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RESEARCH ARTICLE

Seedling emergence and herbage yield of summer-active tall fescue sown at different times and sowing depths

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Abstract

Background: Tall fescue is sensitive to sowing depth and, in the Pampas region of Argentina, its sowing is often delayed from autumn (average air temperature 18.5°C) to winter (average air temperature 10.0°C). Since tall fescue is sensitive to the sowing depth, and temperature determines the emergence period, this study aimed to evaluate the effect of sowing depth at different times on seedling emergence and herbage yield.

Methods: Two field experiments were carried out in Pergamino, Buenos Aires province, Argentina, to evaluate a summer-active tall fescue at two sowing times and five sowing depths. The emergence of seedlings and the herbage yield in the year of sowing were determined.

Results: Seedling emergence was maximal when sown at 1.2–1.5 cm depth and at 230 growing degree days (GDD) in early autumn and 257 GDD in winter. In both years and sowing seasons, herbage yield was positively related to the number of seedlings at maximum emergence.

Conclusions: No differences in seedling emergence were observed between the autumn and winter sowings, and the emergence of tall fescue was well explained by the thermal time. The concept of "critical depth" was determined as the sowing depth at which the greatest seedling emergence and forage yield are achieved.

KEYWORDS

herbage yield, no-till sowing, seedling emergence

INTRODUCTION

Tall fescue (*Schedonorus arundinaceus* (Schreber) Dumort; syn. *Festuca arundinacea Schreber*; syn. *Lolium arundinaceum* (Schreber) S.J. Darbyshire; syn. *Schedonorus phoenix* (Scop.) Holub) is the most important temperate grass in the humid pampas of Argentina, with an ecological niche covering an area of 235 000 km^2 (Scheneiter et al., 2015).

Although it has been widely demonstrated that the way to ensure the establishment of forage species with smaller seeds is shallow sowing, the optimal sowing depth differs between forage species, environments, and soil conditions (Andrews et al., 1997; Brock, 1973; Reaside et al., 2012; Thom et al., 2011). Tall fescue is a species with particular requirements for successful establishment. According to previous studies, natural reseeding (Hume & Barker, 1991) or broadcast seeding without covering the seed after applying glyphosate herbicide results in poor seeding efficiencies (Galizzi et al., 2003). When broadcast seeding is conducted with soil removal, seedling emergence increases slightly as compared with seeding without covering the seed. Shallow sowing (0–0.5 cm) of this species results in poor seedling emergence (Brock, 1973; Charles et al., 1991a; Raeside et al., 2012). On the other hand, sowing at depths greater than 3.0 cm has also been shown to result in poor seedling emergence (Brock, 1973; Porter et al., 1993).

Several studies on different forage species have shown a positive relationship between seed weight and initial seedling growth (Hill, Pearson, et al., 1985; Jones et al., 1995). Andrews et al. (1997) suggested that the increase in emergence with heavier seeds is due to their greater width of the coleoptile and the mesocotyl, which results in greater strength to emerge. Additionally, it has been observed that, among temperate perennial species, tall fescue has a slow initial growth compared to perennial ryegrass (*Lolium perenne* L.) (Braun et al., 2023; Brock, 1973) and phalaris (*Phalaris aquatica*, L.) (Hill, Kay, et al., 1985), both with lower seed weight than tall fescue. Therefore, given the low weight of the seeds of forage species, and the particular slow seedling development of tall fescue, its successful establishment is sensitive to sowing depth.

With adequate moisture, temperature is the main factor determining the germination and emergence of temperate grasses. For tall fescue, Butler et al. (2017) found that maximum germination occurs at temperatures ranging from 15°C to 25°C. Further, the optimal temperature for germination and emergence may differ between tall fescue ecotypes: cultivars with summer dormancy perform better at lower temperatures than summer-active cultivars. In the north of the humid Pampas region, Bertin et al. (1990) found that sowing in May, with a mean air temperature of 13.4°C, led to a greater initial development with a summer-active cultivar than with a cultivar selected from genotypes with summer dormancy. Also, Reed et al. (2008) reported higher seedling vigor in the establishment of summer-active ecotypes than that of ecotypes with summer dormancy.

In the Pampas region of Argentina, it is recommended to sow pastures in early autumn when the temperature and humidity of the soil favor a rapid emergence of the seedlings (Mattera et al., 2019). However, in years with unfavorable soil moisture conditions at that time or when the harvest of the previous crop is delayed beyond early autumn, sowing can be done until late autumn or early winter. In this regard, some studies in the north of the Pampas region have not found differences in the establishment of tall fescue with fall or winter sowing (Zerpa et al., 2000).

Interestingly, Charles et al. (1991b) found that, under a controlled environment, the effect of sowing depth on the seedling emergence of tall fescue and white clover is more apparent at low temperatures. In their experiment, at 24°C and sowing depths of 1.5, 3.0, and 4.5 cm, the days to maximum emergence were similar but, at 9°C and sowing depths of 3.0 and 4.5 cm, emergence was delayed. In this regard, there is no local information on the effect of sowing depth in periods with different temperatures on the emergence of tall fescue seedlings. This could lead to more precise recommendations regarding sowing depth according to the sowing season.

