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Starter irrigation in sulla as a promising practice to climate change adaptation of Mediterranean rainfed forage systems**

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Abstract. Possible climate change scenarios which are projecting altered rainfall patterns and extreme events have the potential to undermine the regeneration ability of Mediterranean rainfed forage systems. Within these systems *Sulla coronaria* (sulla), a much appreciated short-lived Mediterranean legume, tolerates summer drought. Under a rainfed regime, sulla plants regrow due to late summer rain in the year after sowing. The research was performed in Sardinia (Italy) in order to investigate the feasibility of starter irrigation (the land was moistened to restart vegetative regeneration in a timely manner) and to evaluate the productive, environmental and economic implications of cultivating sulla. During a severe autumn drought, the starter-irrigated *vs*. the rainfed crop were compared. The application of the planned starter irrigation assured a prompt plant restart and positively affected the leaf traits and crop performances. In December, leaf length and area reached 42 cm and 90 cm^2, twice the level as the rainfed leaves. Forage dry matter and crude protein yields reaching 5.2 and 1 t ha^{-1} were 9, 8-fold higher. Additionally, seasonal net gains of 120 kg ha^{-1} of fixed N, 548 kg ha^{-1} of saved CO_2 eq. emissions, and an economic gain of 881 € ha^{-1} were recorded. Starter irrigation acted as an effective adaptation strategy to climate change and supplied contextual, productive, environmental and economic benefits.

Keywords: Mediterranean legume, climate change, water, CO_2 emissions, economic convenience

INTRODUCTION

The Mediterranean area is one of the regions in which the effects of climate change, which have already been noted, are going to become more negative (Aguilera *et al.*, 2020). In fact, this region has been identified as one of the most vulnerable climate change hotspots in the 21st century, where increases in temperature will exceed the rate of 20% which is the global average increase and the downward trend of precipitation will lead to an increase in the frequency and severity of droughts and aridity (IPCC, 2021). Some climate change scenarios project altered rainfall patterns and a prolonged dry season with extreme climatic events which interact to affect Mediterranean grassland productivity (Dono *et al.*, 2013a). Undoubtedly, the typically strong dependence of Mediterranean pasture production on the total annual rainfall and its seasonal distribution (Dono *et al.*, 2013b) is being exacerbated by the effects of climate change, which can potentially impact both the quantity and reliability of forage production as well as its quality (Giridhar and Samireddypalle, 2015; Dellar *et al.*, 2018).

In rainfed Mediterranean forage systems in particular a key issue is related to the onset of vegetative regeneration after summer drought, because the prolonged delay

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of effective precipitation results in an asynchrony between the timing of fodder and crude protein production from the meadow and livestock feed requirements.

Moreover, an anticipation of the drought season occurring in the spring might result in a lower capacity to produce feedstocks (Dumont *et al.*, 2015). Finally, the war between Russia and Ukraine has raised concerns over feed and fertilizer supply (FAO, 2022) with a key strategic role being provided by self-produced forages, particularly leguminous ones, as opposed to a dependency on imported feedstocks. Indeed, the agricultural sector of the European Union is a net importer of feed protein. That dependency on imported protein coupled with high input costs is causing production challenges for farmers and increasing uncertainty, which in turn is driving up food prices. In this regard, the Commission is calling on Member States to use all of the available instruments in their CAP strategic plans for the period 2023-2027, such as coupled support to boost protein crops (European Commission, 2018; Puertas *et al.*, 2023). Additionally, due to their N fixation ability, when they are used as a substitute for chemical fertilizers, legumes can: (i) contribute to the mitigation of greenhouse gas (GHG) emissions by avoiding those emissions linked to N fertilizer manufacturing and use (Jensen *et al.*, 2020) and (ii) provide overall agronomic, environmental and climate benefits.

The adoption of practices that may be used to maintain the productive capacity of crops and agroecological measures that increase the resilience of production systems to a changing climate are being advocated to an increasing extent (Lesk *et al.*, 2016; Aguilera *et al.*, 2020). In semi-arid areas, irrigation is often proposed as a strategy to reduce the impact of climate change as the effects of such changes cause the net water requirement to generally increase (Funes *et al.*, 2021). In any case, a generalized increase in the net water requirements and a lower water availability could severely limit the crop productivity of both rainfed and irrigated crops (*e.g.* irrigation restrictions) (Dono *et al.*, 2013a, b). Also, the sustainability of water, energy use and the related greenhouse gas emissions of irrigation may be limited (Aguilera *et al.*, 2019).

In basic terms, lower productivity could have adverse economic implications. In the case of irrigation restrictions, efficiency tends to decrease because water becomes a technical input that is not fully utilized, at least with reference to the potential requirements of the crop. As a consequence, inefficiency could lead to reduced incomes due to a decrease in production or an increase in costs. Therefore, a careful focus on the irrigation water required for rainfed cropping systems needs to be taken into account and developed in order to face extreme drought events.

