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Effect of Rainfall Reduction and Competition on the Phenology of the Mediterranean Forage Perennial Legume *Bituminaria bituminosa* var. *albomarginata* cv. Lanza

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Keywords: climate change | flowering | Mediterranean systems | out-of-season forage

ABSTRACT

Tedera (*Bituminaria bituminosa* (L.) C.H. Stirt.) is a Mediterranean drought-tolerant species that shows potential as a forage perennial legume for Mediterranean livestock systems. This three-year study investigated the phenology of the newly developed variety of tedera (Lanza) in response to an annual 24% rainfall reduction and competition compared to alfalfa (*Medicago sativa* L.) in a typical Mediterranean environment of the Iberian Peninsula. Tedera showed early phenology for the reproductive stages from inflorescence emergence to ripening compared to alfalfa, with a long flowering period from early April to mid-May, overlapping with mature fruits. In general, tedera responded to a 24% reduction in rainfall with earlier inflorescence emergence and flowering, demonstrating plasticity to drier conditions. Competition affected the phenology through delayed start of inflorescence emergence and flowering, and especially by reducing the probability of plants reaching reproductive stages. Tedera exhibited overall later leaf shedding than alfalfa and even retained green leaves throughout the summer of the establishment year, whereas alfalfa shed its leaves in July. Low cold tolerance and competition from weeds affect the phenology of tedera and may limit its persistence. Further research and breeding efforts are needed to define suitable management strategies and ensure the provision of green forage during the summer season by this species, which may play a crucial strategic role in facing future, more arid scenarios in Mediterranean livestock systems.

1 | Introduction

Climate change poses important challenges to extensive crop-livestock systems (Ghahramani and Moore 2016). These will be especially important in Mediterranean areas where climate change is expected to exacerbate the already variable crop and grass production (Dono et al. 2016). Current climate change models forecast a reduction in annual precipitation between 4% and 22% in the Mediterranean basin according to the different emission scenarios (Cramer et al. 2020) and could reach 30% in the most arid regions (EURO-CORDEX 2023; European Environment Agency 2022). In addition, the variability of precipitation is expected to increase (Cramer et al. 2020). This will result in reduced and irregular forage availability in Mediterranean systems and increased summer feed gaps (Moore et al. 2009) due to earlier senescence of grasslands.

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Summary

- *Bituminaria bituminosa* var. *albomarginata* cv. Lanza (tedera) shows early phenology, especially for inflorescence emergence and flowering.
- Tedera showed earlier phenology under 24% rainfall reduction compared to control.
- Tedera maintained green leaves over the first summer but not the two following summers.
- Phenology and early summer weather may play an important role in the maintenance of green leaves over summer.
- Competition reduces the probability of reaching reproductive phenological stages.

These trends may also impact the adaptation of forage plants to the new climatic scenarios as some phenological traits are highly sensitive to climate changes (Cleland et al. 2006; Pérez-Ramos et al. 2013). It is therefore crucial to study the response of key phenological traits of forage plants to the forecasted changes in precipitation and temperatures. Strategies such as advancing reproduction and plasticity in response to drought may play an important role in the adaptation/acclimation of forage plants to increased aridity (Berger and Ludwig 2014; Daryanto et al. 2015). In this context, there is a need for research on candidate forage species with suitable characteristics to enhance the resilience of extensive crop-livestock systems under future climate change scenarios (Rognli et al. 2021). The research on this drought-tolerant candidate species is especially urgent in Mediterranean ecosystems due to their high sensitivity to climate change and its already patent effects on farm management (Dono et al. 2016; Nardone et al. 2010).

Bituminaria bituminosa (L.) C.H. Stirt, tedera by its local name, has been proposed as a candidate out-of-season perennial legume for Mediterranean livestock systems. This species is native to the Mediterranean Basin and Macaronesia where it is adapted to a wide range of environmental conditions. In the Canary Islands, there are three varieties that have been traditionally used to feed livestock: var. *albormarginata*, *crassiuscula*, and *bituminosa* (see Méndez et al. 1991). *Albomarginata* is especially adapted to water-limited conditions, being able to grow with less than 200 mm in Lanzarote Island (Martínez-Fernández et al. 2012). A breeding programme led by Australian and Spanish scientists has produced two cultivars with Plant Breeder's Rights: Lanza (Real 2016) and Palma (Real 2022a) based mainly on *albomarginata* genetics (Oldham et al. 2013; Real et al. 2014). Previous research has shown the drought tolerance of this species (Foster et al. 2015; Martínez-Fernández et al. 2012), its suitability for feeding livestock in Mediterranean environments in terms of forage production and quality, and animal performance (Oldham et al. 2013; Ventura et al. 2009; Raeside et al. 2012), and potential economic impact at farm level (Finlayson et al. 2012). Also, recent research has been compiled in an agronomic package to grow tedera (Real 2022b). However, the phenology of this species and its interaction with contrasting environmental and stand conditions has received less attention, especially for the newly developed varieties. Melis et al. (2018) studied some phenological traits of tedera and found important differences among varieties; for example, in the beginning of the flowering stage and seed production, which might have important implications for its persistence. Having information on the phenology of tedera is essential to fully understand its potential as an out-of-season forage in Mediterranean environments and to define suitable management strategies. In the case of the perennial forage legume *Medicago sativa* L. (alfalfa) for example, the regrowth and the balance between maximum yield and best forage quality are enhanced by harvesting during early flowering (Hycka 1993; Muslera Pardo and Ratera Garcia 1991). In addition, the persistence of perennial legumes depends on phenological traits and the adaptation of these traits to soil and weather conditions. For example, early flowering in spring in a location with frequent frost days can lead to frost damage in inflorescence buds and thus reduced seed production (Real 2023). Also, early spring heat waves can cause terminal drought and lead to severe forage and seed yield losses (Daryanto et al. 2015). In the latter case, early flowering is an important trait of forage legumes of Mediterranean areas prone to early onset of summer drought (Araújo et al. 2015; Berger and Ludwig 2014; Berger et al. 2017; Nadeem et al. 2019; Thomson et al. 1997). A recent review by Sollenberger and Kohmann (2024) highlighted the need for studies on the forage legume responses to climate change factors, which so far are scarce and mostly focused on alfalfa, and several *Trifolium* and *Lotus* species. Also, the phenology of forage legumes may be affected by stand conditions, such as competition from weeds, which is known to impact the establishment and persistence of tedera (Fernández-Habas et al. 2023; Raeside et al. 2012).

The expected role of tedera includes reducing the summer feed gaps and increasing the resilience of livestock farming systems to the reduction and variability of rainfall. To fulfil that role, traits such as early flowering and the ability to maintain green forage over summer will be crucial. In the case of the newly developed varieties of tedera (Lanza and Palma), mainly based on genetic material from the Canary Islands, it is also necessary to test their adaptation in terms of phenology to the conditions of other regions such as the Iberian Peninsula, where, for example, winters are more severe. This information will be crucial to evaluate the strategic use of tedera in Mediterranean livestock systems to increase their resilience to the reduction of precipitations and the increase of summer feed gaps.

