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Modeling the Emergence of Three Arable Bedstraw (*Galium*) Species

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Multiyear field data from Spain were used to model seedling emergence for three bedstraw species (*Galium*) that can coexist in winter cereal fields. The relationships between cumulative emergence and both growing degree days (GDD) and hydrothermal time (HTT) in soil were analyzed as sigmoid growth functions (Weibull). Iterations of base temperature and base water potential were used to optimize the HTT scale. All species were well described with Weibull functions. Both GDD and HTT models provided good descriptions of catchweed bedstraw emergence, as its seedlings have less dependence on soil water potential than false cleavers and threehorn bedstraw, which were described best with HTT. The HTT model for catchweed bedstraw was validated successfully with independent data from the United Kingdom. The models may be useful for predicting bedstraw emergence in semiarid Mediterranean regions and elsewhere.

Nomenclature: Catchweed bedstraw, *Galium aparine* L.; false cleavers, *G. spurium* L.; threehorn bedstraw, *G. tricornutum* Dandy.

Key words: Cleavers, corn cleavers, degree days, hydrothermal time, Weibull function.

Models that estimate the timing of weed seedling emergence are valuable tools to optimize weed control schedules (Forcella 1998; Schutte et al. 2008). Emergence is possibly the most important event for an annual plant as the time it occurs largely determines its survival and success (Forcella et al. 2000). Soil temperature, when converted to soil thermal time, or growing degree days (GDD), has been used to predict seedling emergence (Martinson et al. 2007; Norsworthy and Oliveira 2007; Roman et al. 2000). In these models, average air or soil temperature above a specified threshold is accumulated over days until weed emergence. In recent years, soil water potential and soil temperature have often been integrated into the hydrothermal time (HTT) models that are frequently better at predicting emergence than GDD (McGiffen et al. 2008). In these models, the GDD are used when the daily average of soil water potential and temperatures are over specified threshold values below which seedlings cannot emerge (Gummerson 1986).

Bedstraws or cleavers are among the most important dicotyledonous weeds in winter cereals in Spain (Kuc et al. 2003; Riba et al. 1991). For example, catchweed bedstraw can cause yield losses of up to 57% in England (Wright and Wilson 1987) and 20% in Spain (Aragro 2007). Three species can be found coexisting in the same field: catchweed bedstraw, false cleavers, and threehorn bedstraw. The first two are very closely related species (Malik and Vanden Born 1988). Catchweed bedstraw is more robust, with wider leaves, white flowers, and bigger fruits, whereas false cleavers has narrower, thinner leaves, yellowish flowers, and smaller fruits. The two species have been considered as subspecies of catchweed bedstraw (Ortega-Olivenza and Devesa 2004). For this reason in agriculture the identities of both species are usually combined (Hübner et al. 2003). Threehorn bedstraw is a well-defined species whose main characteristics are its warty and glabrous fruits displayed in groups of three on short curved peduncles (Bolós et al. 1996; Carretero 2004).

In Spain, all three species are annual plants well adapted to disturbed areas, such as winter cereal crops (Aizpuru et al. 2000; Carretero 2004). Most seeds of these species possess an innate dormancy that is generally lost during summer (Masuda and Washinati 1992). As a consequence, large proportions of the seeds germinate and emerge as seedlings in autumn. Those seeds that do not germinate remain in the soil seedbank and may germinate in spring as a second flush (Cussans and Ingle 1999; Mennan and Ngouajio 2006). Models for the emergence of the three species of *Galium* could improve their control. That is, knowing the proportion of maximum emergence represented by each flush provides insight into the need and timing of control operations. Furthermore, because the three species can coexist in the same habitat, another concern is whether emergence of these species should be modeled together or separately? The answer depends on differences among the species in how they respond to regulatory variables such as soil temperature and soil water potential.

The objective of this study was to develop models of seedling emergence for the three *Galium* species present in winter cereal crops and to examine whether GDD and soil HTT are appropriate parameters for describing the timing of emergence of their seedlings.