Through the presented research, with a particular focus on a Mediterranean forage legume species, we attempted to develop an approach to the regularization of vegetative restart in rainfed Mediterranean meadows by applying irrigation. Based on the growth curves for perennial forage species that were developed at different ecological sites and knowing the optimal date for the onset of vegetative restart, "regularization" means that, if at that date rainfall does not occur, "starter irrigation" has the potential to act as a valuable tool in supporting farmers to face climate change uncertainty.

Sulla coronaria (L.) Medik syn. *Hedysarum coronarium* L. (Choi and Ohashi, 2003) is a short-lived perennial legume originating in the Mediterranean basin and is usually grown as a rainfed biennial forage crop due to its notable adaptation to marginal and drought-prone environments (Sulas, 2005; Sulas *et al.*, 2009; De Rossi *et al.*, 2021). Sulla has a remarkable potential in terms of fixing atmospheric N and improving soil fertility and structure, as well as in supplying high-quality fodder and in delivering multiple services (Borreani *et al.*, 2003). Sulla is sown in the autumn and its growth is affected by rainfall distribution; it usually grows in the winter, growth rates increase rapidly in the spring and it remains dormant in the summer, according to the photoperiod and in high temperature conditions. In the subsequent late summer to autumn period, at the beginning of the 2nd year cycle, sulla plants commence their vegetative regrowth after the first rains (Sulas *et al.*, 2000).

We hypothesized that the vegetative regeneration ability of sulla plants during the 2nd year of its crop cycle might be assured and fully exploited by the adoption of appropriate starter irrigation (*i.e.*, occasional watering specifically aimed at moistening the land to restart at a scheduled time the vegetative regeneration of forage species under a rainfed regime). Interventions at the end of summer are designed to mitigate possible and increasingly frequent delays in the occurrence of rain.

The research was broadly aimed at stabilizing the forage legume species and the dry matter and protein yield were examined from the perspective of climate change. The specific objectives of this research were to (i) investigate the feasibility of the adoption of starter irrigation during the vegetative regeneration of the sulla crop, (ii) determine the effect of starter irrigation on certain bioagronomic traits, and on the productive and qualitative performance of this leguminous crop as well as its contribution to the biennial crop cycle, (iii) evaluate the potential environmental benefits and the economic performance derived from the applied starter irrigation.

MATERIALS AND METHODS

The research was conducted in North-West Sardinia (Italy) during the 2020-21 and 2021-22 growing seasons, in a private agropastoral farm (40°39'3" N, 8°37'5" E, elevation 485 m a.s.l.), where the sulla crop was introduced for the first time. The climate is a Mediterranean one with a hot dry summer. Long-term rainfall is 605 mm and the average annual temperature is 15.3°C. The soil was classified as Typic and Lithic Xerorthent, it has a moderately alkaline pH (8.06), a clayey texture with a high degree of stoniness, a nitrogen content of 0.5% (Kjeldahl method), a phosphorus content of 12 ppm (Olsen method) and a reactive limestone content of 28% (Dietrich-Fruhling method). For the last five years, the soil has been cultivated with barley.

After the soil was ploughed, seedbed preparation was carried out and inoculation with a commercial inoculant strain (strain WSM 1592, Western Australia) took place, sulla *cv*. Bellante was sown as pure sward in October 2020 at a density of approximately 300 seeds m^{-2}. Seedling establishment and crop development were observed to be normal.

The experimental field, which was one hectare in size, was arranged according to a randomized complete block design with four replications. Each plot was 20 m^2 in size. A 3 m wide unsampled zone was maintained among the plots and blocks to avoid any interactions between the treatments. The treatments were "starter irrigation" (STI; repeated irrigation events to stimulate and to assure the vegetative regeneration of sulla plants in the autumn, scheduled to take place irrespective of seasonal drought events) as compared to "rainfed" (RAI; subjected to natural precipitation events).

During the first year, in late May, the entire sulla field was cut for hay. At the end of summer (mid-September) the two treatments were differentiated. Starter irrigation events were performed in the time span from the 15th of September to the 29th of October 2021, by using a micro-sprinkler system (Claber, Italy). The starter irrigation experiment was designed to begin according to the occurrence or non-occurrence of late summer rain (between August the 20th and September the 15th). A lack of rainfall or a lack of cumulative rainfall events higher than 20 mm by the 15th of September initiated starter irrigation which triggered a sulla vegetative restart. Water was withdrawn from a farm well and the total volume of applied water was measured with a water meter. The watering events were triggered by a soil moisture sensor network.

Meteorological data were obtained using a private weather station close to the experimental site. From mid-September 2021, the dynamics of the soil water content were measured every two hours with a WatchDog WD 1400 recorder (Spectrum USA) equipped with reflectometry (FDR) probes (WaterScout SM 100 Soil Moisture Sensor – Spectrum USA).

