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Seedling emergence of tall fescue and wheatgrass under different climate conditions in Iran

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Abstract

Seedling emergence is one of the most important processes determining yield and the probability of crop failure. The ability to predict seedling emergence could enhance crop management by facilitating the implementation of more effective weed control strategies by optimizing the timing of weed control. The objective of the study was to select a seedling emergence thermal time model by comparing five different equations for tall fescue and wheatgrass in two sites with different climate conditions (semiarid-temperate and humid-warm) in Iran. In addition, seedling emergence between two target species were studied. Among the five models compared, the Gompertz and Weibull models gave more succesful results. In humid-warm conditions, the total emergence of wheatgrass was higher than observed in tall fescue. In contrast, emergence was faster in tall fescue than wheatgrass in both study sites. Given that early-emerging plants have been described as contributing more to crop yield than later-emerging ones, tall fescue is proposed as a more suitable specie for semiarid- temperate conditions in Iran.

Additional key words: *Agropyron desertorum*; *Festuca arundinacea*; germination; Gompertz model; Weibull model.

Resumen

Emergencia de las plántulas de lastón y triguilla del desierto bajo condiciones climáticas diferentes en Irán

El éxito en el proceso de emergencia de las semillas es un evento determinante en el rendimiento de las cosechas. Por tanto, cualquier mejora en la predicción de este proceso resulta valioso para la mejora de las técnicas de manejo de los cultivos. El objetivo de este trabajo fue la caracterización dinámica del proceso de emergencia de *Festuca arundinacea* Schreb y *Agropyron desertorum* (Fisch. ex Link) J.A. Schultes en dos localidades con diferentes condiciones climáticas (semiárido templado y húmedo calido) de Iran. Los análisis realizados indicaron que, de entre los cinco modelos comparados, los ajustes de Gompertz y Weibull proporcionaron los resultados más satisfactorios en la caraterización dinámica de dicho proceso. En condiciones húmedas y cálidas, el porcentaje total de emergencia de *A. desertorum* fue significativamente superior al observado en *F. arundinacea.* Por el contrario, en ambos ambientes climáticos el proceso de emergencia de *F. arundinacea* fue más rápido que el observado en *A. desertorum.* Dado que la emergencia temprana ha sido descrita como un elemento clave en el éxito de las cosechas en condiciones semiáridas, nuestros resultados sugieren que *F. arundinacea* puede representar una especie más adecuada para su cultivo en los ambientes semiáridos-templados de Iran.

Palabras clave adicionales: *Agropyron desertorum*; *Festuca arundinacea*; función de Gompertz; función de Weibull; germinación.

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Abbreviations used: AIC (Akaike Information Criterion); GDD (cumulative growing degree-days); TS (test statistic).

Introduction

Perennial grasses are seen as key plants in the economic and environmental sustainability of rangeland for livestock grazing in Iran (Gazanchian *et al*., 2006). Iran contains both arid and semiarid regions, with an estimated 397 native grass species belonging to 115 genera (Mozaffarian, 1996). Among these, tall fescue (*Festuca arundinacea* Schreb) and wheatgrass (*Agropyron desertorum* (Fisch. ex Link) J. A. Schultes) are the most important cool-season forage crop (Behtari, 2009). One of the main limitations in adopting native cool-season grasses for rangeland use in Iran is a lack of knowledge on their germination and seedling emergence patterns and subsequent establishment (Gazanchian *et al*., 2006). Seedling emergence constitutes one of the crucial events in the life cycle of plants, often proving decisive in the performance and success of well-adapted species (Harper, 1977; de Luis *et al*., 2008). In this sense, a detailed understanding of seedling emergence patterns is critically important to improving the design of practices for managing native or introduced plant populations (Phil *et al*., 2007).