Materials and Methods

Plant Material. In 2005 to 2006 and 2006 to 2007 seeds of the three species were gathered from late June to early July from mature plants in winter cereal fields; catchweed bedstraw and false cleavers were collected in Coscó (41°49′47″N, 1°10′30″E, elevation 450 m) and threehorn bedstraw was collected in Toló (42°03′25″N, 1°02′30″E, elevation 770 m), both sites in Central Catalonia (NE Spain). The fields and locations selected had similar growing conditions, land use (conventional winter barley), and climate (Mediterranean). Seeds were stored dry in the laboratory until sowing date.

Experimental Sites. Field experiments were conducted in 2005 to 2006 and 2006 to 2007 in a 10-ha commercial winter cereal field (barley) at Castelló de Farfanya, 35 km north of Lleida and approximately 40 km from the collection site of the seeds. The soil was a medium loam (37.7% sand, 43.4% silt, and 19.4% clay), with 1.52% organic matter and pH of 8.3. The field was chisel plowed in October. No crop was sown and no herbicide was applied during the trial.

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Experimental Design. The experiment was arranged as a randomized complete block design with four replications. Plot size was 1 by 2 m. Seeds were sown at a density of 400 seeds m^{-2} on November 21, 2005 and on November 6, 2006. In both years seeds were spread over the soil surface and covered with a thin layer of soil. This was done because light inhibits germination of these species (Chauhan et al. 2006b; Froud-Williams 1985; Malik and Vanden Born 1988); thus emergence of seeds buried 1 to 2 cm is higher than in seeds on the soil surface (Boyd and Van Acker 2003; Chauhan et al. 2006a). Seedling emergence was determined weekly in three 0.33- by 0.33-m permanent quadrats by marking newly emerged seedlings with colored paperclips. A different colored marker was used on each sampling date.

Weather Data. Daily rainfall and maximum and minimum air temperatures were obtained from a meteorology station 14 km away from the experimental field (METEOCAT—Meteorologic Service of Catalonia). GDD were based on the average of the daily minimum and maximum air temperatures (Benvenuti and Macchia 1993; Gupta 1985) using 0 C as base temperature.

Model Description and Parameterization. Simulated water potentials (hydrotime, HT) and soil temperatures (thermal time, TT) were used to calculate HTT on the basis of the equation described by Roman et al. (2000):

$$\mathrm{HTT} = \Sigma(\mathrm{HT} \times \mathrm{TT})$$

where HT = 1 when $\psi > \psi_b$, otherwise HT = 0; and TT = $T - T_b$ when $T > T_b$, otherwise TT = 0. ψ is the daily average water potential in the soil layer from 0 to 5 cm; ψ_b is the base water potential for seedling emergence; T is daily average soil temperature in the soil layer from 0 to 5 cm, and T_b is base temperature for seedling emergence (Ekeleme et al. 2005; Martinson et al. 2007). With this formula, GDD are accumulated only when the water potential and temperature conditions are higher than the base water potential and base temperature. The base water potential and base temperature were determined iteratively calculating HTT using a set of water potentials (0.0 to −5.0 MPa at −0.1MPa intervals) and temperatures (0 to 3 C at 1 C intervals). In other words, the scale of HTT was changed by modifying the ψ_b and the T_b until the highest accuracy was obtained for the relationship between HTT and relative emergence for each species separately. This method was found to be useful in finding the base temperature and soil water potential for wild oat (*Avena fatua* L.) (Martinson et al. 2007) and tropic ageratum (*Ageratum conyzoides* L.) (Ekelema et al. 2005). The HTT was estimated using the STM^2 model (Spokas and Forcella 2009). STM^2 requires as input daily maximum and minimum temperatures and daily precipitation, along with information on the geographical location and soil texture and organic matter. GDD and HTT were accumulated over days beginning on the sowing date in each year.

The functional relationships between cumulative emergence and cumulative GDD and HTT were described by a sigmoid growth function (Weibull 1959) commonly used for this purpose:

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

where y is the percentage of emergence, x is time expressed as GDD or HTT, and K, b, and a are empirically derived constants. K is the maximum percentage of emergence recorded, b is the rate of increase, z is the lag phase, and a is a shape parameter. Fitting of the Weibull function for seedling emergence was performed using SAS (procedure NLIN; SAS 8.1, SAS Institute, 2008). Model parameters were estimated by nonlinear least-squares regression and the goodness of curve fitting by contrast of joint hypothesis ($P < 0.05$). Adjustments of the models were performed, in the three species, by matching these to the 50% emergence (E_{50}) point and then calculating the lag phase: in each *Galium* species real E_{50} was calculated in the four plots and their mean value was used to calibrate each model; then, GDD and HTT for initial emergence was used as lag phase. This concordance permits a better prediction of the emergence than with the beginning of emergence because E_{50} generally coincides with the greatest emergence rate, and thus, is more precise. The three resulting models and their parameters were compared with a likehood ratio test (Kimura 1980); lack of differences among them would allow the development of a common model.