Across the biennial sulla crop cycle, the representative shoot samples (0.2 m^2 each) were cut in spring 2021 (1st year cycle), autumn 2021 and spring 2022 (2nd year cycle). Detailed measurements were carried out during autumn 2021; the shoot samples were repeatedly cut at the vegetative stage at the end of October, November, and December 2021. The SPAD and fluorimeter measurements were carried out between 10.00 AM and 13.00 PM. Photosystem photochemical efficiency (Fv/Fm) was measured in five fully expanded sulla leaves per plot using a portable chlorophyll fluorimeter (Pocket Pea Hansatech Instruments, UK) equipped with black leaf clips. Fluorescence measurements were carried out on the adaxial leaflet lamina, after 15 min of a dark adaptation period. The relative chlorophyll content was measured using a portable chlorophyll meter (SPAD 502, Minolta Camera, Osaka, Japan). On five leaves per plot, the leaf length was measured, and then the leaf area was calculated using a scanner (Epson Perfection V700 Photo) and WINFOLIA™ software (Régent Instruments, Québec, Qc., Canada).

The water productivity (WP) was calculated in terms of the transformation efficiency of water through the cultivation system into yield, as the ratio of the aboveground production of dry matter (DM) to the total volume of irrigation water consumed by the system (Pereira *et al.*, 2012). Since in its broadest meaning, WP is the net return for each unit of water used (Molden *et al.*, 2010), the WP concept was extended to crude protein and condensed tannin contents.

Shoot subsamples were oven dried at 60°C until a constant weight was attained and the dry matter (DM) content was calculated. Dry shoot subsamples were ground finely enough to pass through a 1 mm mesh in order to be analysed for total nitrogen (N, Kjeldahl method). The crude protein (CP) content was calculated by multiplying the N content by 6.25, the crude protein yield (kg N ha^{-1}) was determined by multiplying the shoot DM yield (kg ha^{-1}) per its CP content (%). Additional shoots were sampled for condensed tannin determinations. Sulla shoots were kept on ice, freeze dried and ground to a fine powder. Shoot subsamples (50 mg) were treated with a 2.5 ml acetone/water (7:3) mixture and shaken for 60 min. The samples were then centrifuged for 10 min at 3 900 rpm and the supernatant was stored at 4°C until use for the following determination. The butanol assay of Porter *et al.* (1986) was adapted for the quantification of extractable condensed tannin (CT) contents. The condensed tannin content was expressed in terms of g delphinidin equivalent per kg dry weight (g DE kg^{-1} DW). The forage nutritive value (MFU = French milk forage units) was estimated and expressed in terms of the content per DM and hectare.

Based on the estimates of N fixed in the aboveground sulla organs, the environmental benefits from starter irrigation were calculated in terms of saved CO_2 emissions associated with the production of N fertilizer (*i.e.*, biologically fixed N replaces synthetic N fertilizer thereby avoiding the related CO_2 emissions due to its manufacture). Fixed N values (kg ha^{-1}) were calculated by multiplying the measured N yields by the percentages of nitrogen derived from the atmosphere. In the case of sulla this value was equal to 80% in the autumn, this result was based on previous experiments (Sulas *et al.*, 2009). Finally, an emission value of 4.5 kg CO_2-eq. for the manufacture of 1 kg N-fertilizer product was considered (Tirado *et al.*, 2010).

An economic analysis was performed in order to estimate the feasibility of introducing starter irrigation practice in the sulla cultivation. Differences in terms of costs were calculated by considering the hypothetical conditions of the study (*e.g.*, non-seasonal rainfall occurrence). Net Income was calculated by using the land occupied by sulla (ha) as a reference unit. Concerning revenues, they were estimated from the value related to the increase in milk forage units (MFU) derived from the application of starter irrigation. The unit value considered was the marketable value of barley grain (1 MFU = 1 kg barley grain) which was equal, on average, to 0.31 € kg^{-1} in the Italian market (ISMEA, 2022). The costs associated with labour were estimated in terms of incremental wages according to the total work expended for starter irrigation. In terms of the water cost, we considered the fees of the Water User Association (Consortium for land reclamation and irrigation of Nurra), which supplies irrigation water to a part of the area. Finally, the annual depreciation, insurance, and maintenance quotas related to the irrigation system were also calculated.

The data of dependent variables (the leaf traits, the contents and yields of shoot DM, N, CP and condensed tannins, fixed N, MFU and CO$_2$ emissions were subjected to an analysis of variance using the MIXED procedure (SAS v 9.2 1999). Blocks were considered to be a random effect factor, whereas the two treatments and the sampling dates were considered to be fixed-effect factors. Significance was determined using the F statistic, and $\alpha = 0.05$. All data, when necessary, were log-transformed to obtain a homogeneity of variance.

RESULTS

The total rainfall from September 2020 to August 2021 was 688 mm, about 15% higher than the long-term value, whereas it was 50% lower than the corresponding long-term value from September 2021 to May 2022 (Fig. 1). Rainfall was totally absent in September 2021, whereas in the subsequent October, November and December of 2021 represented 112, 107 and 134% of the corresponding climatic values, respectively. However, the first substantial rainfall event only occurred late (October the 29th) and was coupled with the usual drop in temperature. It is worth noting that the absence of rainfall from the 1st of September to the 29th of October 2021 occurred after an unusually hot and dry summer. Such a prolonged drought event hindered the vegetative regeneration of sulla until early November and prevented soil tillage operations for new sowings.

