Assessing the effect of rotational grazing adoption in Iberian silvopastoral systems with Normalized Difference Vegetation Index time series

Antonio Frongia,[1] Antonio Pulina,[1] Alberto Tanda,[1] Giovanna Seddaiu,[1] Pier Paolo Roggero,[1] Gerardo Moreno[2]

[1]*Department of Agricultural Sciences and Desertification Research Centre, University of Sassari, Italy;* [2]*Forest Research Group, INDEHESA, University of Extremadura, Plasencia (Cáceres), Spain*

Highlights

- *The effect of the adaptive multi-paddock grazing system was assessed in Iberian silvopastoral farms through NDVI time-series analysis.*
- *Land-surface phenology parameters were calculated from the NDVI-time series with the TIMESAT software.*
- *An overall positive effect of rotational grazing on phenological parameters associated with forage availability was observed.*
- *A reduction of NDVI spatial variability was observed after adopting rotational grazing, suggesting higher exploitation of forage resources by animals.*

Correspondence: Antonio Pulina, Department of Agricultural Sciences and Desertification Research Centre, University of Sassari, viale Italia 39/A, Sassari 07100, Italy. E-mail: anpulina@uniss.it

Key words: TIMESAT, adaptive multi-paddock grazing, grazing management, grassland phenology, remote sensing.

Contributions: all the authors made a substantive intellectual contribution, read and approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

Conflict of interest: the authors declare that they have no competing interests, and all authors confirm accuracy.

Funding: the study was within the PhD course in Agricultural Sciences at the University of Sassari. The PhD scholarship of the first author was founded by the Sardinian Regional Government through the P.O.R. SARDEGNA F.S.E. 2014-2020 Axis III program. The study was conducted in the context of the PON-AIM (Attraction and International Mobility) project AIM18CC625 founded by the Italian Ministry for University and Research, the ATLANTIDE project - Advanced Technologies for LANds management and Tools for Innovative Development of an EcoSustainable agriculture - founded by the Autonomous Region of Sardinia, the Project PID2019-108313RB-C31/AEI/10.13039/501100011033 funded by the Spanish State Research Agency, and in the context of the LIFE-Regenerate (LIFE16 ENV/ES/000276) - Revitalizing multifunctional Mediterranean agrosilvopastoral systems using dynamic and profitable operational practices - project.

Availability of data and materials: data and materials are available from the corresponding author upon request.

Received: 21 April 2023.
Accepted: 30 May 2023.
Early view: 31 May 2023.

Italian Journal of Agronomy 2023; 18:2185
doi:10.4081/ija.2023.2185

Abstract

Adaptive multi-paddock (AMP) is a grazing system that combines intensive, rapid grazing livestock rotation with relatively short grazing periods and a long recovery time after grazing. The study assesses, under Mediterranean silvopastoral systems, changes in pasture phenology and spatial variability after adopting the AMP under contrasting land cover (wooded grassland *versus* grassland) with a remote sensing approach based on the time-series analysis of the normalized difference vegetation index (NDVI) from remote sensing through the Landsat satellite. The study revealed an overall positive effect of rotational grazing on pasture phenology and NDVI spatial variability. The AMP adoption resulted in higher estimated values of NDVI at the beginning (under grassland land cover), the end, and the peak of the growing season, while no differences were observed in parameters estimating the length of the growing season. The spatial variability of NDVI was always lower under AMP than in continuously grazed areas, except in the early stages of the growing season under grassland land cover. The results suggested that in a relatively short period (4-5 years), the AMP grazing system can represent a strategy to improve forage availability and exploitation by grazing animals under low stocking rates in extensively managed Mediterranean silvopastoral systems.

Introduction

Mediterranean silvopastoral farms are characterized by multifunctional and extensive management, integrating forage provision for grazing livestock and forestry (Seddaiu *et al.*, 2018; Torralba *et al.*, 2018). In the Iberian peninsula, these systems, covering about 3.14 Mha (den Herder *et al.*, 2017), are mainly managed wooded grasslands known as Dehesas and Montados in Spain and Portugal, respectively (Moreno *et al.*, 2015; Plieninger *et al.*, 2021).