Seedling emergence of a particular species in the field occurs only when all environmental conditions are within the ranges permitting seed germination (Phil *et al*., 2007). Soil temperature, soil water, air quality, and light quantity are the main environmental factors affecting seedling emergence (Forcella *et al*., 2000). Karssen (1982) proposed that seasonal periodicity in field emergence of annual species is the combined result of seasonal periodicity in soil temperatures and physiological changes within seeds that alter the temperature range permitting germination. Thus, as temperature is the primary environmental signal regulating both the dormancy and germination progress of many species, most predictive models for seedling emergence use a thermal timescale (degree-days) to normalize temperature variation over time in the field (Forcella, 1998; Vleeshouwers & Kropff, 2000; Haj Seyed Hadi & González-Andujar, 2009).

Nonlinear regression models have been developed to explain seedling emergence patterns as a function of thermal time (Haj Seyed Hadi & González-Andujar, 2009). However, despite nonlinear models being useful for a wide range of growth curves (Kingland, 1982), several models are suggested by various authors to describe emergence patterns in different species and/or different climate conditions (Mohanty & Painuli, 2004; Haj Seyed Hadi & González-Andujar, 2009).

The main objective of this study was to select a seedling emergence model for tall fescue and wheatgrass under two contrasting climate conditions in Iran and evaluate differences in seedling emergence between the two target species under both climate conditions.

Material and methods

We used seedling emergence data from two forage crop species: tall fescue (*Festuca arundinaceae* Schurb) and wheatgrass (*Agropyron desertorum* (Fisch. ex Link) J. A. Schultes). Data were collected in two different locations in Iran, at Noor (36°47'N, 51°46'E, 15 m above sea level) and at the Private Experimental Field, Ardabil, (38°15'N, 48°17'E, 1332 m above sea level). Noor and Ardabil have humid-warm and semiarid-temperate climates, respectively. The mean annual temperature and precipitation from 1977 to 2008 in Noor were 16.33°C and 1293 mm, and 9.02°C and 304 mm in Ardabil, respectively (Iran Meteorological Organization, 2009). During the experimental period in June 2008, the mean daily temperature was 21.9°C and 9.86ºC and total precipitation was 22.62 mm and 343 mm for Noor and Ardabil, respectively (Figure 1).

The experimental design was a randomized complete block arrangement with three replications in Ardabil and four in Noor. Grass species were grown in 1.5 × 1 m plots, and seeded in 12 cm wide rows, spaced 3 cm apart. The seeding dates were 4th and 5th June 2008 and seedling emergence was determined daily from day 1 to day 21, with the number of newly emerged seedlings counted in a 1m length of row. The emergence percentage was obtained by dividing the number of emerged seedlings at any time by the total number of seeds sown, multiplied by 100.

On the basis of experimental data on the growth of shoots in different climates, a non-linear regression fitting procedure was used to estimate the parameters of the next five S-type functions:

— Gompertz (Gompertz, 1825):

$$Y = kEXP(-EXP(-a(X-m)))$$

— Logistic (France & Thornley, 1984):

$$Y = \frac{k}{(1+EXP(-a(X-m)))}$$

— Verhulst (Verhulst, 1838):