Emergence Model Validation. The models of seedling emergence were validated with data of catchweed bedstraw from DowAgro (2009), part of which was published by Cussans and Ingle (1999). Catchweed bedstraw was grown in Rothamsted, United Kingdom, in 1996 to 1997 and in 1997 to 1998. The characteristics of the field are explained in Cussans and Ingle (1999). This population showed two flushes of emergence in both years, one in autumn and another in spring. As both flushes may suggest the presence of subpopulations, as in giant ragweed (*Ambrosia trifida* L.) (Schutte et al. 2008), data for each year were separated, and those for the autumn flushes and the spring flush of 1998 were used for model validation. The spring flush of 1997 was discarded because it lacked sufficient data. Hydrothermal time was calculated with soil environment data from STM^2. Emergence pattern predictions were superimposed on plots of actual seedling emergence. Differences between predicted and observed seedling emergence values were assessed by root mean-square error (RMSE):

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

where x_i represents observed cumulative percentage seedling emergence, y_i is predicted cumulative percentage seedling 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 lowest RMSE value indicated that emergence model fit had been optimized. The end result was a single model that described seedling emergence in autumn 1996, 1997, and spring 1998. Previously published emergence data for false cleavers and threehorn bedstraw, comparable with that for catchweed bedstraw, could not be located and, therefore, models for the two former species were not validated independently.

Results and Discussion

The two years differed considerably in terms of temperature, rainfall, and temporal patterns (Figure 1). Total rainfall from sowing to harvest in 2005 to 2006 was 68 mm, but was

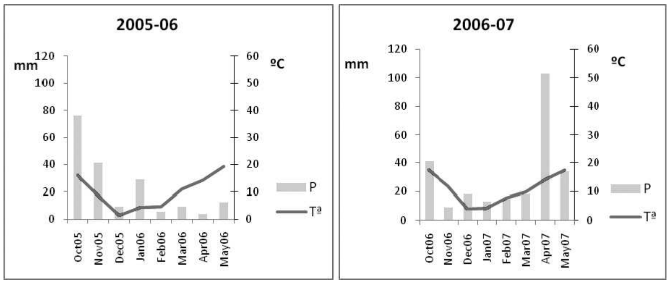

Figure 1. Weather conditions during 2005 to 2006 and 2006 to 2007. Total precipitation (P) in millimeters and mean air temperature (T_a) in degrees C.

208 mm in 2006 to 2007. During the first year, the winter was relatively cold (average temperature 3.3 C) with little rain (29 mm), which mainly fell in January. Spring was dry, with only 30 mm between February and May. The second year was marked by a warmer winter (average temperature 5.4 C) and more rain in spring (103 mm in April). In contrast to typical agronomic research where consistency in weather variables is desirable, highly contrasting weather patterns between experimental years enhanced opportunities for understanding and modeling weed responses to GDD and HTT.

Emergence as a Function of GDD. First seedlings were observed on February 1 during the 2005 to 2006 growing season and on December 5 during 2006 to 2007. In both years, seedlings started to emerge between 250 and 300 GDD. E_{50} was obtained at about 400 GDD for all three species in the year 2005 to 2006, whereas in 2006 to 2007 catchweed bedstraw and false cleavers needed 500 GDD and threehorn bedstraw nearly 700 GDD to reach this same level of emergence.

The relationship between emergence and temperature was tested initially with simple GDD models (Table 1). Figure 2 illustrates the cumulative emergence patterns of these species as a Weibull function of GDD. Differences were apparent among the three species of *Galium*. The model describing catchweed bedstraw emergence had the best fit ($R^2 = 0.95$), especially for 2005 to 2006. However, in 2006 to 2007 the model overestimated emergence. The model describing false cleavers emergence fit well for 2006 to 2007, but underestimated emergence in 2005 to 2006 (Figure 2). The model describing threehorn bedstraw emergence had the lowest fit ($R^2 = 0.83$), which is reflected in a considerable mismatch between predictions and observations in 2005 to 2006.