The grassland vegetative cycle of Mediterranean silvopastoral systems is characterized by seasonal variations in plant species composition and productivity, which are, in turn, linked to the seasonal variability in rainfall and temperatures (Porqueddu *et al.*, 2016; Lumbierres *et al.*, 2017). The pasture annual growing season starts in autumn when the first favorable rains occur, and, after a dormancy period in winter due to the low temperatures, the combination of increasing temperature and water availability establishes the conditions for increasing pasture productivity in spring. In summer, the lack of precipitation and high temperatures negatively influence the final stages of the vegetative pasture cycle (Golodets *et al.*, 2015; Seddaiu *et al.*, 2018). Forage availability during the growing season is also influenced by grazing management (Peco *et al.*, 2006; Castillo-Garcia *et al.*, 2022). In these silvopastoral systems, commonly, grazing occurs continuously under large grazing areas, with low stocking rates that do not vary during the year, independently from seasonal variations in grassland production and forage availability (Olea and San Miguel-Ayanz, 2006; Casals *et al.*, 2010; Pulina *et al.*, 2022). This continuous grazing system can trigger land degradation processes, including reduction of pasture cover and quality (Carmona *et al.*, 2013; Pulido *et al.*, 2018), soil degradation and erosion (Ibáñez *et al.*, 2007; Pulido *et al.*, 2017), and lack of tree regeneration (Carmona *et al.*, 2013; Rossetti and Bagella, 2014).

Adaptive Multi-Paddock (AMP) grazing is a rotational grazing system combining intensive and rapid grazing livestock rotation with adaptive decision-making in terms of stocking rates by varying paddock size and duration of grazing events and species (Gosnell *et al.*, 2020). Different effects of the AMP on ecosystem services are reported in the literature. Some scholars (*e.g.*, Teague *et al.*, 2011; Park *et al.*, 2017) observed that the AMP increases grassland productivity and positively affects the entire ecosystem by improving soil properties (structure, organic substance content, availability of water or nutrients) and meadow species diversity. In their meta-analysis conducted under a wide range of environmental conditions worldwide, Byrnes *et al.* (2018) found that rotational grazing could improve soil organic carbon and bulk density over continuous grazing strategies, which could have eventual benefits for pasture production. On the other hand, the meta-analyses conducted by Briske *et al.* (2008) and Hawkins (2017) reported no evidence that AMP grazing has an enhanced effect on vegetation characteristics compared to less rotational practices. Experimental limitations (*e.g.*, spatial limitations, short-term nature, and inflexible grazing treatments) have prevented researchers from adequately accounting for the spatial heterogeneity of vegetation in AMP systems (Teague *et al.*, 2013).

Remote sensing through satellite data is widely used to quantify crop productivity, forage crops, and grasslands. Studies on biomass production and the impacts of management practices on forage availability through remote sensing data are often focused on homogeneous grasslands (Reinermann *et al.*, 2020). Nevertheless, the shape, complexity, and heterogeneity of agroforestry systems make remote sensing more difficult than in distinct and homogeneous land cover types, such as forests and grasslands (Weiss *et al.*, 2020; Pulina *et al.*, 2023). The complexity increases when remote sensing tools are used to determine the phenological phases and pasture changes since these systems combine an herbaceous and shrubby understory with a low-density tree cover (Arenas-Corraliza *et al.*, 2020; Pulina *et al.*, 2023). Among the spectral indices developed for vegetation monitoring, the normalized difference vegetation index (NDVI) is the most frequently used as a proxy of the fractional absorbed photosynthetically active radiation for monitoring grassland dynamics, which in turn is related to grassland production and then forage availability for grazing (Reinermann *et al.*, 2020; Stumpf *et al.*, 2020). Furthermore, the analysis of NDVI variability can provide information on grazing management efficiency since the NDVI variability indices within grazing units, such as the NDVI standard deviation (SD), are related to the level of exploitation of forage resources by grazing animals (Liu *et al.*, 2021).