$$Y = \frac{k}{(1+m(EXP(-aX))}$$

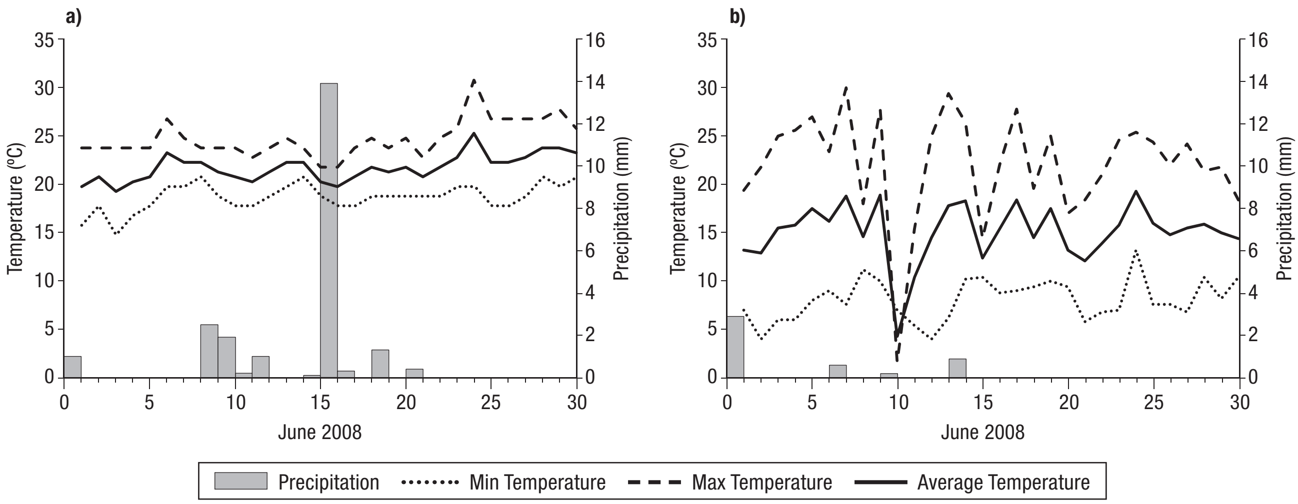

Figure 1. Daily temperature and total precipitation at a) Noor and b) Ardabil in June 2008.

— Weibull (Weibull, 1951):

$$Y = k - aEXP(-mX^{d})$$

— Richards (Richards, 1959):

$$Y = \frac{k}{((1+mEXP(-aX))^{(\frac{1}{d})})}$$

where k is the asymptote, *a* is the rate of increase, *m* is the inflection point and *d* is a shape parameter. In each case, *Y* is cumulative emergence (%) observed in the field experiment. For the *X* variable, we used a thermal timescale (degree-days) to normalize temperature variation over time (Forcella, 1998; Vleeshouwers & Kropff, 2000; Haj Seyed Hadi & González-Andújar, 2009). The number of parameters (p) for the first three models was 3, while for the last two models was 4. These parameters were estimated by regression fitting equations on the whole cumulative seed emergence data using the popular Marquardt-Levenberg algorithm with the SPSS v.12.0 nonlinear procedure (SPSS Inc., Chicago, IL, USA).

Cumulative growing degree-days (GDD) were calculated in each field from total daily mean air temperature recordings from the time of seeding to seedling emergence:

$$GDD_{daily} = \left[\left(T_{\max} + T_{\min}\right)/2\right] - T_b$$

and

$$GDD = \sum_{i=1}^{n} GDD_{daily}$$

where $T_{\max}$ is the maximum daily air temperature, $T_{\min}$ is the minimum daily air temperature, T_b is the base temperature, 3.2 and 4°C for tall fescue and wheatgrass, respectively (Palazzo & Brar, 1997; Kowalenko & Romo, 1998), and *n* is the number of days elapsing from the time of seeding. Estimates of the time taken for cumulative emergence to reach 50% of maximum in each replication were interpolated from the progress of emergence (%) versus time (days) curve.

Subsets of available data by delete-one observation were used to validate the models. The goal of cross-validation is to find out whether the result is replicable or just a matter of random fluctuations. The cross-validity coefficient was computed by correlating predicted scores and observed scores on the outcome variable. After fitting the models to the data using non-linear regression, a comparison was made between predicted value and non-used observation value.

The following hypothesis was tested for equality of variances (H_{σ}^2: $\sigma_{nl}^2 = \sigma_{no}^2$) where *nl* is the predicted value of nonlinear regression and *no* is the non-used observation. Microsoft Excel software was used to calculate the corrected sums of squares for the predicted value of nonlinear regression and non-used observation used in the following test statistic (TS) (Snedecor & Cochran, 1973; Roush & Branton, 2005):

$$TS = \frac{CorrectedSS_{Large}}{CorrectedSS_{Small}}$$

The larger value was placed over the smaller value for determining the *F* statistic. The significance level was set at $p \leq 0.05$.

If validation processes provided succesful results, final models were constructed using all available data. Following this, a comparison of the models was made using the Akaike Information Criterion (AIC) which penalizes the addition of parameters (K), and thus selects a model that fits well, but has a minimum number of parameters (*i.e.,* simplicity and parsimony) (Akaike, 1974). When sample size (N) is small compared to K (*i.e., n/K* < ~40), the second-order Akaike Information Criterion (AICc) should be used (Motulsky & Christopoulos, 2003). As sample sizes increase, the last term of the AICc approaches zero, and the AICc tends to yield the same conclusions as the first-order AIC (Burnham & Anderson, 2002).