Emergence as a Function of HTT. The base temperature and base water potential for HTT were estimated iteratively. The best-fitting base temperature was determined to be 0 C for all three species of *Galium*. The best-fitting base water potential was −2.5 MPa for catchweed bedstraw. (The highest R^2 values [0.96] for describing the relationship between observed emergence and calculated HTT was achieved using base water potentials between −2.5 and −5.0 Mpa.) The best-fitting base water potentials for the other species were estimated at −1.2 MPa ($R^2 = 0.98$) for false cleavers and −0.8 MPa ($R^2 = 0.93$) for threehorn bedstraw. Thus, a sensitivity gradient of emergence to soil water potential appeared to exist across the species, with catchweed bedstraw < false cleavers < threehorn bedstraw. Germination of the sand-dune species, yellow bedstraw (*Galium verum* L.), becomes highly sensitive to water potential between −1.0 and −1.5 MPa (Evans and Etherington 1990). The similarity of these experimentally derived water potentials for yellow bedstraw to those determined for these three bedstraw species suggests that the modeling approach was experimentally based.

Estimates of the variables *K*, *b*, and *a* fitted to HTT for each species are summarized in Table 2 and predicted and observed emergence using Weibull functions are shown in Figure 3. Lag phases (*z*) were established at 1,196, 1,056, and 1,084 HTT in 2005 to 2006 and at 864, 830, and 1,007 HTT in 2006 to 2007 respectively for catchweed bedstraw, false cleavers, and threehorn bedstraw. The best description was achieved for false cleavers, whereas there is a slight misfit for catchweed bedstraw. The model for describing threehorn bedstraw emergence was also good in 2005 to 2006, but not in 2006 to 2007, as there was a major difference between predictions and the highly heterogeneous observations. Kimura analysis proved that the *b* parameter was significantly lower in threehorn bedstraw than in catchweed bedstraw and false cleavers, which means that its emergence rate is also lower and, thus, it takes longer to achieve the maximum percentage of emergence (parameter *K*). The differences in the *b* parameter prevented the development of a common function for the three *Galium* species.

When data from both years were pooled to describe a general curve, the fit of the model for emergence as a function of HTT was better than for GDD. Despite the better fit for catchweed bedstraw in 2006 to 2007, there was a mismatch between predicted and observed proportion of emergence in 2005 to 2006. In fact, the description of the curve using the GDD in 2005 to 2006 was better than for the curve using the HTT. For false cleavers, the fit of the model for emergence to HTT improved, and the underestimation observed in 2005 to 2006 disappeared, while the fit in the next season was similar to the one obtained using the GDD. For threehorn bedstraw a significant improvement of the fit was achieved when the cumulative emergence was fitted to HTT, mainly in 2005 to 2006.

The emergence of the three bedstraw species was related to both temperature and rainfall; for example, the relatively high temperatures in 2006 to 2007 and low rainfall in 2005 to 2006 may have caused an increase in the variation of the

Table 1. Parameter estimates and standard errors of the cumulative emergence as a function of growing degree days as estimated with the Weibull model using data from 2 yr (2005 to 2006 and 2006 to 2007).

	Weibull model parameters and statistics				
Species	*K*	b ($\times 10^{-3}$)	*a*	$P > F$	R^2
Catchweed bedstraw	99.6 ± 2.09	2.13 ± 0.045	4.67 ± 0.54	< 0.0001[a]	0.95
False cleavers	97.9 ± 2.29	2.31 ± 0.065	3.48 ± 0.46	< 0.0001[a]	0.95
Threehorn bedstraw	93.9 ± 6.67	1.75 ± 0.185	1.82 ± 0.39	< 0.0001[a]	0.83

[a] Significant at $P < 0.05$.