In a context of disagreement and uncertainty on the impacts of adopting AMP as a management practice to improve the productivity and stability of forage resources in pasturelands, it becomes crucial to assess the effects over time of grazing management changing from continuous to AMP. Furthermore, an increasing demand for innovative tools supporting the assessment of the impacts of management practices on forage availability under extensive grazing systems emerges. In this context, the NDVI from remote sensing can represent an effective tool to properly explore the quantity and variability of forage availability over time (Blanco *et al.*, 2009).

In the context of Mediterranean silvopastoral grazing systems, this study hypothesized that adopting rotational grazing under different land covers [wooded grassland (WG) and grassland (GR)] can have a positive impact on pasture phenology and forage spatial variability using NDVI time series from the Landsat satellite as a proxy. The aims of the study were, under contrasting land covers, to assess the effect of the adoption of the AMP grazing system on i) a set of NDVI-derived phenological parameters describing the grassland growing season; and ii) the spatial variability of NDVI as a proxy of forage spatial distribution at different phenological stages of the pasture.

Materials and Methods

Study site

The study area was located in the south-western Iberian peninsula, within three livestock farms located in south-western Spain, in the Extremadura region (Zapatera, 38°33'47 "N; 5°48'42 "W), and south-eastern Portugal, in the Alentejo region (Vale de Grau and Defensinhas, 39°6'24 "N; 7°3'14"W and 38°48'1"N; 7°10'8"W, respectively). The climate is Mediterranean pluviseasonal continental (Rivas-Martínez *et al.*, 2011), characterized by a hot, dry summer and a cold, rainy winter. According to Global Climate Monitor (2023), on Portuguese and Spanish sites, the mean annual air temperature is 16.3°C and 16.5°C, and the average annual rainfall is about 700 mm and 520 mm, respectively, most of which falls from October to December. The whole experimental area was about 2250 ha, distinguishable according to CORINE Land Cover as agroforestry silvopastoral land cover (43.3%), non-irrigated arable land (35.5%), grasslands (12.4%), permanently irrigated land (3.9%), transitional woodland-shrub (3.8%) and broad-leaved forest (1.0%). The tree vegetation within agroforestry areas was characterized by scattered trees, mostly belonging to *Quercus ilex* L. subsp. *ballota* and *Quercus suber* L.. The herbaceous layer covered almost all of the study area and was composed of a wide variety of annual grassland species from three main functional plant groups: grasses, forbs, and legumes, with a relative cover of around 50%, 30%, and 20%, respectively (Hernández-Esteban *et al.*, 2019). The more frequent species are *Anthoxanthum aristatum* Boiss., *Festuca bromoides* L., and *Festuca geniculata* (L) Lag. & Rodr., *Plantago lagopus* L., *Tolpis barbata* (L.) Gaertn., *Lotus parviflorus* Desf., *Ornithopus compressus* L., *Trifolum striatum* L., and *Trifolium subterraneum* L. (Migliavacca *et al.*, 2017).

The grassland areas within these livestock farms were grazed by cattle and sheep, traditionally managed with continuous grazing and low stocking rates. Within each farm, two different land covers were identified: WG and GR. The AMP grazing system was introduced in some fields of each farm between 2014 and 2016, thus identifying a period before the AMP adoption (before 2014, 2010-2014), a transition period (2014-2016), and a period after which the AMP grazing system was well established (2016-2021). In addition to these fields, large areas within each farm were managed with continuous grazing (CON) during the same period. In each farm, the stocking rate was, on average, 0.4 LSU ha^{-1} y^{-1}, with an instantaneous density of up to 20 LSU ha^{-1} under AMP with grazing periods of around three days repeated 2-3 times per year in every paddock. Details on farms, grazing animals, land covers, and grazing management schemes are reported in Table 1 and Figure 1.

Remote sensing data collection

Landsat images were collected from the United States Geological Survey (2023) web service. Landsat Level-2 images with less than 10% of cloud cover were collected among those available (every 16 days) by Landsat-5 thematic mapper (TM) and Landsat-7 enhanced thematic mapper (ETM) from January 2010 to March 2013 and by Landsat-8 operational land imager/thermal infrared sensor (OLI/TIR) from April 2013 to December 2020. Images from both satellites had a 30×30 m spatial resolution per pixel. For this study, red and near-infrared (NIR) bands of both

Table 1. Farm location and surface of the pasturelands (ha) within grassland and wooded grassland land cover under adaptive multi-paddock and continuous grazing systems.

