) could limit the germination of Spanish populations, which occurs mainly when temperatures drop at the end of autumn. Thus, two main flushes before (autumn) and after (spring) were observed. In our work, these two main flushes of weed emergence (October and February) were observed in ChP and SS in 2009-10 and 2010-

11 (Figure 1), whereas lower emergences were also recorded in December and January. This delayed emergence would have happened in those seeds with prolonged dormancy. Furthermore, these authors observed that germination of *B. diandrus* seeds exposed to light needs more favourable conditions to germinate once photosensitivity was lost. Within these conditions hydrothermal time plays a key role. In a previous work García *et al*. (2013) developed a model predicting seedling emergence of this species. This model was validated with data from the present experiment (Figure 2). Despite the different climatic conditions registered, the model was feasible for all tillage systems in the three seasons.

No differences were observed on *B. diandrus* fecundity in function of the applied tillage systems. Values were lower than those from Riba (1993) in the same cereal region, but it should be noted that plants from our field plots were sprayed with herbicides during the two seasons when fecundity was registered (June of 2010 and 2011). The effect of mesolsufuron-methyl plus iodosulfuron-methyl sodium was not so evident decreasing population density, but a possible stress effect on fecundity could have been expressed in those survival plants. Kleeman and Gill (2009) recorded fecundities of 71 and 22 caryopsides per plant, respectively, in non-treated and treated populations with mesosulfuron-methyl herbicide. In a nearby experimental field to our study, densities of this species ranged from 20 seeds$\cdot$pl^{-1} to 147 seeds$\cdot$pl^{-1}, depending if the herbicide was applied or not (García *et al.,* submitted).

The differences in crop yield observed between seasons are in accordance with the different climatic conditions recorded. In this sense, the lower yields observed in all tillage systems in 2010-11 are due to the severe drought, whereas seasons 2008-09 and 2009-10 averaged similar yields to those obtained previously in the region. In our study, the highest values of crop yield are obtained in NT and MbP systems, probably because of the lower weed densities. Lampurlanés *et al.* (2002) comparing different tillage systems in a similar experimental field in the region, also observed higher crop yield in NT, which confirm that this management favoured greater and deeper water accumulation in the soil profile. However these same authors suggest that yield depends more of favourable rainfall distribution during the growing season, especially during the grain-filling period, than on tillage system.

In conclusion, the present work appointed that possible changes in biological behaviour of *B. diandrus* could be associated to changes in tillage practices. A possible cumulative effect of soil management could have a selective effect on the population in the sense that seeds that are present on the soil surface could loose their dormancy faster than those seeds buried in the upper layers of soil. Anyway, further works are necessary to confirm possible changes in seed dormancy and verify if an adaptive dormancy or a selection pressure is taking place in these tillage systems.

References

Arrúe, J. L., Cantero-Martínez, C., López, M. V., Moreno, F., Murillo, J. M., Pérez de Ciriza, J.J., Sombrero, A., Tenorio, J.L. and Zambrana, E. (2007): Conservation agriculture research in Spain. KASSA project, Mediterranean platform, deliverable 1.2, appendix A1.

Ball, D. A. (1992). Weed seedbank response to tillage, herbicides, and crop-rotation sequence. *Weed Science* 40: 654-659.

Bàrberi, P. and Lo Cascio, B. (2001). Long-term tillage and crop rotation effects on weed seed bank size and composition. *Weed Research* 41: 325-340

Benech-Arnold, R. L., Sánchez, R. A., Forcella, F., Kruck, B. and Ghersa, C. M. (2000). Environmental control of dormancy in weed seed banks in soil. *Field Crops Research* 67: 105-122.

Buhler, D. D., Hartzler, R. G. and Forcella, F. (1997). Implications of weed seedbank dynamics to weed management. *Weed Science* 45: 329-336.

Carter, M. R. and Ivany, J. A. (2006) Weed seed bank composition under three long-term tillage regimes on a fine loam in Atlantic Canada. *Soil and Tillage Research* 90: 29-38.

Cheam, A. H. (1986). Patterns of change in seed dormancy and persistence of *Bromus diandrus* Roth (great brome) in the field. *Australian Journal of Agricultural Research* 37: 471-481.

Del Monte J. P. and Dorado J. (2011). Effect of light conditions and after ripening time on seed dormancy loss of *Bromus diandrus*. *Weed Research* 51: 581-590.

Dorado, J., Del Monte, J. P. and López-Fando, C. (1999). Weed seed bank response to crop rotation and tillage in semiarid agroecosystems. *Weed Science* 47: 67-73.