The germination and emergence of forage species are conveniently explained by the thermal time. Lonati et al. (2009) consider that the use of this variable to predict the germination and emergence of a particular species is a simple, low-cost method that can be extrapolated to different sowing dates and sites.

The method commonly used to sow pastures of different forage species is no-till sowing. In years with water deficit, during the early establishment of a pasture, no-till sowing is a more efficient method to establish the pasture because the non-disturbance of the soil and the presence of a mulch allow higher water content in the first centimeters of soil than the methods that the soil to prepare the seedbed (Moreno et al., 2015).

According to the above, in the present study, we predicted that seedling density and herbage yield of no-till sown tall fescue would display an interaction between sowing depth and sowing time. Thus, to test this hypothesis, we performed experiments to evaluate the effects of the time and depth of sowing on seedling emergence and herbage yield in the establishment year of tall fescue sown with no-till sowing.

MATERIALS AND METHODS

Study site

Two experiments were carried out at the Pergamino Agricultural Experimental Station of the National Institute of Agricultural Technology (INTA), Buenos Aires, Argentina (33°57′26″ S, 60°33′59″ W; 68 m a.s.l.). The first experiment was carried out in 2020 and the second experiment was carried out in 2021. Each experiment investigated two sowing dates and five sowing depths arranged in a randomized complete block design ($n = 4$). In 2020, no-till sowing of tall fescue was carried out after a foxtail millet pasture, whereas, in 2021, it followed an old and degraded alfalfa–tall fescue pasture. The soil of the experimental site is a Typic Argiudoll with no limitations for pasture growth (organic matter 2.82%, available P 35.2 mg kg^{-1}, pH 5.4, electrical conductivity 0.19 dS m^{-1}). In each year, the experiments were carried out on even ground and a structurally homogeneous soil, with a soil bulk density of 1.26 g cm^{-3}.

Factors studied and agronomic management of the experiments

Two sowing times were considered: autumn and winter. In 2020, sowing was done on March 23 (autumn) and July 6 (winter), whereas in 2021, sowing was done on April 16 (autumn) and July 8 (winter). The sowing depth factor had five levels: 1.2–1.5, 2.5–2.7, 3.4–3.9, 5.1–5.5, and 6.4–6.8 cm. Immediately after sowing, in each treatment, the depth to which the sowing machine penetrated into the soil was checked. To do this, in 10 places of each of two repetitions, the soil was carefully removed from the top of the sowing line and the distance (cm) from the bottom of the furrow to the soil surface was measured with a ruler. The depths effectively achieved in the field were ~0.35 cm deeper in 2020 than in 2021, possibly due to greater soil compaction after an old pasture in 2021 compared to an annual crop in 2020.

Before sowing, the experimental site was sprayed with 2 L ha^{-1} of glyphosate (soluble concentrate, 66.2% a.i.). After sowing, 0.5 L ha^{-1} of Flumetsulam (concentrated suspension, 12% a.i.) was applied for the post-emergence control of spontaneous broadleaf species.

The sowing was done with a no-till seeder, model Crucianelli Pionera 2717®, which has 27 coulters 17.5 cm apart, a 45.7 cm-diameter 28-wave turbo blade, a double furrow disc, double-depth leveling wheels, seed contact wheels, and double-cast capping wheels (Figure S1). The sowing unit is mounted on a deformable parallelogram, with a double fertilization system and continuous variable boxes to adjust the sowing density. The seed distribution and out by a fluted roller system with a gearbox to select the target sowing rate.

In each block (i.e., each sowing time and year), the five sowing depth treatments evaluated were randomly distributed in the 27 sowing lines as follows: three treatments with five sowing lines each in the central part of the seeder and two treatments with six sowing lines at each side of the seeder. The set of rows of each treatment was considered as an experimental unit (Figure S2a). After sowing a block, treatments were reassigned in the 27 planting lines as mentioned above using the sowing depth selector. A space of 15 m was left between the blocks to allow for re-randomization of the treatments in the seeding machine (Figure S2b). Thus, in each block, the experimental unit consisted of five or six sowing lines 17.5 cm apart with a length of 30.0 m (26.5 or 31.5 m^2). The sampling area was the central 17.5 or 21 m^2 of each experimental unit where the seeder worked at the recommended speed (5–7 km h^{-1}).

The tall fescue used was the cultivar "Brava INTA," a summer-active ecotype, widely adapted to the region. The germination percentage was 85% in 2020 and 89% in 2021. The weight of 1000 seeds, treated with fungicide and insecticide and covered by a layer of calcium carbonate, was 3.05 g in both years. Based on the above, the sowing rate was adjusted to 500 viable seeds m^{-2}.