Farm	Coordinates	Grazing animals	Land cover	Grazing management	Surface (ha)	Pixels (n)
Defensinhas	38.79 N-7.18 W	Cattle (Angus breed)	GR	AMP	157.7	1752
				CON	149.3	1659
			WG	AMP	347.9	3866
				CON	285.9	3177
Vale de Grau	39.11 N-7.06 W	Cattle (Angus breed)	GR	AMP	164.8	1831
				CON	117.9	1310
			WG	AMP	34.9	388
				CON	112.1	1246
Zapatera	38.56 N-5.81 W	Sheep (Merina breed)	GR	AMP	172.2	1913
				CON	6.5	72
			WG	AMP	21.3	237
				CON	202.3	2248

GR, grassland; WG, wooded grassland; AMP, adaptive multi-paddock; CON, continuous grazing.

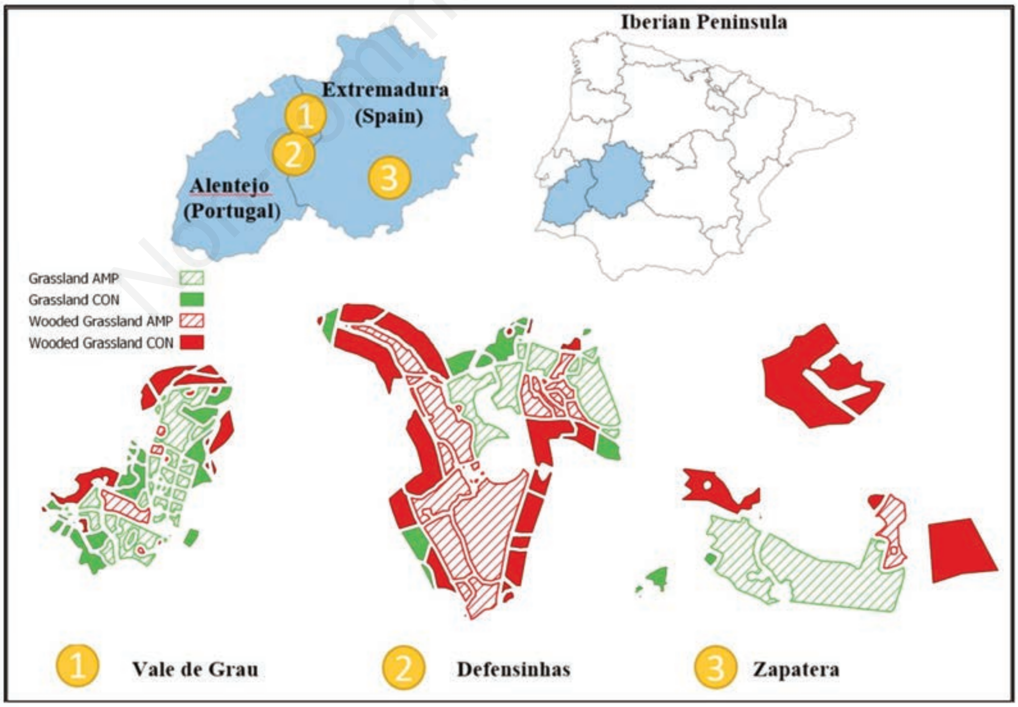

Figure 1. Maps of the 3 farms in the Alentejo (Portugal) and Extremadura (Spain) regions of the Iberian Peninsula. The red areas represent the wooded grassland, and the green areas represent the grassland land cover. Solid areas represent the field in which continuous grazing occurred throughout the study period (2010-2021), while striped areas indicate fields in which the adaptive multi-paddock grazing system has been implemented since 2014-2016. AMP, adaptive multi-paddock; CON, continuous grazing.

satellites were collected, corresponding to a spectral width of 0.63-0.69 µm and 0.64-0.67 µm for red (bands 3 and 4 of Landsat-5/7 and Landsat 8, respectively) and 0.76-0.90 µm and 0.85-0.88 µm for NIR (bands 4 and 5 of Landsat 5 and Landsat 8, respectively).