Dorado, J. and López-Fando, C. (2006). The effect of tillage system and use of paraplow on weed flora in a semiarid soil from central Spain. *Weed Research* 46: 424-431.

Dyer, W. E. (1995). Exploiting weed seed formancy and germination requeriments through agronomic practices. *Weed Science* 43: 498-503.

Ellis, R. H., Hong, T. D. and Roberts, E. H. (1986). The response of seeds of *Bromus sterilis* L. and *Bromus mollis* L., to white light of varying photon flux density and photoperiod. *New Phytologist* 104: 485-496.

Fleet, B. and Gill, G. (2012) Seed dormancy and seedling recruitment in smooth barley (*Hordeum murinum* spp. *glaucum*) populations in southern Australia. *Weed Science* 60: 394-400

Froud-Williams, R. J. (1981). Germination behaviour of *Bromus* species and *Alopecurus myosuroides*. In: *Proceedings of the Association of Applied Biologist Conference: Grass weeds in cereals in United Kingdom*, 31-40. Association of Applied Biologists, Warwick.

García-Baudín, J. M. (1983). Malas hierbas gramíneas en los cereales (trigo y cebada) de la región del Duero. Servicio de Extensión Agraria. Consejo General de Castilla y León. 17 p.

García, A. L., Recasens, J., Forcella, F., Torra, J. and Royo-Esnal, A. (2013) Hydrothermal emergence model for *Bromus diandrus*. *Weed Science*. 61: 146-153.

García, A. L., Torra, J., Royo-Esnal, A. and Recasens, J. Fitness in *Bromus diandrus* in response to cohort effect and herbicide stress (Submitted: *Crop Protection*).

Gill, G. S. and Blacklow, W. M. (1984). Effect of great brome (*Bromus diandrus* Roth.) on the growth of wheat and great brome and their uptake of nitrogen and phosphorus. *Australian Journal of Agricultural Research* 35: 1-8

Gill, G. S. and Blacklow, W. M. (1985). Variations in seed dormancy and rates of development of great brome, *Bromus diandrus* Roth., as adaptations to the climates of southern Australia and implications for weed control. *Australian Journal of Agricultural Research* 36: 295-304.

Gill, G. S., Poole, M. L. and Holmes, J. E. (1987). Competition between wheat and brome grass in Western Australia. *Australian Journal of Experimental Agriculture* 27: 291-294.

Hernández Plaza, E.; Kozak, M.; Navarrete, L. and González-Andújar, J. L. (2011). Tillage system did not affect weed diversity in a 23-year experiment in Mediterranean dryland. *Agriculture, Ecosystems and Environment* 140: 102-105.

Holland, J. M. (2004). The environmental consequences of adopting conservation tillage in Europe : reviewing the evidence. *Agriculture, Ecosystems and Environment* 103: 1-25.

Hilton, J. R. (1984). The influence of temperature and moisture status on the photoinhibition of seed germination in *Bromus sterilis* by the far-red absorbing form of phytochrome. *New Phytologist* 97: 369-374.

Jauzein, P. (1989). Photosensibilite des bromes annuels (*Bromus* L. spp.). *Weed Research* 29: 53-63.

Jensen, P. K. (2009). Longevity of seeds of four annual grass and two dicotyledon weed species as related to placement in the soil and straw disposal technique. *Weed Research* 49: 592-601

Jurozsek, P. and Gerhads R. (2004). Photocontrol of weeds. *Journal Agronomy and Crop Science* 190: 402-415.

Kleemann, S. G. L. and Gill, G. S. (2006). Differences in the distribution and seed germination behaviour of populations of *Bromus rigidus* and *Bromus diandrus* in South Australia: Adaptations to habitat and implications for weed management. *Australian Journal of Agricultural Research* 57: 213-219.

Kleemann, S. G. L. and Gill, G. (2009). The role of imidazolinone herbicides for the control of *Bromus diandrus* (rigid brome) in wheat in southern Australia. *Crop Protection* 28: 913-916.

Kleemann, S. G. L. and Gill, G. (2013) Seed dormancy and seedling emergence in ripgut brome (*Bromus diandrus* Roth) populations in southern Australia. *Weed Science* In-Press. **doi:** http://dx.doi.org/10.1614/WS-D-12-00083.1

Kon, K. F. and Blacklow, W. M. (1988) Identification, distribution and population variability of great brome (*Bromus diandrus* Roth) and rigid brome (*Bromus rigidus* Roth). *Australian Journal of Agricultural Research* 39: 1039-1050.