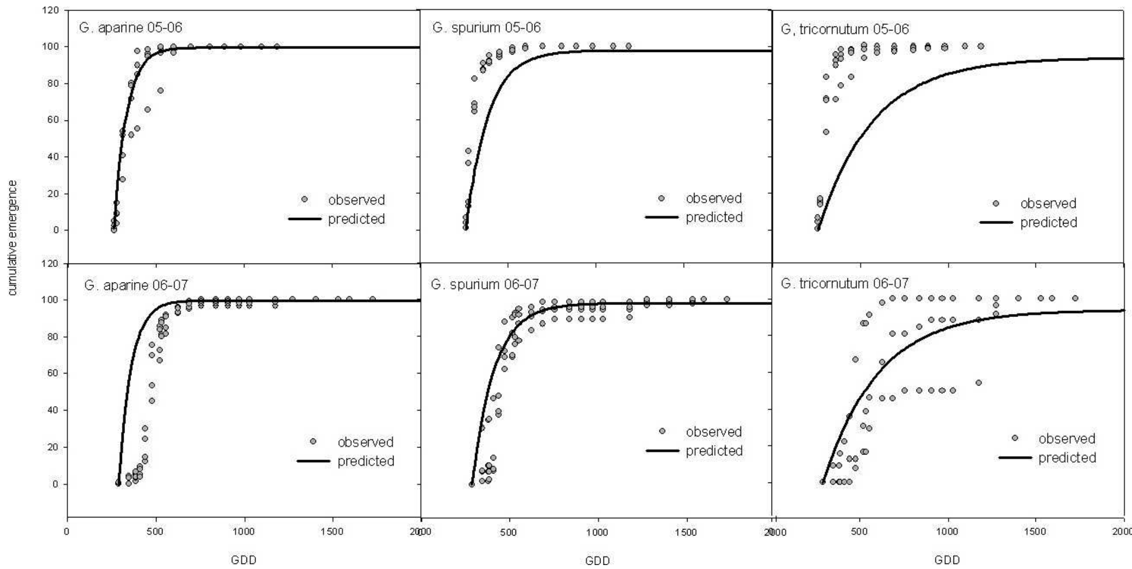

Figure 2. Observed (symbols) and predicted (lines) cumulative emergence of catchweed bedstraw, false cleavers, and threehorn bedstraw. Predictions are on the basis of the Weibull function describing emergence as a function of growing degree days (GDD) in the years 2005 to 2006 and 2006 to 2007.

results. The better emergence of bedstraws at lower temperatures is known (Froud-Williams 1985; Taylor 1999), in particular in the case of threehorn bedstraw (Chauhan et al. 2006a).

The different fit of the proportion of emergence using the Weibull model as a function of either GDD or HTT might be explained with the requirements of base temperature and base water potential of each species. All three bedstraw species required a low temperature period to germinate. Calculation of the HTT was optimal using 0 C as a base temperature for all three species. However, the species differed with regard to the base water potential. Estimates of the base water potential for catchweed bedstraw were more variable and the fit of the model on the basis of HTT was as good at a base water potential of −2.5 MPa as −5.0 MPa. This suggests a wide ecological adaptability and, indeed, catchweed bedstraw can grow in many different habitats (Taylor 1999), from warmer polar regions to the subtropics (Defelice 2002). The base water potential for false cleavers was estimated at −1.2 MPa, which indicates a greater sensitivity to moisture conditions in the soil (Forcella et al. 2000). Thus false cleavers in Spain requires higher soil moisture content for emergence than catchweed bedstraw. This conclusion is in accordance with Malik and Vanden Born (1988), who noted that "the occurrence of false cleavers is rare in very dry plains where summer rainfall is scant," which is a good characterization of the spring climate in western Catalonia. Nevertheless, the minimum moisture requirement must be used with care as field observations from other areas show that false cleavers can occur in sunnier habitats than catchweed bedstraw (Moore 1975). Apparently, catchweed bedstraw can emerge from a wider range of soil water contents, i.e., both drier and wetter