The QGIS software version 3.14.1 (Geospatial Foundation, Beaverton, OR, USA) was used to pre-process Landsat satellite images. The atmospheric correction was performed to remove any atmosphere effect on reflectance, resulting in remotely sensed images to correct reflectance values at the pixel level using the semi-automatic classification plugin (Congedo, 2020). The quality assurance band included in remote-sensed images was used to remove the effects of the presence of terrain shadowing, data artefacts, and clouds. To reduce spectral noise from path radiance and other elements (*e.g.*, windbreak, water surfaces), parts of images were manually cut by overlapping polygons to raster cells. In addition, to reduce disturbance between the fields, pixels up to 30 m from the border of polygons were excluded from the analyses.

Spectral reflectance at the green, red, and NIR bands was extracted from images using the raster package (Hijmans, 2020) within the R (version 4.0.5) environment (R Core Team, 2021). The extraction was performed by using the shapefiles of farms as extracting layers. The borders of the farms and fields were delimited based on information farmers provided about the grazing scheme.

The NDVI was calculated at pixel level, starting from the reflectance of NIR and red bands as follows (Eq. 1):

$$NDVI = \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + \rho_{red}} \quad (1)$$

where ρ_{NIR} was the reflectance at the near-infrared band, ρ_{red} was the reflectance value at the red band.

The OLI data were transformed to refer their value to TM-ETM sensors to harmonize spectral reflectance values from different satellites (*e.g.*, Flood, 2014). Data from 2013, during which scenes were collected by both Landsat-7 ETM and Landsat-8 OLI sensors, were used to fit linear regression parameters that were used to transform remote sensing data from OLI to ETM sensors. Data were coupled by joining the closest sensing dates among satellites. Relationships between ETM and OLI data for red and NIR bands and linear regression parameters are reported in Figure 2.

Seasonal vegetation parameters and phenological stages

The NDVI time series were analyzed by applying the adaptive Savitzky-Golay smoothing method (Chen *et al.*, 2004), through which a set of seasonal vegetation parameters was obtained. The method was implemented using the TIMESAT software (version 3.3; Jönsson and Eklundh, 2004). For the present study, the algorithm was set based on the NDVI seasonal amplitude (Eklundh and Jönsson, 2017), defined as the difference between the maximum and the base values of NDVI. The list of the seasonal parameters and their descriptions are reported in Table 2.

The starting and ending dates of each season, estimated by the algorithm, were used to identify whether the NDVI data should be included in the growing season. According to this partition, each season was subset into phenological stages as follows: the green stage, when NDVI was higher than 80% of the maximum NDVI; the regreening stage, from the start of the season to the beginning of the green stage; the drying stage, from the end of the green stage to the end of the season estimated by the algorithm; the dry stage, which included NDVI data outside the growing period from the end of the season to the beginning of a new one. A schematic representation of phenological stage identification is reported in Figure 3.