Lampurlanés J., Angás, P. and Cantero-Martínez, C. (2002) Tillage effects on water storage during fallow, and on barley root growth and yield in two contrasting soils of the semi-arid Segarra region in Spain. *Soil and Tillage Research* 69: 27-40.

Mas, M. T. and Verdú A. M. C. (2003). Tillage system effects on weed communities in a 4-year crop rotation under Mediterranean dryland conditions. *Soil and Tillage Research* 74: 15-24.

Murphy S. D., Clements, D. R., Belaoussof, S., Kevan, P. and Swanton, C. (2006). Promotion of weed species diversity and reduction of weed seedbanks with conservation tillage and crop protection. *Weed Science* 54: 69-77

Riba, F. and Recasens, J. (1997). *Bromus diandrus* Roth en cereales de invierno. In: Sans, F. X. y Fernández-Quintanilla C. (editores). La biología de las malas hierbas de España. Ed. *Phytoma España-Sociedad Española de Malherbología*. Pp: 25–35.

Riba, F. (1993). Demografía i dinàmica de poblacions de *Bromus diandrus* Roth en cereals d`hivern. PhD thesis, Universitat de Lleida. 117 p.

Roman, E. S., Murphy, S. D. and Swanton, C. J. (2000). Simulation of *Chenopodium album* seedling emergence. *Weed Science* 48: 217-224.

Sánchez-Girón L., Serrano, A., Suárez, M., Herranz, J. L. and Navarrete L. (2007). Economics of reduced tillage for cereal and legume production on rainfed farm enterprises of different sizes in semiarid conditions. *Soil and Tillage Research* 95: 149-160.

Spokas, K. and Forcella, F. (2009). Software tools for weed seed germination modelling. *Weed Science* 57: 216-227.

DISCUSIÓN GENERAL Y CONCLUSIONES

Discusión General

Al igual que en otras malas hierbas (Forcella *et al.,* 2000; Roman *et al.,* 2000; Royo-Esnal *et al.,* 2010) la temperatura y la humedad del suelo constituyen los factores determinantes de la emergencia de *B. diandrus*. Con estos dos factores y utilizando el modelo STM^2 de Spokas y Forcella (2009), se ha desarrollado un modelo hidrotérmico que describe la emergencia de esta especie. Los modelos hidrotérmicos de emergencia basados en observaciones de campo durante la estación de crecimiento permiten elaborar predicciones relativamente fiables a partir de un desarrollo simple (Forcella *et al.,* 2000). El modelo desarrollado en este trabajo es lo suficientemente robusto, ya que fue elaborado con datos de dos campañas completamente diferentes en cuanto a precipitaciones y se ha validado con cuatro conjuntos de datos diferentes (de dos localidades) y puesto en práctica en cinco sistemas de manejo distintos (dos fechas de siembra y tres tipos de labores de suelo) a lo largo de tres campañas (García *et al.,* 2013). El modelo considera como temperatura base 0ºC y como potencial hídrico base -1.35 MPa. La expresión del mismo es:

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

donde *y* es el porcentaje de emergencia acumulada después de las primeras lluvias otoñales, y *x* es el tiempo expresado en grados hidrotérmicos (HTT). Este modelo ofrece una buena predicción de la emergencia de *B. diandrus* y constituye una herramienta útil en el establecimiento de sistemas de manejo de esta especie al mismo tiempo que permite su utilización en distintas áreas cerealistas dentro de un amplio rango de situaciones.

Debido a que la germinación y emergencia de *B. diandrus* se concentra tras las primeras lluvias de otoño (Kleemann y Gill, 2006), el retraso en la fecha de siembra del cultivo comportó una disminución significativa de la emergencia y una menor densidad de plantas de *B. diandrus* compitiendo con el cultivo. En la primera campaña, cuando no se utilizó el herbicida post-emergente específico (Mesolsulfuron metil + Iodosulfuron metil sodio) en las cohortes precoces (primera fecha de siembra) la competencia tanto inter como intra-específica se vió reflejada en una respuesta decreciente en la fitness, pero resultando en definitiva un mayor aporte de semillas a las reservas del suelo. En las cohortes más tardías, la fitness mostró mayores valores, especialmente en fecundidad y esfuerzo reproductor, pero un menor aporte final de semillas. En las siguientes campañas, la eficacia del herbicida mesosulfuron metil + iodosulfuron metil sodio en trigo aumentó con el retraso en la fecha de siembra del cultivo, debido especialmente al estado fenológico más retrasado que presentaba la cohorte y a una menor densidad de la población. Después de tres campañas y combinando el retraso de siembra, la inclusión de trigo en la rotación de cereales y el uso de un herbicida post-emergente selectivo, se confirma una práctica eliminación de la población de *B. diandrus* en campos cerealistas de secano bajo siembra directa, donde las alternativas de cultivo son muy limitadas.