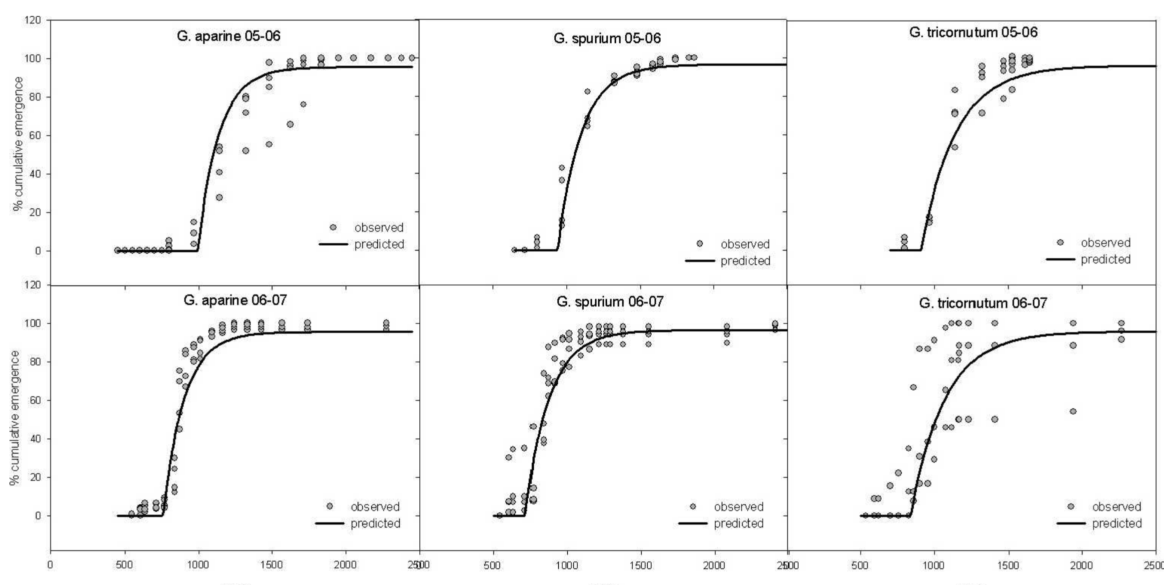

Figure 3. Predicted emergence (line) and observed emergence (symbols): Results of cumulative emergence of catchweed bedstraw, false cleavers, and threehorn bedstraw adjusted as Weibull functions of hydrothermal time (HTT) in 2005 to 2006 and 2006 to 2007.

Table 2. Parameter estimates and standard errors of cumulative emergence as a function of hydrothermal time as estimated with the Weibull model using data from two yr (2005 to 2006 and 2006 to 2007).

Species	Weibull model				
	K	b ($\times 10^{-3}$)	A	$P > F$	R^2
Catchweed bedstraw	95.49 ± 1.78	1.03 ± 0.017	6.74 ± 0.94	< 0.0001[a]	0.96
False cleavers	96.56 ± 1.43	1.07 ± 0.015	5.74 ± 0.61	< 0.0001[a]	0.98
Threehorn bedstraw	95.89 ± 2.63	0.88 ± 0.019	4.90 ± 0.65	< 0.0001[a]	0.93

[a] Significant at $P < 0.05$.

soils, than false cleavers. Catchweed bedstraw can germinate and emerge in both dryer and moister habitats. The lower sensitivity to water potential or the wider range of this factor for catchweed bedstraw may explain the fact that the fit of the model in 2005 to 2006 was better when using GDD than HTT. Because emergence of false cleavers was more affected by the lack of soil moisture, the fit of the model was better when a measure of moisture was included (HTT).

The base water potential was higher in the case of threehorn bedstraw than for the other two species (−0.8 MPa), which means an even greater sensitivity of emergence to water content. This explains why the fit of the model for emergence was better when described as a function of HTT than of GDD. It may also explain the better fit to observed emergence in 2006 to 2007, when the amount of rainfall in October, November, and December was half that of 2005 to 2006 (Figure 1). These results are in accordance with Chauhan et al. (2006b), who described a linear model for germination as a function of osmotic potential, which was fitted to data obtained under laboratory conditions. Their model indicates that the osmotic potential needed for threehorn bedstraw to germinate was about −0.8 MPa. Chauhan et al. (2006a) found the highest percentage of emergence of threehorn bedstraw during cold stratification at 5 C and observed the highest germination rates during the coldest part of winter. The winter of 2005 to 2006 was colder than that of 2006 to 2007, and therefore the lower temperatures may have induced higher emergence of threehorn bedstraw in 2005 to 2006.