This study aimed to provide information on the phenology of the newly developed tedera cv. Lanza (tedera from now on) in a typical Mediterranean environment and its response to a 24% annual rainfall reduction and competition. To do so, we monitored key reproductive phenological stages of tedera in comparison with alfalfa in a three-year field study in Córdoba, south Spain. The two specific objectives were testing (i) the effect of a 24% annual rainfall reduction on phenological stages from inflorescence emergence to dormancy and (ii) the effect of competition from volunteer species on these phenological stages, both in comparison with alfalfa.

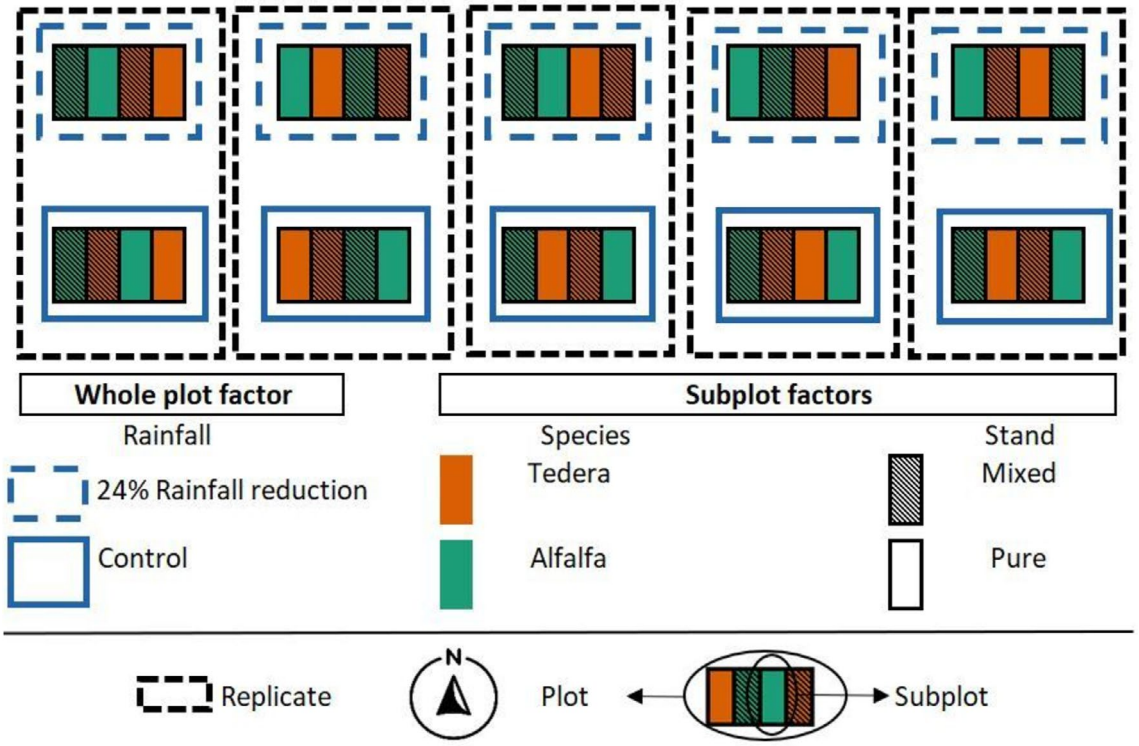


FIGURE 1 | Split-plot design with five replicates, one whole-plot factor (Rainfall) and two subplot factors, Species and Stand.

2 | Material and Methods

2.1 | Experimental Design

The experimental design was a split-plot design established in the experimental farm of the University of Cordoba, Spain (37°55′01″ N and 04°42′57″ W) (Fernández-Habas et al. 2025). The design included a whole-plot factor, rainfall, and two subplot factors: species and stand. Rainfall had two treatments, no rainfall reduction (Control) and 24% rainfall reduction (Reduction). The subplot factor species included tedera and alfalfa as treatments, while the subplot factor stand had two treatments, pure, in which each species was grown alone without interspecific competition, and mixed, in which each legume species grew with the interspecific competition of volunteer species: grasses such as *Avena barbata* Pott ex Link., *Lolium multiflorum* Lam., *Phalaris minor* Retz. and *Bromus rubens* L., and the forbs *Cichorium intybus* L., *Leontodon tuberosus* L., *Sonchus oleraceus* L., *Picris echioides* L., *Hirschfeldia incana* L., *Convolvulus arvensis* L., *Ridolfia segetum* L., *Daucus carota* L., *Anthemis arvensis* L., *Trifolium campestre* Schreb., *Trifolium resupinatum* L. and *Medicago polymorpha* L.

The replicates included two plots (3 × 9.5 m size) assigned to either control or rainfall reduction (whole plot factor) (Figure 1). Due to logistic constraints, the treatments of rainfall (control and reduction) were not randomised within replicates. The plots included four subplots (2 × 3 m size and 0.5 m separation among them) that were randomly assigned to the treatments of the subplot factors species and stand. For this experiment, 5 replicates were used, totalling 40 subplots (4 subplots nested in 2 Rainfall treatments × 5 replicates) (Figure 1).

Rainout shelters (4 × 1.9 × 12 m) were installed to cover the plots with rainfall reduction treatment following the design of Yahdjian and Sala (2002) to exclude 24% of the annual rainfall (Hoover et al. 2018; Kundel et al. 2018). This 24% of annual rainfall was intercepted by polycarbonate gutters of 22 cm in width placed on the shelter's roof at 52 cm distance between gutters. The intercepted water was channelled to storage tanks to avoid runoff and to measure the effectiveness of the rainfall exclusion. An analysis of the effect of the rainout shelter on air temperature, Photosynthetically Active Radiation (PAR) and soil water reported significant effects for soil water only, showing a 13% soil moisture reduction under rainfall reduction compared to control (see Fernández-Habas et al. 2025).

The soils of the experiments are deep Vertisol (Campillo García et al. 1993) with a gentle slope north–south of < 5% and with the following soil physicochemical properties: 40.0% silt, 50.2% clay, 9.8% sand, 1.97% oxidisable organic matter, 0.13% N (Kjeldahl), 7.8 pH, 7 mg kg^{-1} P (Olsen), 370 mg kg^{-1} K. The soil was prepared by conventional tillage before installation of the experiment plus an extra pass with a rototiller after the installation of the shelters with no fertilisation applied.