The relevant microclimatic differences were recorded between the RAI and STI plots (Fig. 2). From mid-September to late October, starter irrigation interventions induced high values in soil water content (SWC) as compared to the rainfed condition, except for an isolated rainfall event on the 6th of October, which produced only a temporary increase in the SWC of rainfed plots. From the end of October

Table 1. Autumn variations in *Sulla coronaria* leaf length, area, mass, chlorophyll contents (SPAD units) and chlorophyll fluorescence (Fv/Fm) in the starter irrigated (STI) and rainfed plots (RAI) (2021)

Date	Leaf length (cm)		Leaf area (cm^2)		Leaf mass (g)			SPAD			Fv/Fm		
	RAI	STI	RAI	STI	RAI	STI	P>F	RAI	STI	P>F	RAI	STI	P>F
04-Nov	19.5(0.7)	27.6(0.9)a	27.3(2.2)	57.6(4.8)a	0.24(0.02)	0.41(0.04)a	*	66.6(2.6)b	46.6(1.8)a	**	0.83(0.00)ab	0.84(0.00)a	ns
18-Nov	19.6(0.5)	33.5(1.0)b	27.9(1.7)	67.3(3.9)a	0.24(0.03)	0.48(0.03)a	*	51.9(1.7)a	46.2(1.2)a	ns	0.82(0.00)ab	0.81(0.00)ab	ns
01-Dec	19.7(0.8)	36.8(0.9)c	35.7(2.8)	78.8(4.8)b	0.28(0.02)	0.55(0.07)b	*	50.8(2.5)a	49.0(1.1)b	ns	0.79(0.00)bc	0.81(0.00)ab	ns
15-Dec	17.7(0.5)	39.2(1.0)d	32.9(2.7)	98.9(6.1)c	0.25(0.02)	0.81(0.06)b	*	46.1(1.0)a	47.6(1.5)b	ns	0.75(0.02)a	0.77(0.01)c	ns
28-Dec	20.7(0.7)	42.0(1.4)e	39.2(1.8)	91.3(5.5)d	0.25(0.01)	0.71(0.03)b	*	50.9(1.2)a	47.5(1.0)b	ns	0.85(0.00)c	0.840.00)a	ns

LSD test for treatment differences. *$p \leq 0.05$, **$p \leq 0.01$, ns – not significant. Different small letters indicate significant differences (LSD test) within treatment among sampling dates.

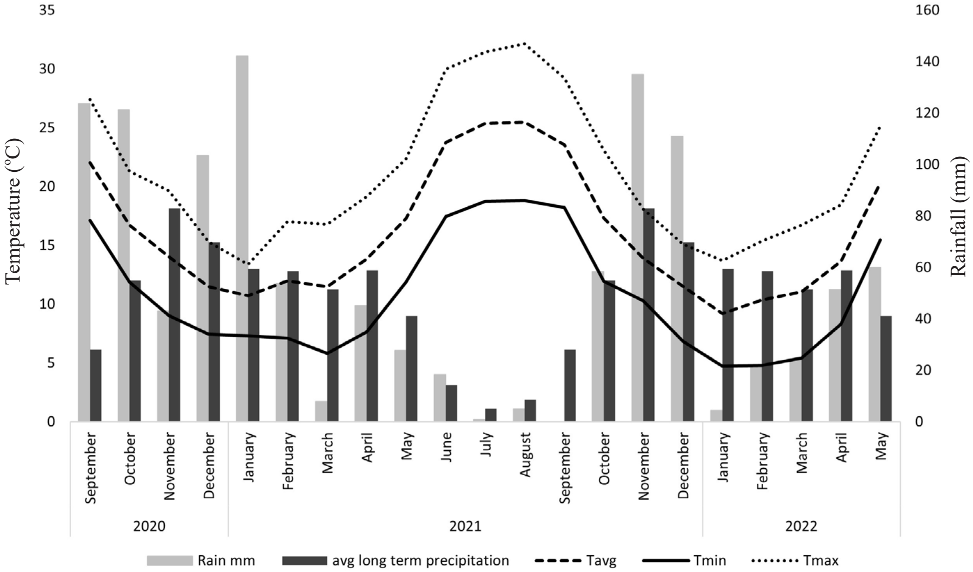

Fig. 1. Monthly temperature and rainfall trends from September 2020 to May 2022.