Where analyses are based on least squares regression for normally distributed errors, the AICc can compute with the following formula:

$$AIC_c = N * Ln\left(\frac{SS}{N}\right) + 2K + \frac{2K(K+1)}{N-K-1}$$

where N is the sample size, SS the residual sum of squares and K is the total number of estimated regression parameters including the intercept and σ^2.

Finally, a two-way analysis of variance (ANOVA) was used to test differences between species and sites in the percentage of final seedling emergence and the number of days taken to reach 50% of the final emergence percentage.

Results

Predicted versus observed seedling emergence from both field experiments are presented in Figure 2. Model parameters are shown in Table 1. The overall results showed that curve fitting gave efficiency higher than 0.99 in all cases and cross-validation analysis indicated that the predictive power of obtained equations is almost constant over different samples from the same population (Table 1).

The Gompertz model resulted in a lower AICc value for tall fescue in Noor and Ardabil (AICc = 26.19 and 16.65, respectively). For wheatgrass, the Gompertz model also resulted a lower AICc value in Noor (17.01), while in Ardabil the lower AICc value is ob-

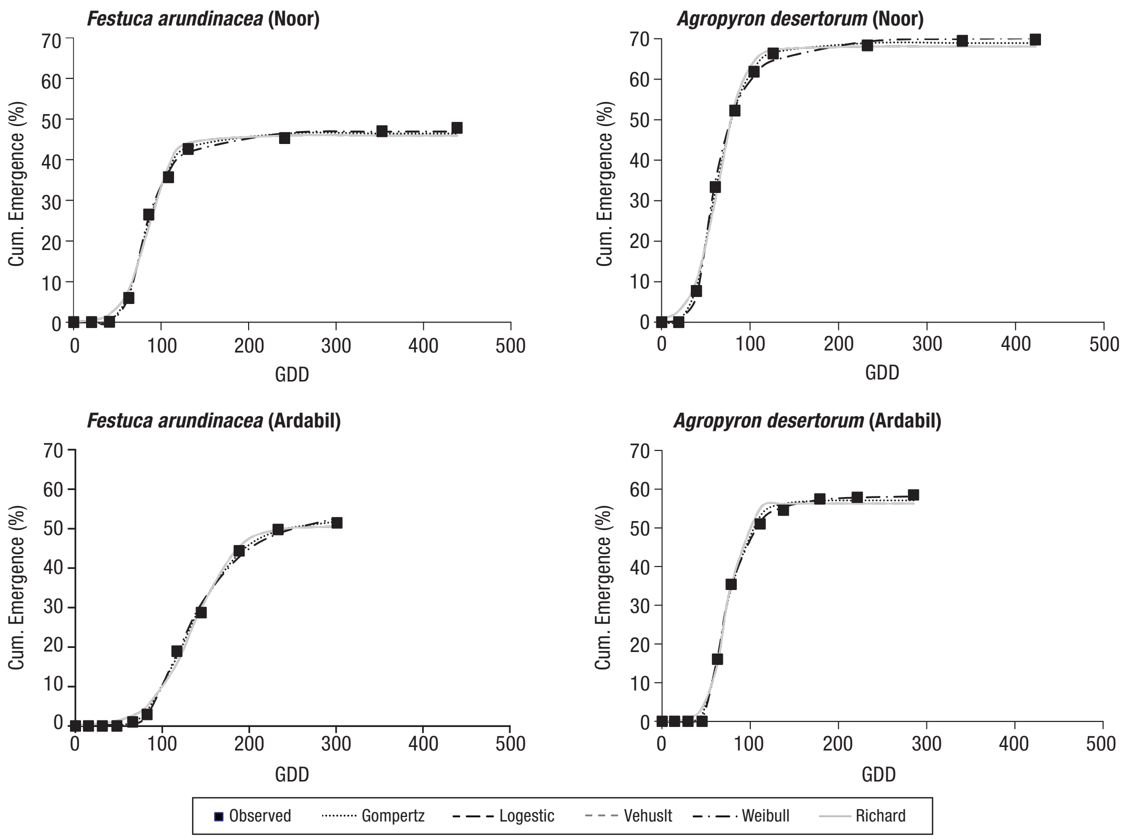

Figure 2. Cumulative emergence curves fitted by nonlinear regression models (Gompertz, Logistic, Verhulst, Weibull and Richards) for two forage species in two sites (Noor and Ardabil). GDD: Cumulative growing degree-days.