2.2 | Growing Conditions

Scarified seeds of tedera were sown in seedling trays and then transplanted into the experimental plots when they developed three leaves. To promote Rhizobium inoculation, the trays were filled with soil collected from natural populations of *B. bituminosa*. Inoculated seeds of alfalfa were directly sown in the experimental plots. Both species were established in rows

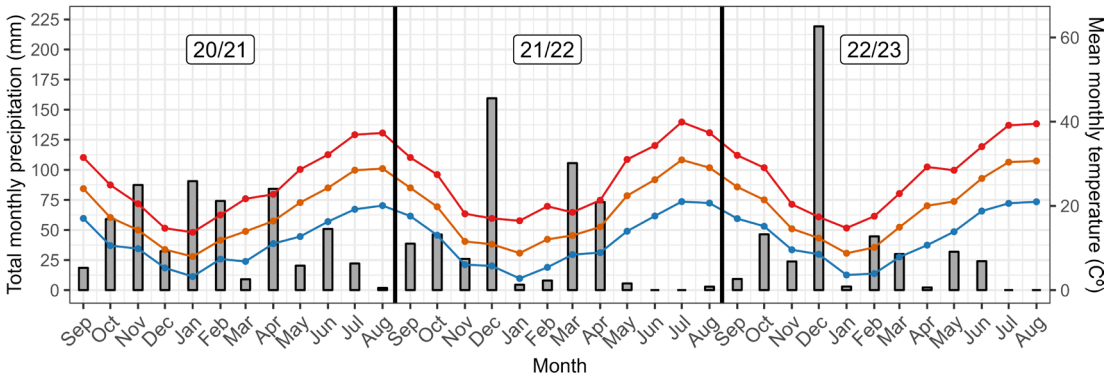


FIGURE 2 | Total monthly precipitation (bars), mean monthly temperature of the daily mean (orange line), maximum (red line) and minimum (blue line) temperature for the three growing seasons of the experiment (2020–2021, 2021–2022 and 2022–2023). Data from the meteorological station at the Campus of Rabanales, Cordoba, Spain (37°55′6″ N and 4°43′30″ W).

20 cm apart and plant spacing of 20 cm and 40 cm in pure and mixed stands respectively, which resulted in a plant density of 25 plants/m^2 in pure stands and 13 plants/m^2 in the mixed treatment. After an initial failed establishment on 14 and 15 December 2020 due to low temperatures in late December and early January (Figure 2), the plants were re-established on 25 and 26 February 2021.

Weeds were controlled in pure stands by hand-weeding and herbicide applications of Pulsar plus es-00646 (Imazamox 2.5% p/v). Occasional attacks of *Colaspidema barbarum* in alfalfa were controlled with the insecticide Cibelte es-18.316/11 (cypermethrin 10% p/v).

The study location has 579 mm of annual rainfall and a mean temperature of 17.7°C (20-year long-term period 2002–2022) while the average number of days below 0°C in Cordoba is 13 (average 2002–2022). The three years showed contrasting weather conditions. The 2020/2021 agricultural crop year (from 1st September to 31st August) had similar annual rainfall (with 550 mm) to the long-term average, while 2021/2022 (470 mm) and 2022/2023 (435 mm) were 19% and 25% drier, respectively. The spring of 2021 was wet, and the summer rainfall in June (51 mm) and July (22 mm) was considerably higher than the long-term average (Figure 2). Thirteen frost days were registered during the winter of 2020/2021, with minimum temperatures of −3.2 in early January and seven consecutive days of minimum temperatures below 0°C, partly due to an unusual winter storm ("Filomena") with historic low temperatures in Spain (Smart 2021). The agricultural crop year of 2021/2022 showed close-to-average rainfall in autumn. December was very wet (with 34% of the total annual rainfall) while January and February of 2022 accumulated little rainfall (Figure 2). Overall, the winter temperatures were mild, with only 6 frost days registered, for which minimum temperatures did not drop below −0.9. From May to the end of August, only 8.4 mm were accumulated (Figure 2) compared to 96 mm in 2021 and 57 mm for the long-term average during the same period. The temperatures during these months were also higher in 2022 than in 2021 and that of the long-term average. The agricultural crop year of 2022/2023 was similar in terms of rainfall to 2021/2022 during autumn and winter (Figure 2). However, winter was especially cold, with 14 frost days and several days under −1°C. The spring was very dry until mid-May, with a severe heat wave at the end of April (maximum temperature of 37°C). From the end of May to mid-June, the 56 mm rainfall after the senescence of annuals was similar to the long-term average.

Senescent plant material was removed (7 cm height) in all stands at the end of July in all subplots except in tedera pure stands for which aerial biomass remained non-senescent over the first summer of 2021. The next year, in 2022, tedera shed leaves in July and all aerial biomass was clipped. In 2023, the persistence of tedera in mixed stands was very low and therefore the phenology of this treatment was not further monitored and analysed. Further information on the yield and quality of both species can be found in Fernández-Habas et al. (2025).

2.3 | Phenology Measurements

Reproductive phenological stages of tedera and alfalfa were recorded following the general scale of the Biologische Bundesanstalt Bundessortenamt und Chemische Industrie (BBCH) (Bleiholder et al. 2001; Enriquez-Hidalgo et al. 2020; Meier 2001) from February to July. The phenological stages recorded were: 5 (Inflorescence emergence), 6 (Flowering), 7 (Development of fruit), 8 (Ripening or maturity of fruit) and 9 (Beginning of dormancy and senescence). Phenology was assessed weekly in 2022 and 2023 at the plant level in five plants per subplot. In total, 25 plants by treatment were monitored for phenology. As the phenology of the year 2021 might have been affected by the late establishment, only the beginning of dormancy and senescence was recorded. As explained before, due to low persistence, the phenology of mixed stands was not recorded in 2023. Each stage was continuously monitored from start to end per plant. Inflorescence emergence was considered to start with the first flower bud visible and end when all buds had flowered. The beginning of flowering was recorded when the first fully emerged flower was observed and was considered to finish when all flowers had petals dry or fallen and showed fruit set visible. The start of development of fruit was recorded when the fruit reached 10% of the final size and the end when all fruits reached the final size. Maturity of fruit was considered to start with the beginning of fruit colouration (green-yellowish) and end when all fruits showed fully ripe colour (light yellow) and the beginning of fruit abscission. The beginning of dormancy

and senescence was recorded as the moment when 50% of the leaves were senescent or shed.

2.4 | Statistical Analysis

For each phenological stage, the day of the year (DOY) to the start/end of the corresponding phenological stage was calculated and used as the target variables for statistical analysis. Some plants in the different treatments did not reach the recorded phenological stages, which was annotated as 0 DOY. Therefore, there was an excess of zeroes in the count data of DOY at each stage. We modelled this data using zero-inflated Poisson regression models with the package "glmmTMB" (Magnusson et al. 2023). These regressions allow the modelling of positive counts following a Poisson distribution in a conditional model and the data containing zeroes in a zero-inflated model using a logit link (Brooks et al. 2017). The zero-inflated model describes the probability of observing an extra zero count not generated by the conditional model (Brooks et al. 2017). We fit a model for each target variable. For the sake of simplicity and due to clear differences among years, all target variables were modelled separately for each year. Species, Stand and Rainfall were set as fixed effects as well as their two-way and three-way interactions. To account for the Split-plot experimental design and repeated measures, subplot nested in plot nested in replicate were set as random effects. Two different models were fitted for each phenological stage (four reproductive stages measured), one for DOY to start of the stage and a second one for DOY to end of the stage. For the stage of the beginning of dormancy, no models were fitted for 2021 and 2022 due to the lack of variance in the data (omnibus test reported non-significance $p > 0.05$) as the time to this stage was highly synchronic; therefore, the results were descriptively explained. The full models were simplified based on the Akaike Information Criterion for small sample size (AICc). In all models, the three main fixed effects were kept in the conditional model to allow graphical comparability among phenological stages. Residual diagnostics were performed using the package "DHARMa" (Hartig 2020). Based on the best-fit models, the estimated means of DOY to start and end of each stage were reported from the conditional model as well as the estimated probability of an extra zero count from the zero-inflation model using the package "emmeans" (Brooks et al. 2017). To facilitate interpretation, the probability of an extra zero count from the zero-inflation was transformed to the probability of reaching a certain phenological stage. A significance level of $p = 0.05$ was chosen throughout. Analyses were performed with R Studio v. 4.3.0. (R Core Team 2023).