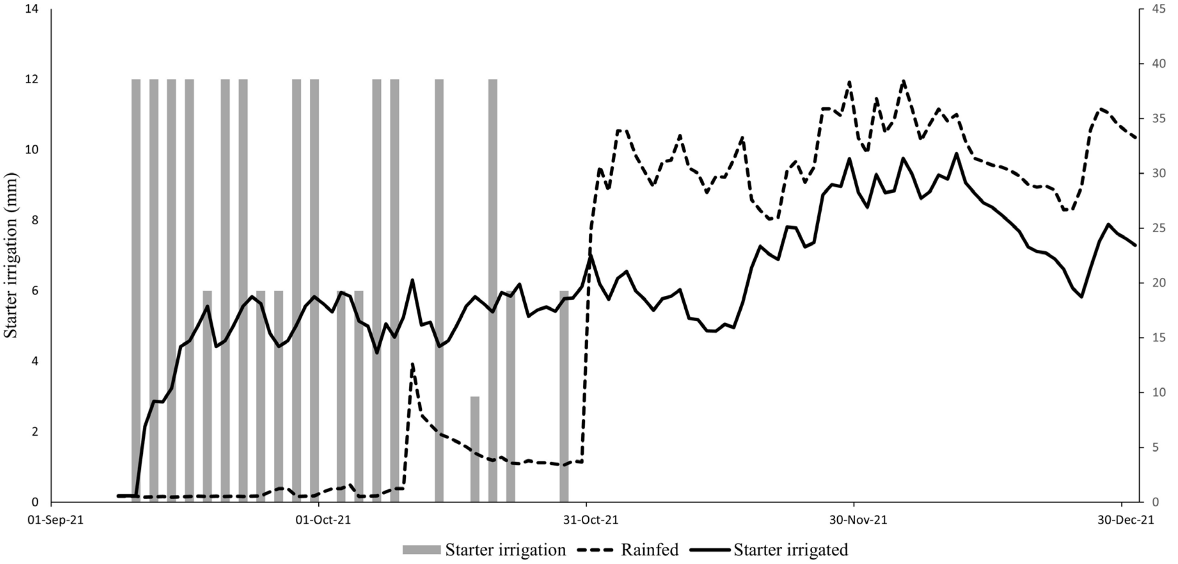

Fig. 2. Soil water content trend from September to December 2021 in the starter-irrigated and rainfed plots.

(at the onset of the important break season rainfall events and at the termination of starter irrigation) to December, SWC values (36 – 42%) differed again between treatments, being higher in rainfed plots.

The leaf length showed significant differences between treatments and measurement dates within those treatments by varying from the first to the last measurement date from 27.6 to 42 cm in STI and from 19.5 to 20.7 cm in RAI, respectively (Table 1). It is worth noting that steady and significant increases in leaf length continued even after the termination of starter irrigation. The leaf area showed significant differences between treatments and dates within STI, ranging from 27 to 39 cm^2 in the rainfed plots and from 58 to 99 cm^2 in the irrigated plots, respectively. In the latter it showed more than a double leaf expansion. The single leaf mass, with significant differences between treatments and sampling dates within STI, showed an average weight of 0.24 – 0.28 g in RAI leaves as compared to 0.41 to 0.81 g in STI leaves, with an average of double the amount of dry matter per leaf. The different treatments did not influence the chlorophyll content of the sulla leaves, except on the 4th of November when starter-irrigated leaves showed 50% higher values than rainfed ones. Measurements of chlorophyll fluorescence such as Fv/Fm (maximum quantum efficiency of Photosystem II) were unaffected by the treatment, with mean values of 0.80 and 0.81 in RAI and STI leaves, respectively.

Table 2. Evolution of dry matter percentage (DM), crude protein (CP), condensed tannin (CT) contents and yields and milk forage units (MFU) in *Sulla coronaria* shoots as affected by starter irrigation (STI) or rainfed condition (RAI) treatments and different cutting dates

Parameter	October			November			December		
	RAI	STI	P>F	RAI	STI	P>F	RAI	STI	P>F
DM content (%)	14.05(0.11)c	9.03(0.03)b	**	12.15(0.20)b	8.89(0.18)ab	**	10.41(0.09)a	8.53(0.12)a	**
DM yield (kg ha^{-1})	197.0(35.9)a	1231.3(238.6)a	**	298.8(39.2)b	2704.8(128.4)b	**	530.7(47.0)c	5237.2(581.9)c	**
CP content (%)	21.9(0.06)a	25.6(0.03)b	ns	21.5(0.03)a	20.6(0.04)a	ns	25.5(0.3)b	20.8(1.0)a	ns
CP yield (kg ha^{-1})	43.1(7.8)a	315.5(61.2)a	**	64.2(8.5)b	556.2(26.0)b	**	135.3(11.6)c	1090.0(135.7)c	**
CT content (g DE kg^{-1} DM)	33.54(0.34)c	20.45(0.58)c	**	23.34(0.16)a	13.67(0.80)b	**	27.14(0.49)b	6.99(0.18)a	**
CT yield (kg ha^{-1})	6.44(0.07)a	25.18(0.71)a	**	6.97(0.05)a	36.97(2.16)b	**	14.40(0.26)b	36.59(0.93)b	**
MFU (kg^{-1} DM)	0.71(0.00)	0.67(0.00)	ns	0.73(0.00)	0.72(0.00)	ns	0.70(0.00)	0.70(0.00)	ns

LSD test for treatment differences. **$p \leq 0.01$, ns – not significant. Different small letters indicate significant differences (LSD test) within treatment among sampling dates.