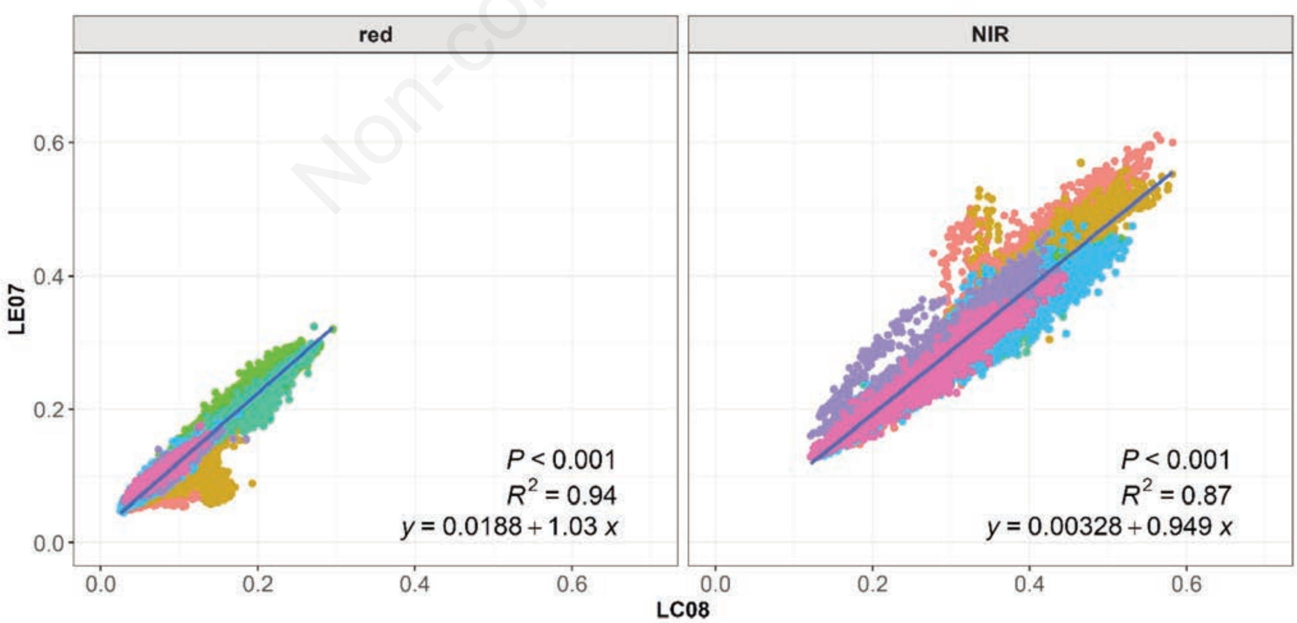

Figure 2. Relationships between the spectral reflectance at the red (left) and near-infrared (right) bands detected with LC08 (Landsat-8 operational land imager) and LE07 (Landsat-7 enhanced thematic mapper) and linear regression equation. Different colors represent different groups of sensing dates. NIR, near-infrared.

Data analysis

After the adoption of the AMP grazing system, a split-plot design with three replicates (farms) was adopted to test the effect of the interaction between land cover (main factor, GR *versus* WG) and grazing scheme (subfactor, AMP *versus* CON) on the seasonal phenological parameters (Table 2). The analysis was carried out by fitting a generalized least squares model (gls), through which the fixed effect of land cover, grazing, and their interaction was computed. Moreover, a compound symmetry matrix was adopted to describe the within-correlation structure through which the random effect of main plots (farm×land cover) and seasons was computed. The analysis of variance (ANOVA) was performed to test the significance of factors and their interactions. When significant effects emerged from the ANOVA, the estimated marginal means (emmeans) of the fitted gls models were computed to compare means at the significant interaction levels and at the simple factors level when the interaction was not.

Table 2. List of TIMESAT (version 3.3) seasonal phenology parameters, units, and their description.

Variable	Abbreviation	Unit	Description
Start of the growing season	SOS	Doy	Time for which the left edge has increased to 20% of the seasonal amplitude measured from the left minimum level
End of season	EOS	Doy	Time for which the right edge has decreased to 20% of seasonal AMP measured from the right minimum level
Time peak	TP	Doy	Time for the seasonal maximum
Length of season	len	Days	Time from the start to the end of the season
Value of the start of the growing season	val_start	NDVI	Value of the function at the time of the start of the season
Value of the end of season	val_end	NDVI	Value of the function at the time of the end of the season
Value of time peak	val_peak	NDVI	Value of the function at the seasonal maximum
Base level	val_base	NDVI	Average of the left and right minimum values
Amplitude	ampl	NDVI	Difference between the maximum value and the base level
Rate of increase	der_l		The ratio of the difference between the left 20% and 80% levels and the corresponding time difference at the beginning of the season
Rate of decrease	der_r		The ratio of the right 20% and 80% levels and the corresponding time difference. The rate of decrease is thus given as a positive quantity.
Large integrated value	integ_large		Integral of the function describing the season from the SOS to the EOS
Small integrated value	integ_small		Integral of the difference between the function describing the season and the val_base from SOS to EOS

NDVI, normalized difference vegetation index; AMP, adaptive multi-paddock.