3 | Results

3.1 | Response of Reproductive Stages to Rainfall Reduction and Competition

Figure 3 shows the phenological development of tedera and alfalfa in every treatment for 2022 and 2023. Overall, tedera showed earlier phenology than alfalfa, especially for inflorescence emergence and flowering (Figure 3). In 2022, these stages together with the development of fruit lasted for tedera for more than a month and overlapped among them. This year, tedera showed emergence of inflorescences approximately at the beginning of March and started flowering a month later, in April (although with differences among treatments), 54 and 44 days before alfalfa, respectively. Tedera also completed these stages earlier than alfalfa (Figure 3). In 2023, tedera showed a more delayed phenology compared to 2022, while these differences between years were not so clear for alfalfa (Figure 3).

The interactions Species × Rainfall and Species × Stand were significant in 2022 for the DOY to start of inflorescence emergence and flowering (Table 1, conditional models). The interaction Species × Rainfall revealed earlier inflorescence emergence and flowering of tedera under reduced rainfall compared to control (10 days), whereas alfalfa showed no differences (Figure 3). This interaction was only marginally significant ($0.05 < p < 0.1$) for the end of both phenological stages (Table 1, conditional models). The interaction Species × Stand indicated a delayed phenology of tedera in mixed stands with a later start and end of inflorescence emergence (15 days approximately) and later start of flowering (10 days), while alfalfa showed no differences among stand treatments (Figure 3). Concerning the stages of development and maturity of fruit, the beginning of both stages was significantly affected by the main effects Species and Stand with no significant interactions (Table 2, conditional models). However, there were no differences in the DOY to completion of both stages which ended by mid-June. Tedera started the development of fruit by mid-end April and fruit maturation by mid-May, 30 days and 21 days earlier than alfalfa, respectively (averaged over stand and rainfall) (Figure 3). Also, for both species, competition in mixed stands delayed the beginning of development and maturity of fruit (6 days) (Table 2, conditional models, Figure 3). Rainfall showed only a marginally significant effect on the earlier start of the development and maturity of fruit under reduced rainfall (Table 2, conditional models).

In 2023, tedera showed a more delayed phenology compared to 2022 (especially for inflorescence emergence and flowering) with a shorter length of the phenological stages (Figure 3). There was a significant interaction Species × Rainfall (Table 1, conditional models) showing that tedera reached the end of flowering earlier under reduced rainfall with no differences for alfalfa (Figure 3). The rest of the significant effects were due to the main effects Species and Rainfall (Tables 1 and 2, conditional models). Tedera started and finished the inflorescence emergence earlier (20 days) than alfalfa (averaged across Rainfall). Also, for both species, the rainfall reduction induced an advanced inflorescence emergence (20 days) (Figure 3). These differences were not significant for the start of flowering. However, this stage was considerably shorter and ended significantly earlier in tedera under rainfall reduction compared to the rest of the treatments (Table 1, conditional models, Figure 3). The differences in stages of development and maturity of fruit in 2023 were less clear. There was a significant main effect of Species for the end of the development of fruit (Table 2, conditional models), which ended 12 days earlier for tedera than for alfalfa (averaged across Rainfall) (Figure 3). Concerning the maturity of fruit, both species showed an earlier start of this stage of 10 days under reduced compared to control rainfall (Table 2, conditional models, Figure 3).