Number of seedlings

After sowing, the number of seedlings was counted weekly. Each emerging and visible leaf was considered a seedling. For the autumn sowing, the count was made up to 4 weeks after sowing, while for the winter sowing, it was extended to 7 weeks. The end of the counting period was determined when the number of plants remained unchanged for 3 consecutive weeks. From then on, it was not possible to distinguish individual seedlings. In each plot, the seedlings were counted inside three fixed frames of 0.088 m^2 each (0.175 m × 0.5 m), randomly located in the central area of each plot. At each sampling site, the longest side of each frame was positioned over the sowing line. The number of seedlings that emerged in the three fixed frames was averaged and the density of seedlings per unit area was calculated for each plot as seedlings m^{-2}.

Herbage yield

In each year and experiment, herbage yield was measured between the sowing date and December of the sowing year. The first cut was made when the canopy of the treatments with the highest seedling density covered the ground, and the rest of the cuts were made at 550 growing degree days (GDD). The base temperature (t_b) was set at 4.5°C. This resulted in three to four cuts in the autumn sowings and two to three cuts in the winter sowings. Each cut was made on a surface of 0.53 m^2 (0.35 m × 1.5 m) in the central part of each plot with a cordless hand mower (Stihl HAS 26®) at a height of 7 cm. The samples were taken to the laboratory, weighed, and then a 200-g subsample was dried in an oven with forced-air circulation at 65°C to determine the percentage of dry matter (DM). The resulting data were used to estimate the DM yield per hectare. After sampling, the experimental area was harvested with a self-propelled forage harvester (Wintersteiger Classic®) at a height of 7 cm and the harvested forage was discarded.

GDD

After sowing, GDD was calculated weekly through the seedling emergence period. According to Moott et al. (2000), the base temperature and the GDD for the emergence of several forage species, including tall fescue, are different depending on whether they are computed based on the soil surface or the air temperature. These authors estimated a coefficient of determination of 0.82 between the soil temperature and the mean air temperature. For the calculation of the GDD in this experiment, the average air temperature was used since these data are relatively easy to obtain in many sites of the humid Pampas region. The t_b was set at 4.5°C according to that reported in several studies (Butler et al., 2017; Charles et al., 1991a; Moot et al., 2000).

According to the above, and considering the number of seedling counts, four GDD were determined for the autumn sowing and six GDD for the winter sowing, since for winter, the first count was rejected because no plants had emerged yet. Because at both sowing times, there was a significant and high correlation between the GDD determined in 2020 and that determined in 2021 (autumn $GDD_{2021} = 32.14 + 0.92\,GDD_{2020}$, $p < 0.01$, $R^2 = 1.00$; winter $GDD_{2021} = -1.51 + 1.05\,GDD_{2020}$, $p < 0.001$, $R^2 = 1.00$), an average of both years was used for the statistical analysis of the autumn and winter sowings (Table S1).

Seedling development

In order to observe the development of seedlings at the different sowing depths evaluated in the field experiment, a simple test was carried out under controlled conditions. For this purpose, two 15-cm deep, 15-cm wide, and 45-cm long pots were each subdivided into five 15-cm deep, 15-cm wide, and 9-cm long segments. Then, in each of the segments of each pot, 50 seeds were sown at depths of 1.5, 3.0, 4.0, 5.5, and 7.0 cm. Soil extracted from the upper 10 cm was used as a substrate. The pots were kept outdoors and watered regularly. After reaching 210 GDD, the seedlings were carefully extracted and washed. The lengths of the first leaf, the coleoptile plus the non-emerged leaf, and the seminal root were measured with a ruler for 20 seedlings from each depth.

Temperature and rainfall in the experimental site

Monthly rainfall was lower than the long-term average between May and August and in November 2020 and June, September, and October 2021. December was dry in both years (Table S2). The mean air temperature during the experimental period in March and August 2020 and April 2021 was ≥2°C higher than the long-term average (Table S2).

Statistical analysis

To evaluate the effect of sowing depth on the number of seedlings that emerged throughout the GDD levels and, at the same time, evaluate whether it was statistically different in the 2 years of study, an analysis of variance (ANOVA) was carried out using linear mixed models. The linear mixed-models approach allows modeling the variance–covariance matrix of the errors, when the assumptions about the errors are not met. Each sowing time was evaluated separately because the weekly GDD records were different between autumn and winter.

The effect of sowing depth on herbage yield (added to the effect of sowing year and time and the double and triple interactions) was evaluated through ANOVA using linear mixed models. Multiple comparisons for the significant effects were performed using Fisher's LSD test.

Finally, the relationship between the number of seedlings at maximum emergence and herbage yield was evaluated through simple linear regression analysis.

All statistical analyses were performed using Infostat software (Di Rienzo et al., 2020).

RESULTS

Seedling emergence

In autumn, seedling emergence differed between the 2 years of the experiment, the sowing depth, GDD, and all their interactions. In winter, however, year × GDD and year × depth × GDD interactions were not significant (Table 1).

Autumn

In autumn, when evaluating the effect of sowing depth, GDD, and the year of study on the number of emerged seedlings, a significant year × planting depth × GDD interaction was detected ($p = 0.034$, Table 1). Multiple comparisons for this interaction are shown separately in Figures 1 and 2 for 2020 and 2021, respectively.