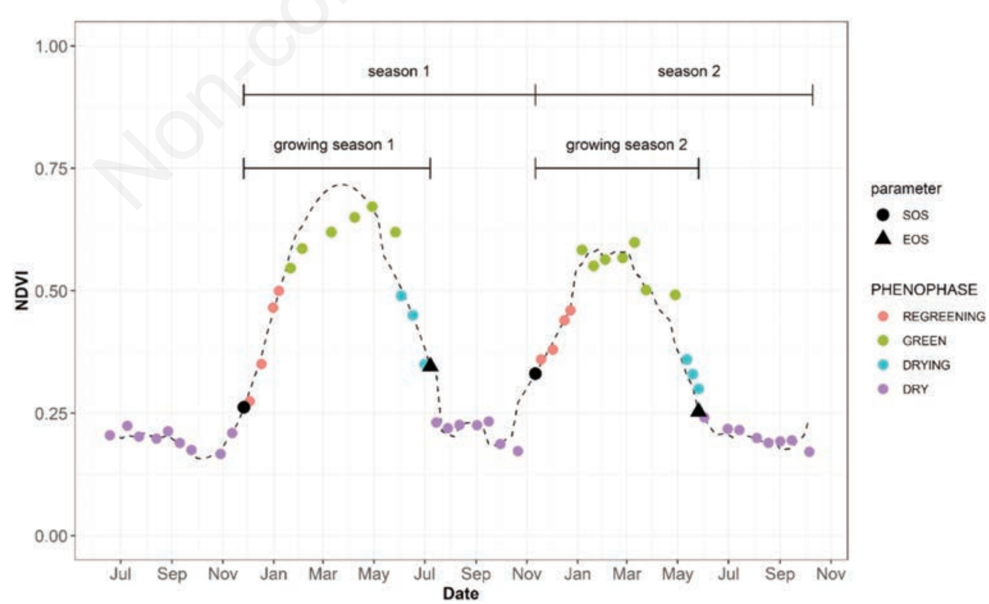

Figure 3. Schematic representation of phenological stage identification over 2 years. The colored dots represent the average normalized difference vegetation index observed in a sensing date within a plot; the black dots and triangles represent the start and the end of the season estimated through the TIMESAT software; the dashed line represents the fitted normalized difference vegetation index values obtained through the Savitzky-Golay smoothing method.

The difference between the average values of the seasonal phenological parameters within each farm before and after the AMP adoption was tested with a Student's two-tail paired *t* test (*t*_test function). To perform the analysis, the differences between the average values of parameters under AMP and CON in both land covers in the after period and the average values of parameters estimated before the AMP adoption were computed.

The effect of grazing management on NDVI variance within sensing dates after the AMP adoption was tested with a 2-tail F-test, through which the significance of the ratios between the variance in AMP and CON areas was tested. To assess the temporal variability, the null hypothesis for which, at each phenological stage and land cover, the average log-transformed F ratios were equal to 0 was tested with a Student's *t*-test.

The significance of statistics was assessed at p<0.05 unless otherwise stated. The gls (Pinheiro *et al.*, 2018), emmeans (Lenth, 2018), ANOVA, and *t* test computations were performed by using the RStudio application of the R environment (version 4.0.5; R Core Team, 2021).

Results

Normalized difference vegetation index dynamics

The NDVI dynamics within each farm before and after the AMP adoption in WG and GR are summarized in Table 3. The NDVI before the AMP adoption ranged between 0.06 and 0.72 in GR (mean 0.34, SD=0.05) and from 0.15 to 0.64 (mean 0.37, SD=0.02) in WG land cover. The NDVI in the after period ranged from 0.06 to 0.74 (mean 0.33, SD=0.07) in GR and from 0.12 to 0.68 (mean 0.37, SD=0.03) in WG land cover.