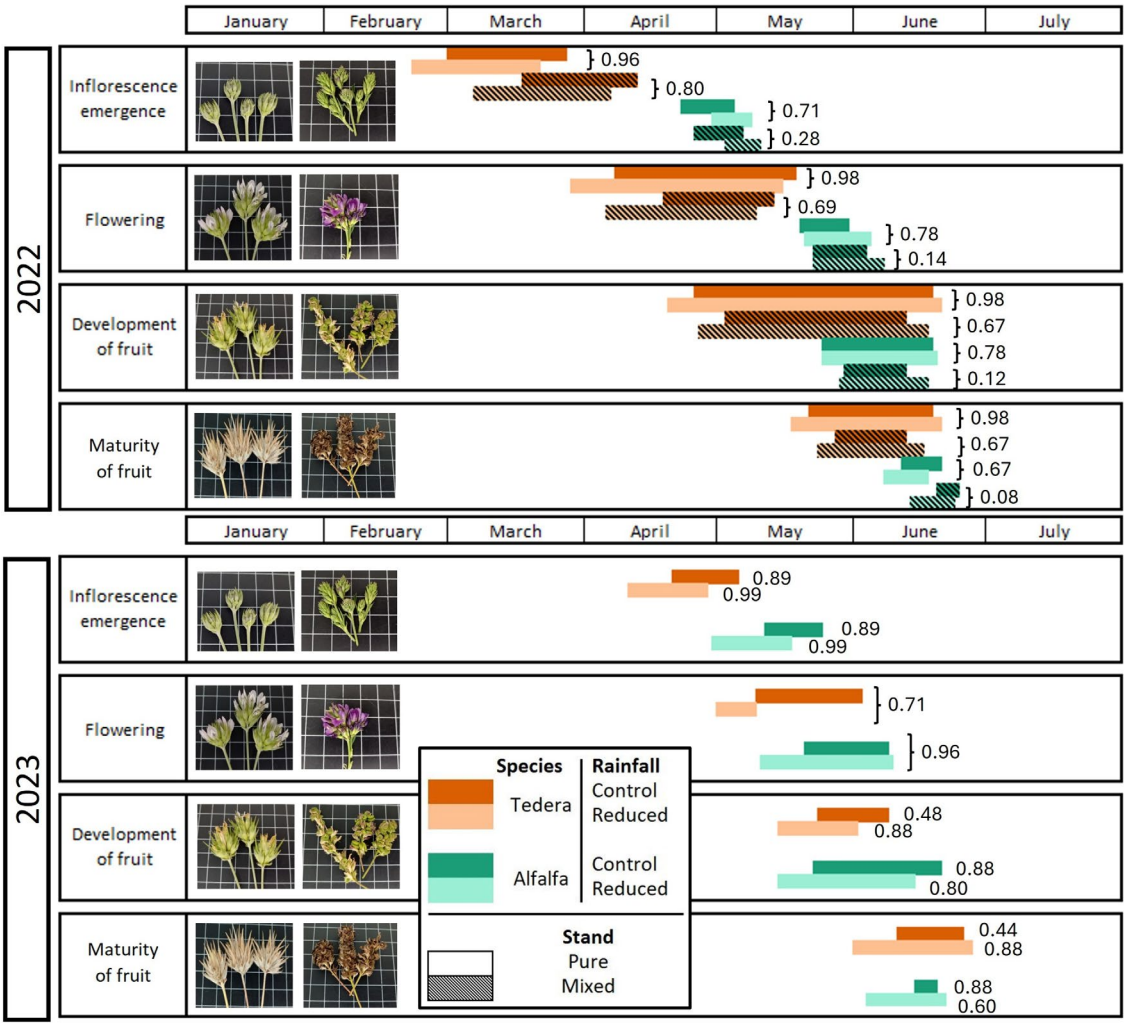


FIGURE 3 | Reproductive phenological stages of alfalfa and tedera for each factor in 2022 and 2023. Start and end of the bars represent the estimated marginal means of the day of the year (DOY) to start and end of each stage by treatment. Numbers indicate the probability of reaching the corresponding phenological stage, estimated by the zero-inflated component of the models (see Tables 1 and 2 for interpretation of significant effects). Note that the Stand factor was not included in 2023. Images are an example of the phenological stages for tedera (left) and alfalfa (right).

As shown by the zero-inflated models, in 2022 the probability of reaching the recorded reproductive phenological stages was influenced by the main effects of Species and Stand, while Rainfall showed no influence (Tables 1 and 2, zero-inflated models). Figure 3 shows in numbers the estimated probabilities reaching the corresponding phenological stage from zero-inflation models by Species and Stand (see Tables 1 and 2 for interpretation of significant effects). Tedera showed higher probabilities of reaching reproductive stages than alfalfa, and for both species, competition reduced the probabilities of reaching the different reproductive stages (Figure 3).

Contrary to 2022, in 2023 Rainfall affected the probability of reaching some of the phenological stages (Tables 1 and 2, zero-inflation component). Plants under reduced rainfall had higher probabilities of reaching the stage of inflorescence emergence, 0.89 in control versus 0.99 under reduced rainfall (Figure 3). This difference was not significant for the start of flowering (Table 1, zero-inflation component). Contrary to 2022, in 2023 the probability of reaching flowering was lower for tedera than for alfalfa (Figure 3). The interaction of Species × Rainfall for the development and maturity of fruit in 2023 (Table 2, zero-inflation component) revealed lower probabilities of reaching these stages for tedera under control treatment whereas no differences were observed in alfalfa (Figure 3).

3.2 | Response of Beginning of Dormancy to Rainfall Reduction and Competition

There were important differences between years and Species treatments for the stage of the beginning of dormancy, while Rainfall had no impact. In 2021, 90% of the plants in alfalfa in pure stand reached 50% of leaf shedding by the end of July and lost all the leaves over the summer. On the same date, only 5% of tedera plants in pure stand showed 50% of leaf shedding. Tedera maintained green leaves over the rest of the summer (Figure 4A,B). Competition delayed the beginning of dormancy, only 16% of the plants of both species showed 50% of leaf shedding at the end of July. However, in 2022 both species reached the beginning of dormancy in early June, with no differences either by Species or Stand factors. By the end of July, both species

TABLE 1 | Results of zero-inflated Poisson mixed models for the start and end of the phenological stages inflorescence emergence and flowering.

		Inflorescence						Flowering					
		Start			End			Start			End		
Year	Effect	Estimate	*z*	*p*	Estimate	*z*	*p*	Estimate	*z*	*p*	Estimate	*z*	*p*
2022	Conditional model												
	Intercept	4.46 ± 0.02	191.5	< 0.001	4.68 ± 0.02	293.2	< 0.001	4.76 ± 0.01	392.8	< 0.001	4.97 ± 0.01	519.3	< 0.001
	Species [Tedera]	−0.31 ± 0.02	−15.2	**< 0.001**	−0.17 ± 0.01	−12.3	**< 0.001**	−0.19 ± 0.01	−18.0	**< 0.001**	−0.07 ± 0.01	−7.3	**< 0.001**
	Stand [Competition]	0.07 ± 0.02	3.2	**0.001**	0.05 ± 0.01	3.4	**0.001**	0.03 ± 0.01	2.6	**0.010**	−0.01 ± 0.01	−0.6	0.560
	Rainfall [Reduced]	−0.02 ± 0.02	−1.0	0.3417	−0.01 ± 0.02	−0.6	0.5736	−0.03 ± 0.01	−2.8	**0.006**	−0.001 ± 0.01	0.2	0.879
	Species × Stand	0.06 ± 0.02	2.7	**0.007**	0.04 ± 0.01	2.9	**0.004**	0.02 ± 0.01	2.0	**0.049**	−0.02 ± 0.01	−1.7	0.097
	Species × Rainfall	−0.05 ± 0.02	−2.5	**0.011**	−0.02 ± 0.01	−1.8	0.070	−0.03 ± 0.01	−3.6	**< 0.001**	−0.0 ± 0.01	−1.7	0.081
	Zero-inflation model												
	Intercept	−1.14 ± 0.21	−5.4	< 0.001	−1.14 ± 0.02	−5.4	< 0.001	−1.03 ± 0.22	−4.7	< 0.001	−1.03 ± 0.22	−4.7	< 0.001
	Species [Tedera]	−1.15 ± 0.21	−5.6	**< 0.001**	−1.16 ± 0.02	−5.6	**< 0.001**	−1.31 ± 0.23	−5.6	**< 0.001**	−1.31 ± 0.23	−5.6	**< 0.001**
	Stand [Competition]	0.92 ± 0.23	4.6	**< 0.001**	0.92 ± 0.02	4.6	**< 0.001**	1.54 ± 0.24	6.4	**< 0.001**	1.54 ± 0.24	6.4	**< 0.001**
2023	Conditional model												
	Intercept	4.75 ± 0.03	156.02	**< 0.001**	4.87 ± 0.02	203.0	**< 0.001**	4.87 ± 0.02	203.9	**< 0.001**	5.00 ± 0.02	301.5	**< 0.001**
	Species [Tedera]	−0.09 ± 0.02	−3.8	**< 0.001**	−0.07 ± 0.02	−3.7	**< 0.001**	−0.04 ± 0.02	−1.6	0.110	−0.06 ± 0.01	−4.5	**< 0.001**
	Rainfall [Reduced]	−0.04 ± 0.02	−2.0	**0.048**	−0.03 ± 0.02	−1.4	0.171	−0.04 ± 0.02	−1.5	0.130	−0.04 ± 0.01	−2.9	**< 0.001**
	Species × Rainfall	—	—	—	—	—	—	—	—	—	−0.04 ± 0.01	−3.0	**0.002**
	Zero-inflation model												
	Intercept	−3.88 ± 1.4	−2.7	**0.006**	−3.88 ± 1.4	−2.7	**0.006**	−2.08 ± 0.6	−3.8	**< 0.001**	−2.22 ± 0.6	−3.6	**< 0.001**
	Species [Tedera]	—	—	—	—	—	—	1.17 ± 0.5	2.5	**0.013**	1.30 ± 0.5	2.4	**0.015**
	Rainfall [Reduced]	−1.81 ± 0.9	−1.9	**0.050**	−1.81 ± 0.9	−2.0	**0.050**	−0.52 ± 0.4	−1.2	0.216	—	—	—
	Species × Rainfall	—	—	—	—	—	—	—	—	—	—	—	—

Note: Estimates ± standard error, *z*-values and *p*-values are shown for the conditional and zero-inflation model. Levels in squared brackets are the reference level related to the estimate shown. Note that in the zero-inflated model, negative estimates indicate lower probabilities of an extra zero count and positive estimates higher probabilities than the not shown level (Species: Alfalfa, Rainfall: Control, Stand: Pure). Bold values indicate statistically significant factors or interactions ($p < 0.05$). Factors and interactions not shown or with "—" were not retained in the final model. Estimates and standard error are in log scale.