In 2020, at 136 GDD, the number of seedlings per m^2 was higher at 1.2–1.5 cm than at the other depths evaluated, whereas in 2021, there were no differences between treatments. Furthermore, in 2020, from 230 to 373 GDD, the treatment at 2.5–2.7 cm had a greater number of plants per m^2 than that performed at 3.4–3.9 cm, while in 2021, no differences were detected between these two treatments. Based on the above, the results are presented for each year separately.

In 2020, the treatment at 1.2–1.5 cm had the highest number of seedlings per m^2 at all the GDD, while that at 2.5–2.7 cm had intermediate values and those at 3.4–3.9, 5.1–5.5, and 6.4–6.8 cm had the lowest (Figure 1). From 230 and up to 373 GDD, there were no differences in the seedling number in any of the treatments.

In 2021, the treatment at 1.2–1.5 cm had a higher number of seedlings per m^2 than the other sowing depth treatments, except at 136 GDD. The treatments at 2.5–2.7 and 3.4–3.9 cm had intermediate numbers of seedlings per m^2 and those at 5.1–5.5 and 6.4–6.8 cm had the lowest numbers of seedlings per m^2 (Figure 2). Between 230 and 373 GDD, the number of emerged plants remained constant for each treatment.

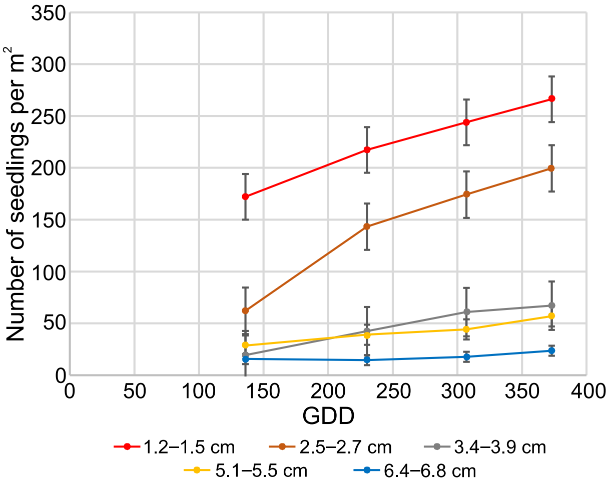

FIGURE 1 Least squares means and standard errors of the number of tall fescue seedlings sown with no-till sowing, in autumn 2020, at five sowing depths and four GDD after sowing. The bars at each point indicate the standard error of the mean (LSD = 50.8). GDD, growing degree days; LSD, least significant difference.

TABLE 1 *F*-values and *p*-values and *F*-test numerator degrees of freedom (*df*) of the factors affecting the number of seedlings that emerged.

	Autumn			Winter		
Effect	***F***	***p***	***df***	***F***	***p***	***df***
Year	41.44	<0.001	1	7.74	0.006	1
Depth	253.95	<0.001	4	342.71	<0.001	4
GDD	75.83	<0.001	3	208.42	<0.001	5
Year × Depth	9.35	<0.001	4	9.23	<0.001	4
Year × GDD	18.80	<0.001	3	0.84	0.526	5
Depth × GDD	9.93	<0.001	12	20.50	<0.001	20
Year × Depth × GDD	1.96	0.034	12	1.17	0.281	20

Abbreviation: GDD, growing degree days.

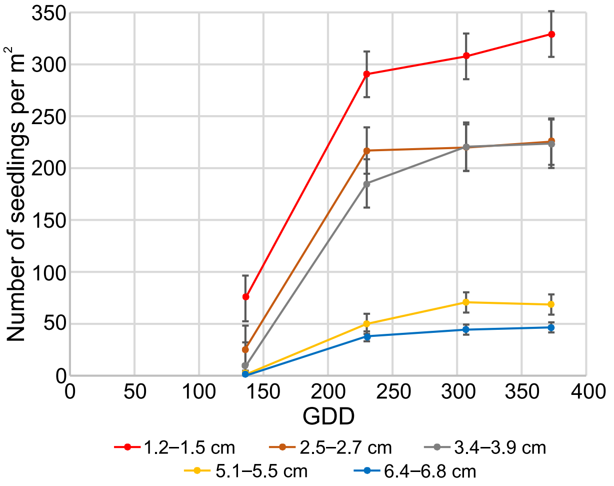

FIGURE 2 Least squares means and standard errors of the number of tall fescue seedlings sown with no-till sowing, in autumn 2021, with five sowing depths at four GDD after sowing. The bars at each point indicate the standard error of the mean (LSD = 50.8). GDD, growing degree days; LSD, least significant difference.

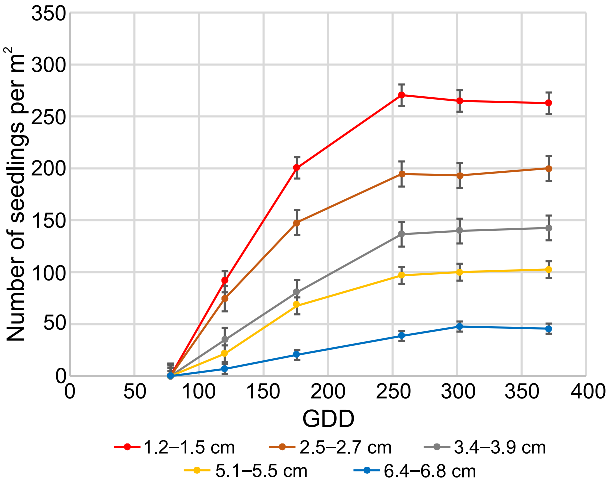

FIGURE 4 Least squares means and standard errors of the number of tall fescue seedlings sown with no-till sowing, in winter, at five sowing depths and six GDD. The bars at each point indicate the standard error of the mean (LSD = 28.0). GDD, growing degree days; LSD, least significant difference.