Table 1. Parameter estimation for seedling emergence models in both studied species and sites, and cross-validation results for testing the models

Species	Model parameter							Cross-validation results	
	Model	k ± S.E.	a ± S.E.	m ± S.E.	d ± S.E.	R^2	p-value	Mean	Std. Dev.
Noor									
F. arundinacea	Gompertz	46.4 ± 0.7	0.05 ± 0.00	76.317 ± 1.3	–	0.997	<0.001	0.9948	0.0032
	Logistic	45.9 ± 1.14	0.07 ± 0.01	85.370 ± 2.3	–	0.992	<0.001	0.9928	0.0038
	Verhulst	45.9 ± 1.14	0.07 ± 0.01	387.9 ± 309.3	–	0.992	<0.001	0.9928	0.0038
	Weibull	–0.04 ± 0.63	–46.9 ± 0.8	20680569.4 ± 200	–3.9 ± 0.2	0.998	<0.001	0.9958	0.0032
	Richards	47.6 ± 0.52	0.07 ± 0.02	387.9 ± 422.9	0.96 ± 0.3	0.992	<0.001	0.9928	0.0038
A. desertorum	Gompertz	68.9 ± 0.4	0.05 ± 0.002	54.8 ± 0.5	–	0.999	<0.001	0.9993	0.0005
	Logistic	68.1 ± 1.2	0.07 ± 0.01	63.92 ± 1.7	–	0.995	<0.001	0.9975	0.0013
	Verhulst	68.1 ± 1.2	0.07 ± 0.01	91.2 ± 40.6	–	0.995	<0.001	0.9975	0.0013
	Weibull	0.8 ± 1.2	–69.5 ± 1.5	112881.9 ± 82237	–2.9 ± 0.2	0.998	<0.001	0.9988	0.0005
	Richards	243.8 ± 0.4	0.07 ± 0.001	91.2 ± 46.9	0.3 ± 0.01	0.995	<0.001	0.9975	0.0013
Ardabil									
F. arundinacea	Gompertz	52.411 ± 0.8	0.03 ± 0.001	120.5 ± 1.5	–	0.998	<0.001	0.9967	0.0021
	Logistic	50.6 ± 1.2	0.04 ± 0.004	135.8 ± 2.9	–	0.995	<0.001	0.9950	0.0026
	Verhulst	50.6 ± 1.2	0.04 ± 0.004	267.4 ± 135.9	–	0.995	<0.001	0.9950	0.0026
	Weibull	0.3 ± 0.6	–56.2 ± 2.4	1384140.7 ± 215.6	–2.9 ± 0.3	0.997	<0.001	0.9957	0.0021
	Richards	53.3 ± 2.5	0.04 ± 0.004	267.4 ± 161.5	0.9 ± 0.3	0.995	<0.001	0.9950	0.0026
A. desertorum	Gompertz	57.1 ± 0.7	0.1 ± 0.004	66.7 ± 0.8	–	0.998	<0.001	0.9940	0.0046
	Logistic	56.3 ± 1.1	0.1 ± 0.01	73.1 ± 1.43	–	0.994	<0.001	0.9917	0.0035
	Verhulst	56.3 ± 1.1	0.1 ± 0.01	1346.8 ± 1331.2	–	0.994	<0.001	0.9917	0.0035
	Weibull	–0.18 ± 0.3	–58.5 ± 0.4	23987665.03 ± 1438	–4.1 ± 0.1	0.999	<0.001	0.9950	0.0036
	Richards	99.7 ± 14.7	0.1 ± 0.02	1346.6 ± 223425	0.0564 ± 5.6	0.994	<0.001	0.9917	0.0035

tained from the Weibull model (11.28). Thus, out of the five models, the Gompertz gave more succesful results in three out of four cases, as the AICc values were lower (Table 2).