The observation that temperature is one of the most important factors determining catchweed bedstraw emergence, as for other species in temperate climates (Forcella et al. 2000; Van der Weide 1992), was confirmed in the year with lower winter temperatures. However, in warmer years for catchweed bedstraw, and in all cases for false cleavers and threehorn bedstraw, rainfall seems to be the determinant factor in that it can delay emergence. Consequently, soil moisture must be included to model emergence correctly for these species.

Emergence Model Validation. Emergence predicted by the model of Rothamsted (U.K.) populations of catchweed bedstraw showed a good correspondence and reasonable accuracy with observed emergence during autumn 1996 (RMSE 7.0%) and 1997 (13.4%) and spring 1998 (9.8%) (Figure 4). These values are similar to those achieved by Schutte et al. (2008) for emergence models of giant ragweed (range of 8.0 to 9.5%) and generally smaller than those that Roman et al. (2000) obtained in the emergence models for common lambsquarters (*Chenopodium album* L.) (range of 6.5 to 37.1%).

Compared with our own observations, in the case of catchweed bedstraw the model using either GDD or HTT described emergence acceptably depending on seasonal characteristics. The most accurate model for false cleavers was obtained using HTT. It only varied within 3.5% from the predicted emergence. Populations of these two species are known to be variable, and it is likely that this variability extends to the requirements for emergence. For example, Froud-Williams (1985) observed that dormancy of hedgerow populations of catchweed bedstraw was shorter than that of arable populations, and Van der Weide (1992) noted that hedgerow populations needed lower temperature for vernalization than arable populations. Despite this, the models for catchweed bedstraw and false cleavers seem to be robust as they were developed in two yr with very different climatic conditions, of which one had an unusually dry autumn and winter. In the case of catchweed bedstraw, it also has been validated with data from a completely different climate (U.K.) and in two different seasons (autumn and spring).

The model for threehorn bedstraw, whose emergence is more dependent on adequate soil water content, seems to describe emergence very well in years without droughts, using HTT. Threehorn bedstraw populations in the area usually occur in the higher and colder regions of the Pre-Pyrenees and the Spanish Central Plateau, where soil moisture is usually higher than in the lowlands.

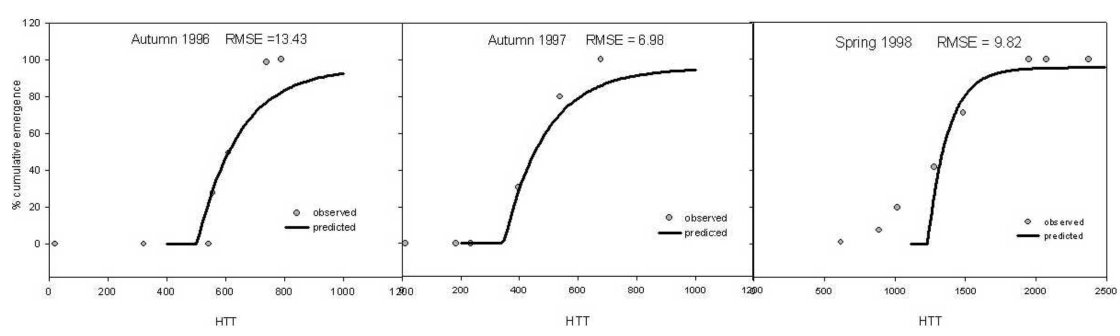

Figure 4. Hydrothermal-based seedling emergence model validation for catchweed bedstraw with data from DowAgro (2009) obtained in Rothamsted, U.K., in 1996 to 1997 and 1997 to 1998. Predicted emergence (line) and observed emergence (symbols). Root mean-square error (RMSE) values are in units of percentage cumulative emergence.

In summary, the models developed in this study may be useful tools to predict the emergence of three *Galium* species such that the proper control methods can be used in a timely manner in the dry winter cereal fields of the semiarid regions of northeast Spain. To apply the models, we recommend that HTT accumulation be started in mid-November or at the date of crop sowing. Thereafter, managers can use emergence predictions to make more informed decisions regarding, for example, the need for autumn vs. spring applications of POST herbicides. Moreover, perhaps these models also can be used as starting points to model the emergence of bedstraws in other climatic regions.

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