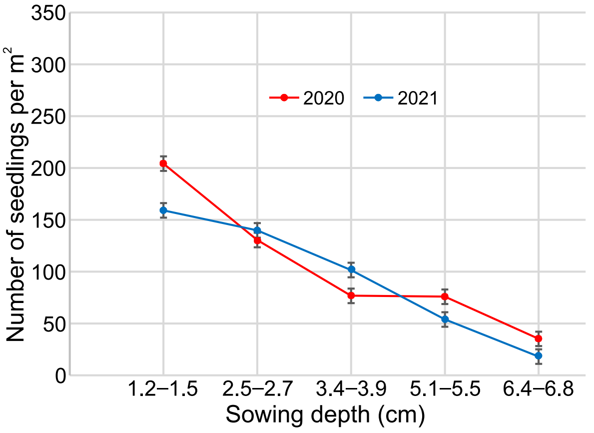

FIGURE 3 Least squares means and standard errors of the number of tall fescue seedlings sown with no-till sowing, in winter, at five sowing depths in two years (2020 and 2021). The bars at each point indicate the standard error of the mean (LSD = 16.1). LSD, least significant difference.

Winter

The number of seedlings per m^2 was subject to year × depth ($p < 0.001$) and depth × GDD ($p < 0.001$) interactions (Table 1). The number of seedlings decreased between 1.2–1.5 and 6.4–6.8 cm, except in 2020, when 3.4–3.9 and 5.1–5.5 cm had the same values. In 2020, compared to 2021, the number of seedlings per m^2 was higher with the treatments conducted at 1.2–1.5, 5.1–5.5, and 6.4–6.8 cm, whereas the opposite occurred with the treatment at 3.4 cm × 3.9 cm, and there were no differences between years at 2.5–2.7 cm (Figure 3).

The first emerged seedlings in all treatments were observed at 120 GDD and the maximum values of seedlings per m^2 for each depth were reached at 257 GDD. From these values, and up to 371 GDD, the number of seedlings at each sowing depth remained unchanged. In all treatments, as sowing depth increased, the number of seedlings per m^2 decreased (Figure 4).

On evaluating the number of seedlings at 1.2–1.5 cm, no significant effect of either the year or the sowing time was found. Then, the linear relationship between GDD and the number of emerged seedlings was evaluated (seedlings per m^2 = GDD × 1.08; R^2: 0.93, $p < 0.001$). This analysis showed that 50% of the maximum number of seedlings (262 seedlings m^{-2}) was reached at 121 GDD.

Herbage yield

The interactions between year and sowing time, year and sowing depth, and sowing time and sowing depth were significant ($p < 0.001$). In 2020 and 2021, the herbage yield was greater in the autumn sowing than in the winter sowing. In 2020, at both sowing times, herbage yield was greater at 1.2–1.5 cm (Table 2). In 2021, in autumn, sowing at 1.2–1.5 cm yielded more herbage than that at 3.4–3.9, 5.1–5.5, and 6.4–6.8 cm. In winter, sowing at 1.2–1.5, 2.5–2.7, 3.4–3.9, and 5.1–5.5 cm yielded more herbage than sowing at 6.4–6.8 cm, which produced a significantly lower value.

The relationship between the number of seedlings at maximum emergence (SME) and herbage yield (HY) was satisfactorily explained by a linear model in both 2020 (HY = SME × 19.62; R^2: 0.92, $p < 0.001$ and HY = SME × 4.80, R^2: 0.93, $p < 0.001$ for autumn and winter, respectively) and 2021 (HY = SME × 29.67, R^2: 0.83, $p < 0.001$ and HY = SME × 13.38, R^2: 0.86, $p < 0.001$, for autumn and winter, respectively). The models obtained indicate that for every 50 seedlings that emerged at 372 GDD, herbage yield in the establishment year increased by 981 and 240 kg DM ha^{-1} and by 1484 and 669 kg DM ha^{-1} with the autumn and winter sowings, in 2020 and 2021, respectively.

Seedling development

After germination, tall fescue seeds developed the seminal root and, shortly after, the coleoptile with

TABLE 2 Herbage yield of tall fescue sown with no-till sowing, in autumn and winter, at five sowing depths in 2020 and 2021 (kg DM ha^{-1}).