Across the three autumn sampling dates, the dry matter percentage was significantly higher in rainfed plants with a decreasing trend from the first to the last sampling, when the difference between the STI shoots was reduced (Table 2). The evolution of undisturbed herbage accumulation showed relevant and significant differences between treatments and sampling dates within the treatment. From the first to the last sampling date, the available DM ranged from 197 to 531 kg ha^{-1} in the RAI plots, whereas it markedly increased from 1 231 to 5 237 kg ha^{-1} in STI plots, corresponding to an approximately 9-fold increase in DM production. For the conditions of the experiment, this indicated that the starter irrigation was a useful practice to guarantee remarkable amounts of forage before winter. The crude protein content was unaffected by the treatment but it was significantly affected by the sampling date. In STI plants this value was higher for the first sampling as compared to the remaining sampling dates. By contrast, this value was higher for the last sampling date in rainfed plants. The crude protein yield was significantly affected by both the treatment and the sampling date. The final values of the crude protein yield in STI plants increased 3-fold as compared to the first sampling. Also, the final yields were about 9-fold higher than the corresponding values for rainfed plants. Interestingly, the content of condensed tannins in rainfed shoots was significantly higher (range 23.3 - 33.5 g DE kg^{-1} DM, corresponding to a 1.6 – 3.9-fold increase) for all of the sampling dates. In the STI plants, a consistently decreasing trend of condensed tannin contents was recorded from the first to the last sampling date. The yield of condensed tannins was significantly affected by the treatment in all sampling dates and by the sampling date within the treatment. Overall, the yield of condensed tannins in sulla shoots was significantly higher (from 2.5 to 5.3-fold) in starter-irrigated plants. The value of milk forage units per kg of DM did not differ significantly across the sampling dates, it ranged from 0.67 to 0.73.

It is worth noting that the seasonal water productivity increased from 0.20 (RAI) to 1.05 (STI) kg of forage DM m^{-3}. For the same samples, the WP values increased from 50 to 220 g of crude protein m^{-3} and from 5 to 7 g of condensed tannins m^{-3}. Therefore, the adoption of starter irrigation significantly increased the efficiency of the transformation of water into forage and CP thereby improving the overall yield and quality of the forage (Fig. 3).

In considering the entire biennial crop cycle, 5 600 and 400 kg ha^{-1} of forage and crude protein were supplied through 2021 spring cutting and these values were in line with previous results in the same region. For the average results produced by the STI and RAI plots, the spring cutting values for 2022 were half what they were for the previous year as they were markedly reduced by unfavourable weather. It is worth noting that, compared to the rainfed treatment, the starter irrigation applied in the

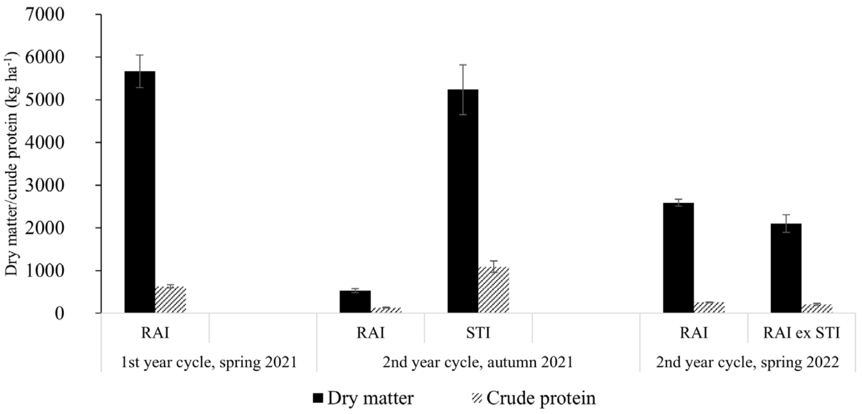

Fig. 3. Forage dry matter and crude protein yield at different seasonal cutting times during the biennial crop cycle of *Sulla coronaria* with the application of starter irrigation (STI) in autumn 2021 and also rainfed (RAI). The bars are standard errors of the mean (n = 4).

Table 3. Trend of the estimated of biologically fixed N in *Sulla coronaria* shoots and saved CO_2 emissions (CO_2-eq. kg^{-1} N – fertilizer product) as affected by starter irrigation (STI) or rainfed condition (RAI) treatments and different cutting dates

October			November			December		
RAI	STI	P>F	RAI	STI	P>F	RAI	STI	P>F
				Biologically Fixed-N (kg ha^{-1})				
10.2(1.0)	40.4(7.8)a	**	8.2(1.1)	62.4(3.3)b	**	17.5(1.5)	139.4(17.4)c	**
				Emission saved CO_2-eq. (kg ha^{-1})				
46.1(4.5)	181.9(35.3)a	**	36.9(4.9)	281.5(15.0)b	**	78.5(6.7)	627.5(78.2)c	**

LSD test for treatment differences. **$p \leq 0.01$, ns – not significant. Different small letters indicate significant differences (LSD test) within the treatment between the different cutting dates.

autumn induced 41 and 67% increases in forage and crude protein yields within the scope of the entire biennial crop cycle.