TABLE 2 | Results of zero-inflated Poisson mixed models for the start and end of the phenological stages development of fruit and maturity of seed.

		Development of fruit						Maturity of seed					
		Start			End			Start			End		
Year	Effect	Estimate	*z*	*p*	Estimate	*z*	*p*	Estimate	*z*	*p*	Estimate	*z*	*p*
2022	Conditional model												
	Intercept	4.87 ± 0.01	474.3	< 0.001	5.12 ± 0.01	548.7	< 0.001	5.03 ± 0.01	545.7	< 0.001	5.13 ± 0.01	516.1	< 0.001
	Species [Tedera]	−0.12 ± 0.01	−11.3	**< 0.001**	−0.00 ± 0.01	0.3	0.739	−0.07 ± 0.01	−8.0	**< 0.001**	−0.01 ± 0.01	−0.6	0.516
	Stand [Competition]	0.02 ± 0.01	2.2	**0.025**	−0.01 ± 0.01	−1.4	0.156	0.02 ± 0.01	2.2	**0.030**	−0.01 ± 0.01	−1.2	0.247
	Rainfall [Reduced]	−0.02 ± 0.01	−1.7	0.081	0.01 ± 0.01	0.7	0.488	−0.01 ± 0.01	−1.9	0.059	0.00 ± 0.01	0.3	0.757
	Species × Stand	0.01 ± 0.01	0.6	0.521	—	—	—	—	—	—	—	—	—
	Species × Rainfall	−0.1 ± 0.01	−1.6	0.108	—	—	—	—	—	—	0.01 ± 0.01	0.7	0.495
	Zero-inflation model												
	Intercept	−0.97 ± 0.22	−4.4	< 0.001	−0.97 ± 0.22	−4.4	< 0.001	−0.6974 ± 0.21	−3.4	< 0.001	−0.6974 ± 0.21	−3.4	< 0.001
	Species [Tedera]	−1.34 ± 0.24	−5.6	**< 0.001**	−1.34 ± 0.24	−5.6	**< 0.001**	−1.58 ± 0.26	−6.0	**< 0.001**	−1.58 ± 0.26	−6.0	**< 0.001**
	Stand [Competition]	1.62 ± 0.25	6.5	**< 0.001**	1.62 ± 0.25	6.5	**< 0.001**	1.58 ± 0.26	6.0	**< 0.001**	−1.58 ± 0.26	−6.0	**< 0.001**
2023	Conditional model												
	Intercept	4.93 ± 0.02	219.9	**< 0.001**	5.08 ± 0.01	350.4	**< 0.001**	5.07 ± 0.01	345.5	**< 0.001**	5.16 ± 0.01	566.8	**< 0.001**
	Species [Tedera]	0.00 ± 0.02	0.13	0.894	−0.04 ± 0.01	−2.6	**0.010**	−0.01 ± 0.01	−0.8	0.435	0.02 ± 0.01	1.7	0.095
	Rainfall [Reduced]	−0.03 ± 0.02	−1.48	0.139	−0.02 ± 0.01	−1.5	0.124	−0.033 ± 0.01	−2.2	**0.025**	0.01 ± 0.01	0.6	0.570
	Species × Rainfall	—	—	—	—	—	—	—	—	—	—	—	—
	Zero-inflation model												
	Intercept	−1.32 ± 0.3	−4.9	**< 0.001**	−1.32 ± 0.3	−4.90	**< 0.001**	−1.06 ± 0.3	−3.7	**< 0.001**	−1.04 ± 0.3	−4.0	**< 0.001**
	Species [Tedera]	0.37 ± 0.3	1.4	0.175	0.37 ± 0.3	1.4	0.175	0.17 ± 0.3	0.6	0.544	0.16 ± 0.3	0.6	0.544
	Rainfall [Reduced]	−0.37 ± 0.3	−1.4	0.175	−0.37 ± 0.3	−1.4	0.175	−0.17 ± 0.3	−0.6	0.544	−0.16 ± 0.3	−0.6	0.544
	Species × Rainfall	−0.67 ± 0.3	−2.5	**0.013**	−0.67 ± 0.3	−2.5	**0.013**	−0.97 ± 0.3	−3.5	**< 0.001**	−0.96 ± 0.3	−3.6	**< 0.001**

Note: Estimates ± standard error, *z*-values and *p*-values are shown for the conditional and zero-inflation model. Levels in squared brackets are the reference level related to the estimate shown. Note that in the zero-inflated model, negative estimates indicate lower probabilities of an extra zero count and positive estimates higher probabilities than the not shown level (Species: Alfalfa, Rainfall: Control, Stand: Pure). Bold values indicate statistically significant factors or interactions ($p < 0.05$). Factors and interactions not shown or with "—" were not retained in the final model. Estimates and standard error are in log scale.