2020				2021			
Depth (cm)	**Autumn**	**Winter**	**Depth average**	**Depth (cm)**	**Autumn**	**Winter**	**Depth average**
1.2−1.5	5247a	1412cd	3329D	1.2−1.5	8520a	3015d	5767A
2.5−2.7	3218b	1020def	2119E	2.5−2.7	7745ab	2633d	5189AB
3.4−3.9	1985c	587ef	1286F	3.4−3.9	6961b	2358d	4561BC
5.1−5.5	1623cd	485f	1054F	5.1−5.5	5843c	2162d	4101C
6.4−6.8	1386cde	328f	857F	6.4−6.8	3093d	902e	1998E
Time average	2692B	766D		Time average	6432A	2214C	

Note: For 2020 and 2021, different lowercase letters in columns indicate differences at $p < 0.05$ in herbage yield mean for the interaction between sowing time and sowing depth. Different capital letters in the row "Time average" indicate differences at $p < 0.05$ in herbage yield for the interaction between year and sowing time. Different capital letters in the columns "Depth average" indicate differences at $p < 0.05$ in herbage yield for the interaction between year and sowing depth.

Abbreviation: DM, dry matter.

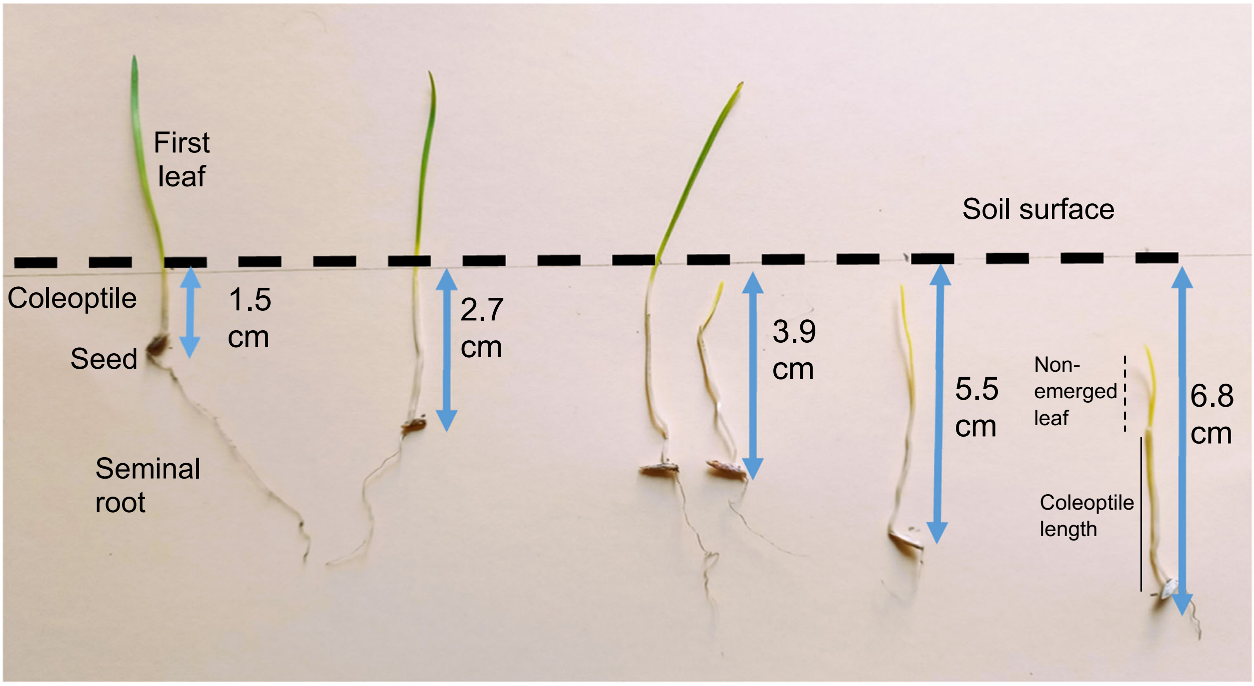

FIGURE 5 Development, at 210 GDD, of the first leaf, coleoptile, seminal root, and non-emerged leaf of tall fescue seedlings sown at five different depths under controlled conditions. LSD, least significant difference.

TABLE 3 Seedling emergence (%), first leaf, coleoptile + non-emerged leaf, and seminal root lengths (mm) of emerged and non-emerged seedlings of tall fescue sown at five sowing depths (cm).

		Emerged seedlings			Non-emerged seedlings	
Depth	**Seedling emergence**	**First leaf length**	**Coleoptile length**	**Seminal root length**	**Coleoptile length + Non-emerged leaf**	**Seminal root length**
1.5	79	42	14	27	–	–
2.7	54	37	30	23	–	–
3.9	30	35	39[a]	22	42	15
5.5	0	–	–	–	47	13
6.8	0	–	–	–	43	10
	p	<0.09	<0.01	<0.09	ns	ns
	LSD Fisher	–	6	–	–	–

Abbreviations: LSD, least significant difference; ns, not significant.

[a] Coleoptile length + Non-emerged leaf.

the first leaf enclosed within it (Figure 5). There was no seedling emergence when seeds were sown at 5.5 and 6.8 cm depths (Table 3). Seedling emergence and coleoptile length were ranked by sowing depth as 1.5 > 2.7 > 3.9 cm. Seedlings sown at 1.5 cm showed a tendency to have a longer first leaf and seminal root than seeds sown at 2.7 and 3.9 cm depths (Table 3).