For the last sampling of December, fixed N was 17.5 kg ha^{-1} in the RAI plots whereas they reached approximately 140 kg ha^{-1} in the STI plots, this corresponded to an approximately 8-fold increase in fixed N values (Table 3). The same trend was found in terms of saved CO_2 emissions. Importantly, the data from Table 3 indicated seasonal net gains of approximately 120 kg ha^{-1} of fixed N and 548 kg of saved CO_2 eq. ha^{-1} due to the effects of the starter irrigation. These gains in values are conservative estimates as the estimation of N fixation was made with reference to the sulla aerial biomass and the below-ground N contribution was not considered. Additionally, CO_2 emissions for N fertilizer transportation and distribution were not computed. A balance-sheet analysis considering the possible incremental revenues and costs was applied. Interestingly, MFU expressed on a per hectare basis showed an increasing trend from the first to the last sampling, when the values of the irrigated plants were 4.5-fold higher than the initial values in October (data not shown).

Importantly, the results show that the annual profitability would increase by 881 € ha^{-1} (Table 4). The cost associated with the implementation of starter irrigation is

Table 4. Results on balance-sheet analysis on introduction of starter irrigation

Variable	Unit	Value
A. Revenues		
A.1 Value of incremental MFU*	€ ha^{-1}	1 020.210
Incremental MFU	MFU ha^{-1}	3 291.000
Unit value of MFU	€ MFU^{-1}	0.310
Total revenues		1 020.210
B. Cost		
B.1 Labour	€ ha^{-1}	36.000
Wage	€ h^{-1}	12.000
Time spent for each irrigation shift	H	0.250
Number of irrigation shifts	n.	12.000
B.2 Water	€ ha^{-1}	12.960
Volume of seasonal watering	m^3 ha^{-1}	2 160.000
Rate of water consume	€ m^{-3}	0.006
B.3 Irrigation system (quotas)	€ ha^{-1}	90.000
Total cost	€ ha^{-1}	138.960
Net income (A – B)	€ ha^{-1}	881.250

*MFU – French milk forage unit.

relatively low with respect to the revenues, which are due to the value of the additional forage produced. Therefore, these findings suggest that the economic benefits derived from the introduction of starter irrigation largely overcome the incremental costs, meaning that a valid economic case exists for its implementation.

DISCUSSION

The previous literature focused on the need for a more regular forage availability for alleviating the forage shortages typical of traditional rainfed Mediterranean farming systems (Fois *et al.*, 2000). There is a consensus concerning the valuable traits of sulla as a pasture, forage and multipurpose plant and the recent availability of the commercial inoculant strain allows for its full exploitation outside the traditional cropping area (Sulas *et al.*, 2017). However, the effects of climate change might jeopardize the productive potential of sulla by hindering its autumn vegetative regeneration ability, which is a valuable trait of this forage legume.

In accordance with the previously noted extent and frequency of autumn drought and temperature increases (Fiori *et al.*, 2017; Caloiero *et al.*, 2021), the drought event experienced in autumn 2021 delayed the vegetative regeneration of sulla plants. As a consequence, the availability of forage was very scarce which represented a severe drawback at the farm level. The water supplied with starter irrigation, served to buffer the drought event, and has led to excellent results in terms of both forage availability and quality.

Overall, when comparing starter-irrigated vs. rainfed sulla plants, the relevant effects were recorded on most of the investigated biometric traits, which indicated the productive and qualitative performances of each cultivation approach. Interestingly, these effects were maintained over time, even after the suspension of starter irrigation. Taken together, our results indicate the precise role of applying starter irrigation in favouring the leaf development and vegetative growth of sulla. Under the conditions of a Mediterranean climate, herbage growth usually slows down during the colder months and may actually stop depending on the altitude (Fois *et al.*, 2000; Molle *et al.*, 2004). Other than assuring soil cover, the amounts of green leaves and leaf area are essential for plant growth, which is based on their ability to intercept sunlight and transform non-organic carbon into carbohydrates. Starter irrigation induced huge differences in terms of the available forage in late autumn as compared to the rainfed conditions. Fois *et al.* (2000) reported 1.9 t ha^{-1} available sulla forage and values in the range 1.7 – 2.2 t ha^{-1} were obtained by Sulas *et al.* (2009). Undoubtedly, the amplitude of differences is mainly attributable to the unfavourable and extreme weather conditions experienced from summer to October 2021 that hampered and delayed the vegetative regeneration of sulla plants. It is worth noting that starter irrigation supported the values of available forage exceeding 5 t ha^{-1}, which may be regarded as a relevant and strategic stock of standing forage. It also represents an absolute peak value about twice as high as the usual yield obtained in the previous years, which were not subjected to extreme weather events. Unfortunately, other results dealing with starter-irrigated sulla plants have not been made available to date, with the exception of the results obtained in Menorca (Spain), where a 2nd year sulla stand produced 9-fold more DM than the unirrigated control, which was similar to our results (Cifre *et al.*, 2012). In that experiment, sulla was irrigated during the entire crop cycle which is unusual, the abovementioned management regime is quite questionable in the context of a typical Mediterranean drought tolerant legume (summer dormancy) and considering the superior productive potential of other irrigated perennial legumes (*e.g*. lucerne).