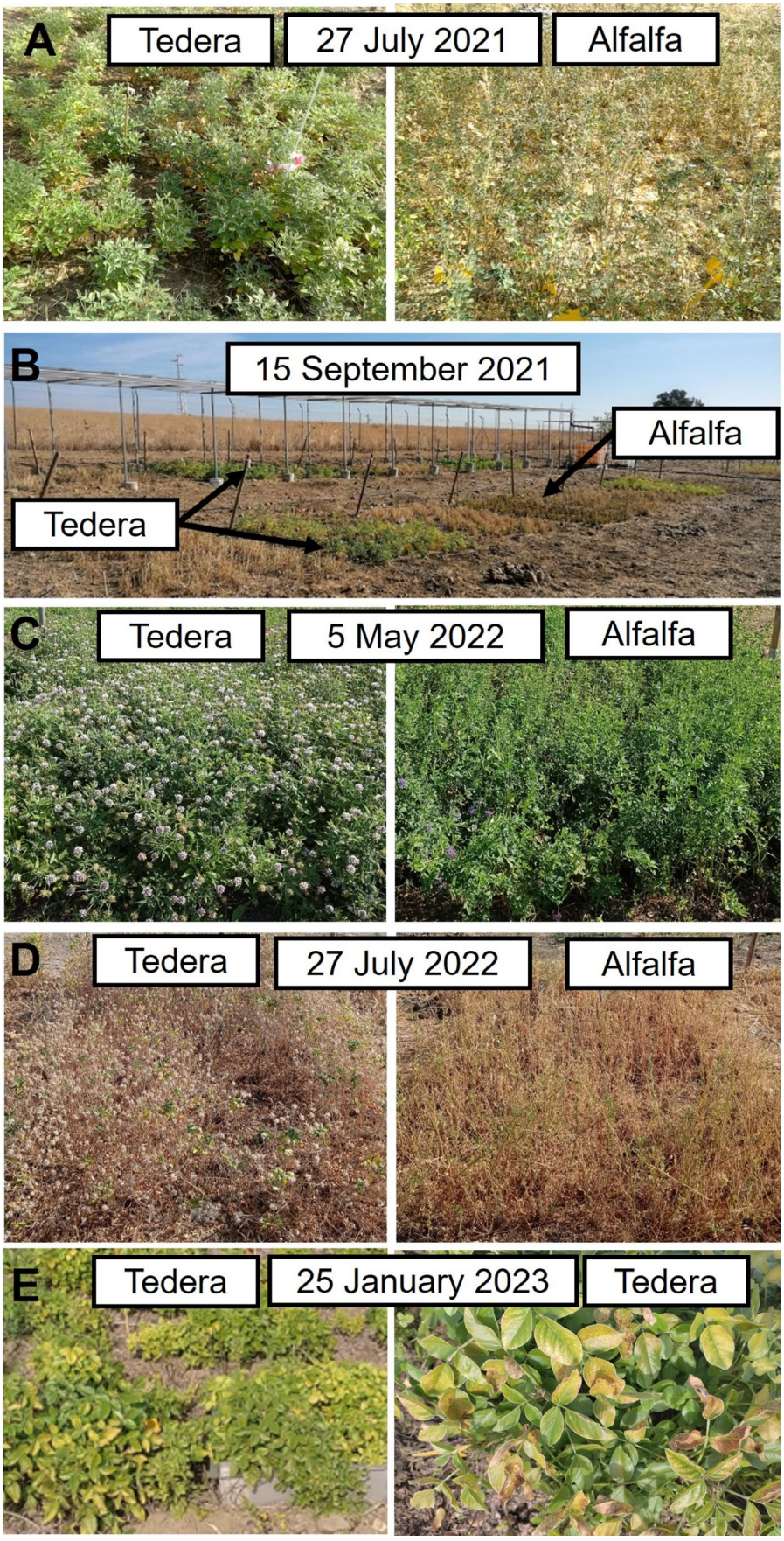


FIGURE 4 | Overview of subplots of tedera and alfalfa in pure stand in July of 2021 (A) with alfalfa at 50% leaf shedding and in July of 2022 (D) with both species in dormancy after complete leaf shedding. (B) Overview of the experiment showing subplots of tedera with green leaves after the summer of 2021. (C) Shows tedera in early May with flowers comparatively with alfalfa. (E) Tedera with frost damage at the end of January 2023.

were in dormancy after complete leaf shedding (Figure 4D). As in the previous years, in 2023, Rainfall had no impact on the beginning of dormancy. In this year, neither species was able to retain green forage over the whole summer, however, tedera showed a later beginning of dormancy than alfalfa ($z = -3.17$, $p = 0.002$). Alfalfa reached dormancy by mid-June (16 of June) and tedera 18 days later (4 of July).

4 | Discussion

This study investigated the phenology of a newly developed variety of tedera (Lanza) in a typical Mediterranean environment of the Iberian Peninsula, and how this phenology responds to an annual 24% rainfall reduction and competition from volunteer species. The results provide insights to elucidate the potential of this species as a new forage perennial legume and to define suitable management strategies.

4.1 | General Patterns of Tedera Phenology and Its Response to Reduced Rainfall

In the conditions of years 2022 and 2023, tedera showed overall earlier phenology than alfalfa for all reproductive stages. Tedera plants responded to 24% rainfall reduction with an earlier inflorescence emergence and flowering denoting plasticity to rainfall reduction which may also play an important role in reducing the effect of an increased irregularity of rainfall (Daryanto et al. 2015; Franks et al. 2007). Early flowering is a key trait for the persistence of annual legumes in Mediterranean environments of short seasons and variable spring climate, but is also important for perennials, as it enables suitable seed production before the onset of summer drought, ensuring the recruitment of new seedling (Araújo et al. 2015; Berger et al. 2017; Berger and Ludwig 2014; Nadeem et al. 2019; Real et al. 2012; Revell et al. 2012; Thomson et al. 1997). In environments prone to early drought, terminal drought is known to compromise forage and seed production (Daryanto et al. 2015). This was demonstrated by the short flowering of alfalfa in 2022, which was terminated in early June, due to the strong water stress that imposed the high temperatures and lack of rainfall in May–June 2022. In fact, in pure stand, only 76% of alfalfa plants flowered against the 100% of flowering in tedera plants. In the context of climate change, the impact of terminal drought in forage resources is expected to increase and thus the associated effects on livestock systems such as more severe feed gaps (Bell et al. 2018; Dono et al. 2016; Ghahramani and Moore 2016; Moore et al. 2009) and dependence on concentrates (Iglesias et al. 2016). The selection of forage species with traits adapted to these impacts might provide Mediterranean farming systems with higher resistance and resilience to climate change (Porqueddu et al. 2016). For example, Daryanto et al. (2015) reported that droughts during early reproductive stages (flowering) cause higher yield losses compared to those that occur during the late generative stage (maturity of seed). In this sense, tedera shows early flowering as a suitable trait for Mediterranean farming systems. Melis et al. (2018) also evaluated first flower appearance among other traits in tedera accessions of *B. bituminosa* and *B. morisiana* in Sardinia (Italy). In general, they reported later first flower emergence than in this study, although the higher spring temperatures in Cordoba and the provenance of seeds may account for these differences. In fact, the Canarian accessions of *B. bituminosa* tend to flower earlier than their counterparts from the Iberian Peninsula (Correal et al. 2008). In the same study by Melis et al. (2018), they found a negative correlation between seed yield and days to first flower appearance. This supports the positive relationship between early flowering and high seed yield for legumes in Mediterranean rainfed systems (Melis et al. 2018; Thomson et al. 1997). This relationship has important implications for the persistence of tedera. It has been reported that tedera can recruit new seedlings from seeds in pure stands (Real 2023), contrary to other perennial legumes such as alfalfa which shows autotoxicity (Chon et al. 2006). Therefore, seed production may play an important role in the persistence of tedera stands, which highlights the importance of early flowering and the use of tedera varieties with this trait. The vast genetic diversity of tedera and its variability in traits such as the start of flowering (Correal et al. 2008; Melis et al. 2018) and cold tolerance (Gisbert et al. 2015; Raeside et al. 2012; Walker et al. 2011, 2012) provide opportunities for selected ideotypes for the wide range of Mediterranean environmental conditions (Pazos-Navarro et al. 2011).