As sowing depth increased beyond 3.9 cm, the development of the emerging seedling was insufficient to reach the soil surface (Figure 5). When sown at 3.9 cm depth, only 30% of the seedlings reached the soil surface. Seeds sown at 2.7 cm depth reached the soil surface but, compared with those sown at 1.5 cm depth, they showed a longer coleoptile.

DISCUSSION

The sowing depth affected the number of tall fescue seedlings that emerged, whereas the sowing time had no effect. According to previous studies, broadcast sowing or shallow sowing (0.0–0.5 cm) causes failures or low emergence percentages (Charles et al., 1991a; Galizzi et al., 2003; Raeside et al., 2012) and, with widely used seeders, many of the seeds would remain uncovered. On the other hand, if the seed is placed deeper (≥3.0 cm), seedling emergence is poor (Jones et al., 1996; Porter et al., 1993; Sanderson & Elwinger, 2004). This is consistent with that observed in winter in our experiment, when the percentage of seedling emergence decreased steadily as the seed was sown deeper. In autumn, a different behavior was detected in the 3.4–3.8 cm treatment between the 2020 and 2021 sowing. In 2020, the number of plants that emerged with the treatment at 2.5–2.7 cm was greater than that treatments at 3.4–3.9, 5.1–5.5, and 6.4–6.8 cm. In 2021, the treatments at 2.5–2.7 and 3.4–3.9 cm did not differ from each other and had greater seedling emergence than those at 5.1–5.5 and 6.4–6.8 cm. This discrepancy between the 2 years could be due to the different sowing depths since, in 2020, the treatment at 3.4–3.9 reached 3.9 cm depth (1.2 cm deeper than that at 2.5–2.7), while in 2021, it reached 3.4 cm (0.9 cm deeper than that at 2.5–2.7 cm).

The growth during seedling emergence is dependent on the amount of starch reserves in the seed, which in turn depends on the size of the seed. Consequently, in species with small seeds, the potential elongation of the coleoptile is limited (Robson et al., 1988). In tall fescue, Brock (1973) observed that the length of the hypocotyl–mesocotyl assembly increases with sowing depth and failure in seedling emergence is due to insufficient endosperm reserves to support greater elongation of this assembly (Jones et al., 1995). Some experiments evaluating a range of temperate grass species at different depths (Porter et al., 1993; Sanderson & Elwinger, 2004) have shown some emergence at depths of 6.0 cm. However, our experiment under controlled conditions showed that seeds placed at depths of 5.5 and 6.8 cm failed to emerge. A possible explanation for this discrepancy can be found in the performance of the seeder machine in the field. In this regard, fine-grain seeders place the seed at the bottom of the furrow through a continuous seed delivery system, where the uniformity of the surface, the structure of the soil, and the working speed of the seeder affect the spatial location of the seed within the sowing furrow, resulting in a variable range of depths along the furrow (Woodman et al., 1990). Consequently, with shallow sowing, some seeds remain on the surface of the soil with little chance of germination, while, with sowing depths of 2.5–2.7 cm or deeper, emergence depends on the percentage of seeds deposited at lesser depth (Figure 6).

An additional factor to take into account is the soil bulk density. For example, the upper 5 cm of the soil at the experimental site has a soil bulk density of 1.26 Mg m^{-3} (Ferreras et al., 2007), a value that, compared to less dense soils, impairs the emergence of tall fescue, if the sowing depth is 3 cm or more (Charles et al., 1991b). However, the possibility of increasing the sowing depth in soils with low bulk density would have a limit of approximately 3 cm imposed by the small size of the seed (and its consequent low amount of reserves), the low capacity for remobilization of reserves shown by tall fescue, and that the elongation of the coleoptile would not exceed 3 cm.

With sufficient moisture availability in the first few centimeters of soil, temperature is the main factor