Es conocido que la densidad de las especies de malas hierbas varía de un año a otro y entre los sistemas de laboreo del suelo (Dorado and López-Fando, 2006) y el efecto que pueden tener estos últimos varían de acuerdo al tipo de malezas presentes en el campo. Según Ball (1992) el laboreo con chisel expone las semillas en la parte más superficial del suelo facilitando su germinación y emergencia. Este proceso se fundamenta en que, tras el laboreo, muchas semillas fotosensibles pueden percibir la luz e iniciar su germinación (Jurozsek y Gerhards, 2004). Sin embargo, a diferencia de la mayoría de malas hierbas, *B. diandrus* muestra fotoblastismo negativo (Del Monte y Dorado, 2011) de forma que la luz induce dormición. En siembra directa, las semillas quedan expuestas en la superficie del suelo durante los meses de verano y la inducción de dormición parece evidente. Sin embargo es posible que tras la pérdida de la fotoinhibición, las semillas de esta especie encuentren las condiciones más favorables para germinar en siembra directa que en situaciones de laboreo. En las parcelas experimentales donde se ha realizado siembra directa tanto del campo experimental 1 como del 2, las nascencias de esta especie se concentraron de forma preferente tras las lluvias otoñales, pudiendo reducir la población con los métodos de control de pre-siembra. En estas parcelas sin laboreo, pueden darse las situaciones necesarias para que las semillas detecten la oscuridad que les permita romper la dormición (Del Monte y Dorado, 2011). La presencia de paja y restos del rastrojo pueden ser factores significativos.

En cambio, en aquellas parcelas del campo experimental 2 donde se realizó un mínimo laboreo, se observaron mayores densidades que en parcelas con siembra directa. No resulta fácil encontrar una justificación para este paradigma, aunque cabría buscarlo en el efecto acumulado (más de 22 años) de un mismo tipo de manejo sobre la población. Recientemente, Kleemann y Gill (2013) han demostrado que esta especie muestra una variabilidad interpoblacional en el nivel de dormición y a su vez esta dormición puede resultar adaptativa al tipo de manejo. En sus observaciones comprueban que la pérdida de dormición puede llegar a ser más lenta de lo hasta ahora conocido, permitiendo a la población de *B. diandrus* emerger en los meses posteriores a la siembra del cultivo. Nuestros resultados permiten evidenciar una situación donde, en general, la emergencia se prolonga hasta el mes de abril. Sin embargo, la mayor presencia de *B. diandrus* en las parcelas con mínimo laboreo (chisel y subsolador) podría deberse a una pérdida de dormición más prolongada y a una posible dormición adaptativa como resultado de un continuado manejo durante muchos años. En cualquier caso resultarían necesarios más estudios para confirmar posibles cambios en el ritmo de dormición, y poder verificar si existe una dormición adaptativa y/o una selección poblacional.

Los resultados de este trabajo permiten evaluar tres aspectos fundamentales a la hora de establecer un programa de manejo integrado de *B. diandrus* en los secanos cerealistas bajo siembra directa. En primer lugar, la importancia de una rotación cebada-trigo que permita ampliar el espectro de herbicidas post-emergentes. En segundo lugar, la importancia de integrar en este tipo de manejo un retraso en la fecha de siembra que permita una reducción significativa de la densidad de *B. diandrus*, tanto en cebada como en trigo, mediante herbicidas de pre-siembra no selectivos (p.e. glifosato), y en tercer lugar, la importancia de realizar el tratamiento herbicida post-emergente en el momento oportuno y de acuerdo al estado fenológico de la población -de acuerdo con los datos obtenidos a partir del modelo hidrotérmico desarrollado- y poder así reducir la densidad final, limitando significativamente tanto la fecundidad de las plantas sobrevivientes como las posibilidades de reestablecimiento de la población la campaña siguiente.

Los distintos ensayos realizados en la presente tesis doctoral permiten poner de relieve aspectos clave de la emergencia y desarrollo de *B. diandrus* en sistemas cerealistas de secano en sistemas de siembra directa. Las dificultades que esta especie siempre ha planteado en estos sistemas y las limitadas opciones existentes hasta ahora para afrontar una estrategia de control eficaz, pueden verse finalmente superadas.

Bibliografía

Ball, D. A. (1992). Weed seedbank response to tillage, herbicides, and crop-rotation sequence. *Weed Science* 40: 654-659.