Other important implications refer to the obtained results regarding variations in the crude protein content and in the yield of sulla shoots, ranging from 20.6 to 25.6% and suppling a fodder resource, which represents a valuable alternative to the more expensive purchasing of concentrate supplements from the marketplace. Additionally, our results supported new insights regarding the seasonal variation in condensed tannins, which demonstrated the strong effect of environmental conditions (*e.g*., variations in soil water content) on the autumn concentration of condensed tannins. The results demonstrated that the stress conditions induce a higher concentration of condensed tannin in sulla shoots, this is in agreement with previous findings, which indicate that leaflets are plant organs with the highest content of phenolic compounds, this was confirmed by Piluzza *et al.* (2014). Furthermore, it should be pointed out that in less developed rainfed leaves, the leaflet contribution to the entire leaf is higher than that of the petioles. Re *et al.* (2014) reported a value of 33.8 (g DE kg^{-1} DM) for sulla leaves in spring regrowth, in agreement with our results (33.5 g DE kg^{-1} DM) for rainfed sulla in October.

Condensed tannins play a pivotal role in animal production and welfare. Several authors have documented the positive effects of grazing sulla in improving the nutrition and performance of sheep as well as on ewe milk production and its quality (Di Trana *et al.*, 2015). The high nutritive value of sulla forage and the beneficial level of condensed tannins are reported to be linked to more rapid growth rates in young sheep, an increased protein use efficiency in rumen, bloat safety, and a decreased rate of gastrointestinal parasite infection and methane production in ruminants (Piluzza *et al.*, 2014).

As sulla has not been treated with N fertilizer, the remarkable amounts of N incorporated in the starter-irrigated sulla shoots is a reliable clue concerning the satisfactory N fixation activity by sulla. Previous studies have documented the ability of this legume to fix atmospheric nitrogen through its symbiosis (Sulas *et al.*, 2009, 2017, 2019). Fixing N represents a net N gain for the cropping systems leading to a saving in terms of the synthetic

N fertilizer used, with biologically fixed N from the atmosphere as well as higher amounts of biomass resulting in a higher storage level of carbon dioxide. The application of starter irrigation avoids the CO_2 emissions associated with synthetic N fertilizer and thereby proved to be a successful mitigation measure. It is important to note that Gazoulis *et al.* (2023) recommend that weed control should be considered an essential agronomic practice when using starter irrigation in order to avoid weed competition. However, in the conditions of our experiment, starter irrigation did not promote weed emergence and pressure on the crop.

Starter irrigation, which is a type of supplemental irrigation, provides water at the critical stages when rainfall didn't occur, and proved to increase the productivity of the available water (Molden *et al.*, 2010). This practice is considered to be particularly effective when water supplies are constrained by the limited supply or the high costs of water. According to Molden *et al.* (2010) many factors must be considered in the effort to improve water productivity. These include changes in the prices of agricultural commodities, the increasing demand for biofuels, urbanization and dietary changes occurring as a consequence of a rising population (Molden *et al.*, 2007a, b), considerations involving the trade-off between water prices and financial assistance, at the EU, national and regional level, in order to help producers to recover from production and physical losses due to drought. The policies that influence these drivers will also influence water use, and thereby influence the scope for gains in water productivity.

It is interestingly to note that economic benefits were obtained in terms of the potential extra product that the farmer can place on the market or through savings made on the costs of feed.

Based on our findings, it is evident that important benefits for ruminants coupled with services provided to the ecosystem can be guaranteed through a targeted exploitation of water resources aimed at supporting vegetative regeneration for the successful re-establishment of the sulla crop. Our results indicated that the establishment of unconventional watering interventions in a typical rainfed cropping system may contribute, by improving the efficient use of natural resources, to overcoming the challenges imposed by climate change. Lastly, it has been demonstrated that the economic convenience of starter irrigation is coupled with proven environmental benefits arising from the remarkable amounts of saved CO_2 emissions, this is worthy of serious consideration.

Further studies based on the implementation of digital agriculture technologies are required in order to optimize the efficacy and efficiency of starter irrigation, as a proposed simple technology for climate-smart agriculture in Mediterranean rainfed ecosystems. In fact, this study is a screening trial, the preliminary results of which will help to provide information for more robust multifactorial field irrigation trials in the future that may be used to assess the impact of additional agricultural practices on sulla yield and quality.

CONCLUSIONS

1. In the scenario of an altered rainfall pattern, the adoption of starter irrigation proved to be an effective tool to assure and optimize the vegetative regeneration ability of a sulla crop.
2. The results achieved new insights regarding both quantitative and qualitative sulla performance and the efficiency of transforming water into forage and crude protein.
3. Starter irrigation positively affected the seasonal leaf biometric traits leading to substantial increases in forage and crude protein yields.
4. In the meantime, it contributed substantially via fixed N to the lowering of CO_2 emissions and also to increasing the annual income per hectare.
5. Starter irrigation is a viable proposition which should be implemented in typical rainfed sulla cropping as a promising practice for contributing to more regular forage availability and as an effective adaptation strategy against the adverse effects of climate change.

Conflicts of interest. The authors declare no conflict of interest.

Data availability statement. The data presented in this study are available on request from the authors.

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