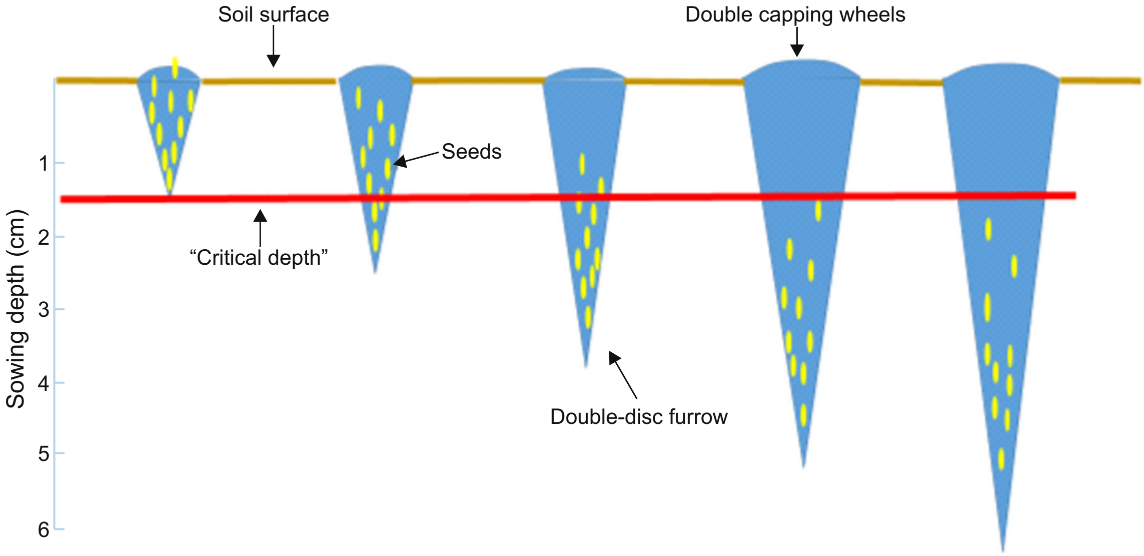

FIGURE 6 Schematic representation of a cross section of the sowing furrow with the spatial location of the seeds at different sowing depths. The red line indicates the sowing depth below which seedling emergence decreases with increasing seed depth.

determining the rate and percentage of emergence of temperate perennial grasses. In this work, the limited rainfall that occurred between May and August 2020 (~14% of the historical average) did not alter the emergence of the seedlings sown in winter. This could be because no-till sowing systems conserve soil humidity. Also, in the 2 months before sowing, 308.8 mm of rain fell, 39.8% more than the historical average, and this reduced the risk of temporary drying of the upper few centimeters of the soil and its effect on seedling emergence. The latter is important since germination depends more on variations in conditions than on the total amount of water received by the seed during imbibition and absorption (Jiang & Su, 2018).

Under controlled conditions, the optimum temperature for maximum emergence of tall fescue is 15–25°C for 14 days. However, at 10°C, summer-active ecotypes have significantly decreased germination (Butler et al., 2017). In this regard, Charlton et al. (1986) found that summer-active tall fescue had a slow germination rate compared to other temperate perennial grasses, but that with a regimen of 5/10°C (16/8 h light/dark), more than 75% germination was achieved at 29 days. In other research, Charles et al. (1991b) pointed out that germination failures in tall fescue occur when temperatures are below 9°C. In our experiment, the mean air temperature before reaching maximum emergence was 21.1°C and 17.8°C in the autumns of 2020 and 2021, respectively, and 10.6°C and 9.5°C in the winters of 2020 and 2021, respectively. Consequently, there were no restrictions to reaching maximum emergence within 2 weeks in autumn and 4 weeks in winter.

The results of the present study showed that maximum emergence was recorded simultaneously at the same GDD at all the sowing depths evaluated. This finding is in agreement with that reported by Peri et al. (2000), under controlled conditions. However, Charles et al. (1991b) observed that, with temperatures of 9°C, the first seedlings emerged between 13 and 17 days later (compared to the 1.5 cm depth) when sown at 3.0 and 4.5 cm, respectively.

The present results also showed that the effect of sowing depth on maximum plant emergence was marginally affected by the sowing time. Based on our data under non-limiting moisture conditions, maximum emergence of tall fescue with no-till sowing in autumn and winter is within a range of 230–257 GDD (t_b 4.5°C). Therefore, the chronological range can be conveniently condensed into thermal time without substantial differences between sowing times.

However, the thermal time requirement observed in this experiment was higher than that determined by Moot et al. (2000) under field conditions. For example, in our experiment, 50% of seedling emergence at 1.2–1.5 cm occurred by 121 GDD (t_b 4.5°C), whereas Moot et al. (2000) reported 94 GDD (t_b 5.1°C), although it should be taken into account that the method of recording the average daily temperature was different in the two experiments.

In the sowing year, variations in the sowing depth have a significant effect on the density of emerged seedlings and consequently on herbage yield. Most experiments on the sowing depth in tall fescue and other grasses have focused on seedling emergence and size, whereas few have focused on herbage yield. For example, Brock (1973) determined that herbage yield at 140 days after planting was greater when tall fescue was planted at 1.25 cm depth than at 2.5 cm. However, it must be taken into account that tall fescue has mechanisms of lateral expansion of plants through tillering and the development of short rhizomes (Brock et al., 1997), as well as a tiller size/density compensation mechanism (Scheneiter & Assuero, 2010), which could, over time and with adequate defoliation management, compensate for low plant density.

At this point, when sowing with a mean air temperature between 9.5°C and 21°C and in a soil with a bulk density of 1.26 g cm^{-3}, it is possible to define a "critical depth" for summer-active tall fescue. Under these conditions, the "critical sowing depth," below which seedling emergence and herbage yield in the first year significantly decrease with increased sowing depth, is between 1.2 and 1.5 cm.

AUTHOR CONTRIBUTIONS

María José Beribe: Formal analysis; software; visualization; writing–review and editing. **Pablo Barletta:** Methodology; data curation; writing–review and editing. **Jorge O. Scheneiter:** Conceptualization; funding acquisition; investigation; visualization; writing–original draft preparation; writing–review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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