Final seedling emergence and the number of degree-days to reach 50% of the final emergence percentage was calculated and compared for each site and species (Table 3) according to the selected models. The results showed no significant effect on site conditions ($F = 1.14$; d.f.: 1, 12; $p = 0.317$) but significant differences between species ($F = 27.92$; d.f.: 1, 12; $p < 0.001$) in the final emergence percentage. Interaction between site and species was also significant ($F = 7.06$; d.f.: 1, 12; $p = 0.029$), indicating that in the humid-warm site (Noor), wheatgrass total emergence was higher that observed in fescue, but there were no significant differences between species in dry-temperate conditions (Figure 3a). Results also showed significant differences between species in seedling emergence dynamics ($F = 11.36$; d.f.: 1, 12; $p = 0.009$), while no differences were observed between sites ($F = 2.10$; d.f.: 1, 12; $p = 0.185$), with interaction being non-significant ($F = 1.91$; d.f.: 1, 12; $p = 0.204$). Thus, emergence was faster in tall fescue than in wheatgrass (Figure 3b).

Table 2. Model selection by using the second-order Akaike Information Criterion (AICc) of seedling emergence models of both species and in the two sites studied

Species	Model	N	RSS	K	AICc
Noor					
F. arundinaceae	Gompertz	10	11.265	5	26.19
	Logistic	10	31.575	5	36.50
	Verhulst	10	31.575	5	36.50
	Weibull	10	4.871	6	32.81
	Richards	10	31.575	6	51.50
A. desertorum	Gompertz	10	4.499	5	17.01
	Logistic	10	39.807	5	38.81
	Verhulst	10	39.807	5	38.81
	Weibull	10	40.625	6	40.62
	Richards	10	39.807	6	53.81
Ardabil					
F. arundinaceae	Gompertz	11	6.762	5	16.65
	Logistic	11	22.633	5	29.94
	Verhulst	11	22.633	5	29.94
	Weibull	11	11.269	6	33.27
	Richards	11	22.633	6	40.94
A. desertorum	Gompertz	11	13.289	5	24.08
	Logistic	11	40.848	5	36.43
	Verhulst	11	40.848	5	36.43
	Weibull	11	1.528	6	11.29
	Richards	11	40.849	6	47.43

Table 3. Analysis of variance of final seedling emergence percentage and number of degree-days it takes to reach 50% of the final emergence percentage ($E_{50\%}$) from two field experiments

	Type III Sum of squares	d.f.	Mean square	F value	Significance
Final emergence					
Corrected model	791.8	3	263.9	12.04	0.0025
Intercept	38,250.5	1	38,250.5	1,745.14	<0.0001
Site	24.9	1	24.9	1.14	0.3172
Species	612.0	1	612.0	27.92	0.0007
Site × Species	154.8	1	154.8	7.06	0.0289
Error	175.3	8	21.9		
Total	39,217.7	12			
Corrected Total	967.1	11			
$E_{50\%}$					
Corrected model	1,925.3	3	641.8	5.12	0.0288
Intercept	82,430.8	1	82,430.8	658.23	<0.0001
Site	263.5	1	263.5	2.10	0.1850
Species	1,422.5	1	1,422.5	11.36	0.0098
Site × Species	239.3	1	239.3	1.91	0.2042
Error	1,001.8	8	125.2		
Total	85,357.9	12			
Corrected Total	2,927.1	11			