Del Monte J.P. and Dorado J. (2011). Effect of light conditions and after ripening time on seed dormancy loss of *Bromus diandrus*. *Weed Research* 51: 581-590.

Dorado, J. and López-Fando, C. (2006). The effect of tillage system and use of a paraplow on weed flora in a semiarid soil from central Spain. *Weed Research* 46: 424-431.

Forcella, F., Benech Arnold, R. L., Sánchez, R. and Ghersa, C. M. (2000). Modeling seedling emergence. *Field Crops Research* 67: 123-139.

García, A. L., Recasens, J., Forcella, F., Torra, J. and Royo-Esnal, A. (2013) Hydrothermal emergence model for *Bromus diandrus*. *Weed Science* . 61: 146-153

Kleemann, S. G. L. and Gill, G. S. (2013) Seed dormancy and seedling emergence in ripgut brome (*Bromus diandrus* Roth) populations in southern Australia. *Weed Science* In-Press. **doi:** http://dx.doi.org/10.1614/WS-D-12-00083.1

Kleemann, S. G. L. and Gill, G. S. (2006). Differences in the distribution and seed germination behaviour of populations of *Bromus rigidus* and *Bromus diandrus* in South Australia: Adaptations to habitat and implications for weed management. *Australian Journal of Agricultural Research* 57: 213-219.

Jurozsek, P. and Gerhards, R. (2004) Photocontrol of weeds. *Journal Agronomy and Crop Science* 190: 402-415.

Roman, E. S., Murphy, S. D. and Swanton, C. J. (2000). Simulation of *Chenopodium album* seedling emergence. *Weed Science* 48: 217-224.

Royo-Esnal, A., Torra, J., Conesa, J. A., Forcella, F. and Recasens, J. (2010). Modeling the emergence of three arable bedstraw (*Galium*) species. *Weed Science* 58: 10-15.

Spokas, K. and Forcella, F. (2009). Software tools for weed seed germination modeling. *Weed Science* 57: 216-227.

Conclusiones

Las principales conclusiones de este estudio son las siguientes:

- Se ha desarrollado un modelo de emergencia de *B. diandrus* en base a grados hidrotérmicos. Este modelo se ha validado en distintas situaciones agronómicas y se ha aplicado en diferentes escenarios cerealistas.

- El retraso en la fecha de siembra del cultivo tiene un efecto en la emergencia y densidad de *B. diandrus*. Las siembras realizadas en mitad de noviembre permiten una reducción poblacional significativa de la mala hierba (entre un 82 y un 98% según campañas) sin que se viese comprometido el rendimiento del cultivo.

- La posibilidad de implementar una rotación cebada-trigo en estos sistemas cerealistas con siembra directa, permiten integrar técnicas culturales (retraso fecha de siembra) con métodos de control químico. Tras tres campañas y mediante un ciclo cebada-trigo-trigo se ha conseguido prácticamente reducir la población de *B. diandrus*.

- La aplicación de un herbicida antigramíneo post-emergente (mesosulfuron metil + iodosulfuron metil sodio) en trigo ha dado una respuesta desigual. Sin embargo, cuando el retraso en la fecha de siembra permite una reducción de densidad y un desarrollo fenológico mas retrasado en *B. diandrus*, esta eficacia alcanza valores cercanos al 100%.

- Se ha observado una clara respuesta denso-dependiente en distintos parámetros que definen la fitness de *B. diandrus*, a excepcion del número de cariópsides por espiguilla. Al aplicar el herbicida selectivo en trigo, esta respuesta en la fitness presenta una clara disrupción en aquellas plantas supervivientes, proceso que queda reflejado por un significativo aumento del esfuerzo reproductor.

- Se confirma una desigual asignación de recursos en las estructuras reproductoras de *B. diandrus.* Las cariópsides con mayor peso corresponden a aquellas ubicadas en posición basal dentro de las espiguillas y, a su vez, en espiguillas ubicadas en posiciones apicales en el interior de la panícula.

- Un manejo continuado (22 años) de distintos tipos de manejo del suelo comporta diferencias significativas en la emergencia acumulada y densidad de *B. diandrus*. Las parcelas sometidas de forma prolongada a siembra directa muestran menores valores en esos parámetros que las parcelas sometidas a laboreos con chisel y subsolador.

- Tanto en siembra directa como en los distintos tipos de laboreo ensayados se han observado emergencias de *B. diandrus* hasta el mes de abril, aunque los máximos de emergencia y densidad se dan en momentos distintos según los tipos de manejo.