A disadvantage of early flowering by tedera might be frost damage in inflorescence and flowers in late February and early March in cold environments (Real 2023). This was evident in 2023 when the lower biomass production before winter and the low temperatures during January–February (14 frost days) caused considerable frost damage in tedera plants (see Figure 4E) leading to a delayed and shorter phenology of tedera in 2023 compared to 2022 (Figure 3). In fact, the zero-inflated models showed lower probabilities for tedera to reach some reproductive stages (i.e., inflorescence emergence and maturity of fruit) under control compared to reduced rainfall. This might be caused by a protective effect against frost damage by the shelters as explained in Fernández-Habas et al. (2025). Previous research has highlighted the susceptibility of tedera to cold temperatures, especially for the variety *albomarginata* (Raeside et al. 2012; Fernández-Habas et al. 2025) which was the main genetic basis for the breeding of the Lanza variety. Future studies should test the Palma variety, developed for higher cold tolerance and explore the potential of ascensions from the Iberian Peninsula adapted to sub-zero temperatures to improve this trait (see Walker et al. 2011). Grazing tedera stands at the end of winter might also delay flowering and therefore reduce frost damage risk in reproductive organs, although it might come at the expense of lower seed production (Correal et al. 2008; Sternberg et al. 2006). In addition to frost damage, selection for early flowering may not always increase seed yield in climates with unpredictable weather as it might limit the ability to respond to additional late spring rainfall (Turner et al. 2001). However, tedera shows an indeterminate-like growth and flowering pattern which allows producing new leaves while and after flowering (Gulumser et al. 2010) and restarting flowering after cessation due to short spring droughts or mild frosts (Real 2023). Nevertheless, as shown by the results this ability may be impaired by severe frost damage.

4.2 | Effect of Competition

Competition affected the phenology through delayed start of inflorescence emergence and flowering, and especially by

reducing the probability of plants reaching reproductive stages (Figure 3). The delayed start of inflorescence emergence and flowering might be caused by the shade of the species that dominated in competition treatment in agreement with a delayed flowering of legumes in response to shade (Lorenzo et al. 2019; Mauro et al. 2014; Qin et al. 2022). Tedera plants were strongly suppressed by volunteer species limiting their ontogeny (Fernández-Habas et al. 2023, 2025) which also resulted in lower probabilities of reaching reproductive stages. Therefore, competition from weeds can affect the persistence of tedera by impairing its ability to recruit new seedlings from seeds (Real 2023).

4.3 | Leaf Shedding During the Summer Season

Regarding the ability of tedera to retain green leaves over the summer season, the results reveal important weather and phenological-dependent relationships. During the first year, pure tedera stands remained with green leaves over the summer showing potential to provide good quality forage during the summer feed gap (Real et al. 2014; Suriyagoda et al. 2013). The rainfall events of June and July 2021 might have also allowed tedera to maintain green leaves over the summer while alfalfa showed leaf shedding by mid-July and lost all aerial biomass over the rest of the summer. These results show the potential of Mediterranean perennial legumes like tedera to face summer feed gaps in Mediterranean livestock systems. Perennial species can resist mid-spring heat waves and lack of rainfall to continue producing while annuals advance their phenology to terminate their cycle (Cleland et al. 2006; Segrestin et al. 2018; Volaire et al. 2014). In 2023, an early heat wave caused senescence of annuals at the beginning of May while tedera remained green until mid-July after taking advantage of late spring rainfall (Figure 2). However, in 2022 the dry conditions from May onwards, with high temperatures and only 8.4 mm (Figure 2) there was an overall leaf shedding at the beginning of June. The long reproductive phenological cycle of tedera together with high biomass production (9526 kg ha^{-1} see Fernández-Habas et al. 2025) may have led to soil water depletion and anticipated dormancy as a drought escape strategy under severe water stress (Varshney et al. 2021). Leaf shedding affected the oldest leaves from the bottom half of the plants, which is a common strategy of other perennial species to reduce evapotranspiration under water stress (Begg and Turner 1976; Munné-Bosch and Alegre 2004; Pérez-Ramos et al. 2013). This might have been aggravated by the higher plant density of tedera in this experiment of 25 plants/m^2 compared to the plant densities between 8 and 16 plants/m^2 recommended by Real et al. (2022) and Suriyagoda et al. (2013), although annual rainfall in these locations is lower than in the location of this experiment. In the conditions of 2023, with lower DM yield than in 2022 (Fernández-Habas et al. 2025), tedera was not able to retain green leaves over summer even after late spring rainfall (56 mm from the end of May to mid-June), although it reached dormancy 18 days later than alfalfa. The contrasting interannual responses of tedera concerning dormancy suggest that phenology (namely seed production) and biomass accumulation may play an important role in the maintenance of green leaves over summer (Real 2023). Further research should also study the effect of grazing at different stages on leaf senescence and regrowth of tedera, and possible trade-offs with seed production and plant survival. For example, although spring grazing may reduce seed production (Sternberg et al. 2006) it could also promote regrowth of younger leaves, which display better water regulation under drought stress (Foster et al. 2013; Real 2023). It must be noted that the phenological dynamics of tedera may differ in shallower and sandy soils with a lower water-holding capacity which might lead to earlier flowering and leaf shedding (Daryanto et al. 2015; Tardieu et al. 2018).

These results indicate that tedera may be a suitable alternative to rainfed alfalfa for direct grazing, helping to address seasonality and the increased aridity predicted by climate change models. Unlike alfalfa, tedera can grow in sandy, acidic soils (Fernández-Habas et al. 2023; Méndez et al. 2006), is able to recruit new plants from seed (Real 2023) and exhibits earlier flowering and later leaf shedding than alfalfa. However, further research is needed to investigate the long-term dynamics of tedera under different management regimes (e.g., grazing time and frequency) to fully understand its potential as an alternative perennial forage legume.

5 | Conclusion

Lanza tedera shows desirable traits for a new forage perennial Mediterranean legume for Mediterranean livestock systems such as early and long flowering and beginning of dormancy equal to or later than alfalfa. It also shows plasticity to an annual 24% rainfall reduction by advancing flowering. Its ability during the first year to extend the offer of green forage over the summer season shows promising potential as an out-of-season forage species. However, the contrasting responses during the three years of study indicate that early summer weather conditions and ontogeny may determine the ability of tedera to fulfil this role. Low cold tolerance of Lanza tedera and competition from weeds can severely impact its phenology, persistence and provision of out-of-season forage. Further research should study suitable management strategies to favour the persistence of tedera and maintenance of green forage over the summer season. The genetic variability of this species should be leveraged to select ideotypes adapted to the wide range of Mediterranean environmental conditions.

Author Contributions

Jesús Fernández-Habas: conceptualization, methodology, data curation, investigation, formal analysis, visualisation, writing – original draft, writing – review and editing. **Daniel Real:** conceptualization, investigation, writing – review and editing. **Tom Vanwalleghem:** conceptualization, supervision, funding acquisition, project administration, writing – review and editing. **José Ramón Leal-Murillo:** conceptualization, methodology, investigation. **Pilar Fernández-Rebollo:** conceptualization, methodology, investigation, supervision, funding acquisition, project administration, writing – review and editing.

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Conflicts of Interest

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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