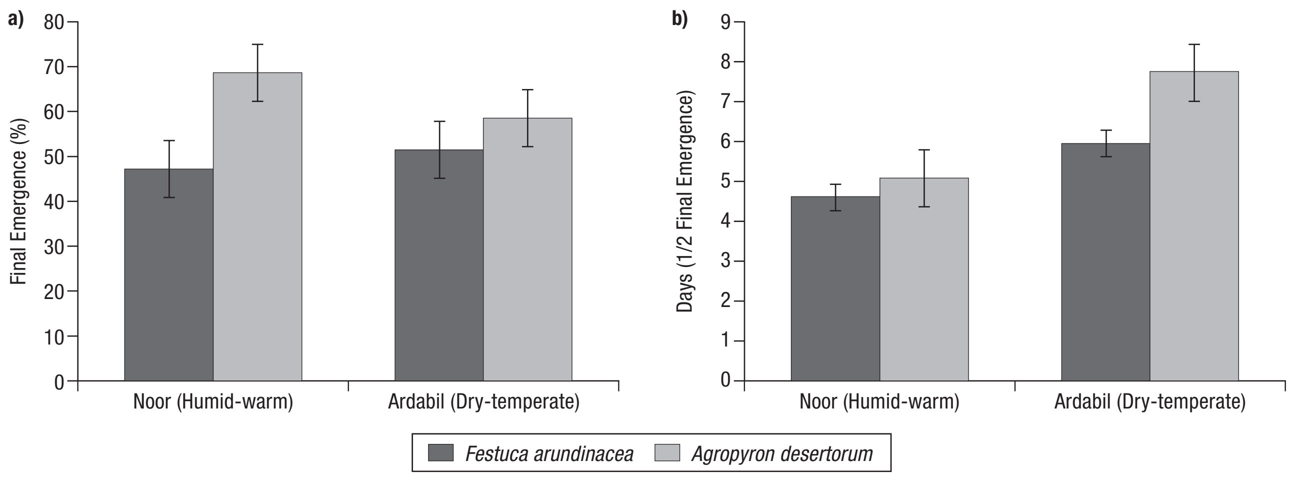

Figure 3. Seedling emergence of fescue and wheatgrass in the two sites studied in Iran (Noor and Ardabil, with humid-warm and semiarid-temperate climates, respectively) during the year 2008. Vertical lines represent 95% confidence intervals. a) Final seedling emergence; b) number of days it takes to reach 50% of total emergence.

Discussion

Despite their importance as agricultural forage species around the world, quantitative information about temperature effects on seedling emergence in tall fescue (*Festuca arundinacea*) and wheatgrass (*Agropyron desertorum*) is scarce (Gazanchian *et al*., 2006).

The ability to predict seedling emergence could enhance crop management through facilitating the implementation of more effective weed control strategies by optimizing the timing of weed control (Leblanc *et al*., 2004; Myers *et al*., 2004). The use of models to determine weed control strategies is becoming increasingly relevant for growers because of current pressure to reduce chemical inputs or adopt non-chemical methods (Grundy *et al*., 2000).

In other species, several mathematical models have been developed that predict seedling emergence with some success. Thus, Mohanty & Painuli (2004), in a comparison of three models (Gompertz, logistic and monomolecular models) on rice influenced by different tillage and residual management found that the Gompertz model gave the best fit. On the other hand, Haj Seyed Hadi & González-Andujar (2009) demonstrated that there were no significant differences in curve and there was only a slight difference in the parameter estimations for logistic and other emergence models, including the Gompertz, general logistic and genetic algorithm. In our study, the Gompertz model gave the most satisfactory results in three out of the four conditions analysed. Following this, our results partially agree with Mohanty & Painuli (2004), who reported that the Gompertz model was deemed to provide a better fit than the other models for rice seedling emergence.

Using the selected models, we demonstrated that in humid-warm conditions, wheatgrass total emergence was higher than that observed in fescue, but emergence was faster in tall fescue than in wheatgrass both in humid-warm and semiarid conditions. Rapid emergence of vigorous seedlings leads to high grain yield potential by shortening the time from sowing to complete ground cover, allowing the optimum canopy structure to be established, which minimises interplant competition, maximises crop yield, and provides plants with time and spatial advantages to compete with weeds (Soltani *et al*., 2001). Gan *et al*. (1992) reported that plants that emerge early contribute more to crop yield than those that emerge later. Thus, desirable crop yields are achieved by providing seeds with an environment that encourages early germination and emergence; therefore, tall fescue can be proposed as a more suitable species for both types of climate.

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