Seasonal vegetation parameters

The effects of land cover, grazing management, and their interaction on the seasonal vegetation parameters after the AMP adoption are reported in Table 4. The land cover significantly influenced val_end (p<0.0001), which was higher under WG (0.30±0.01) than GR (0.25±0.01), while ampl (p=0.0004, GR=0.43±0.04, WG=0.36±0.04), der_l (p=0.0105, GR=0.024±0.004, WG=0.019±0.004), der_r (p=0.0136, GR=0.034±0.005, WG=0.028±0.005), and integ_small (p=0.0009, GR=9.84±0.95, WG=8.17±0.95) parameters were higher under GR than WG. The grazing scheme significantly influenced the TP (p=0.0219), which occurred later under CON (62±7) than AMP (54±7), while val_end (p=0.045, AMP=0.29±0.01, CON=0.26±0.01), val_peak (p=0.0243, AMP=0.62±0.04, CON=0.58±0.04), and integ_large (p=0.0409, AMP=16.7±1.1, CON=15.6±1.1) values were significantly higher under AMP than CON. The interaction between land cover and grazing scheme significantly influenced the val_start (p=0.0125) parameter, which was higher under AMP (0.27±0.01) than CON (0.24±0.01) under GR land cover, while no differences between grazing systems were observed under WG (0.31±0.01 under both AMP and CON grazing systems). The interaction between land cover and grazing also influenced the val_base (p=0.0427), which was higher under AMP (0.18±0.01) than CON (0.16±0.01) in GR land cover, while no differences between grazing systems were observed under WG (0.24±0.01 and 0.23±0.01 under AMP and CON, respectively).

The average values of seasonal parameters before and after the rotational grazing under both GR and WG are reported in Table 5. Under GR, significant differences between after and before periods were observed for val_start (p<0.0001), val_peak (p=0.0247), val_base (p=0.0113), and the rate of increase (p=0.0445) parameters in AMP areas, while no differences were observed between the before and after values in CON zones. Under WG, significant differences between after and before periods were observed for val_start (p=0.0185), val_end (p=0.0433), and val_base parameters (p=0.0108), while no differences were observed in CON areas.

Normalized difference vegetation index variability

The F values calculated as the NDVI variance ratios between

Table 3. Minimum, maximum, and mean value and standard deviation of normalized difference vegetation index within each farm before and after the adaptive multi-paddock (AMP) grazing system adoption under grassland and wooded grassland land cover in continuously grazed areas and in areas where rotational grazing was implemented.

Period	Farm	Land cover	Grazing	Min NDVI	Max NDVI	Mean NDVI	SD NDVI
Before	Defensinhas	GR	CON	0.17	0.72	0.39	0.18
		WG	CON	0.20	0.65	0.39	0.14
	Vale de Grau	GR	CON	0.14	0.71	0.34	0.17
		WG	CON	0.18	0.63	0.35	0.13
	Zapatera	GR	CON	0.06	0.70	0.29	0.16
		WG	CON	0.15	0.65	0.35	0.14
After	Defensinhas	GR	AMP	0.15	0.74	0.40	0.19
			CON	0.16	0.74	0.38	0.19
		WG	AMP	0.18	0.68	0.41	0.15
			CON	0.16	0.67	0.41	0.14
	Vale de Grau	GR	AMP	0.17	0.67	0.35	0.16
			CON	0.14	0.73	0.34	0.18
		WG	AMP	0.20	0.67	0.37	0.15
			CON	0.20	0.63	0.37	0.14
	Zapatera	GR	AMP	0.10	0.64	0.32	0.18
			CON	0.06	0.64	0.21	0.13
		WG	AMP	0.13	0.61	0.34	0.14
			CON	0.12	0.61	0.33	0.14

Min, minimum; Max, maximum, SD, standard deviation; NDVI, normalized difference vegetation index; AMP, adaptive multi-paddock; GR, grassland; WG, wooded grassland; CON, continuous grazing.

AMP and CON areas at each date after rotational grazing adoption are reported at the log scale in Figure 4. Under GR land cover, the NDVI variance was significantly higher in CON areas in 67%, 68%, 71%, and 81% of dates in regreening, green, drying, and dry phases. Under WG, the NDVI variance was higher in CON areas at 95%, 81%, 71%, and 93% of regreening, green, drying, and dry phases, respectively. Under GR land cover, the average log(F) values were significantly lower than 0 in the green, drying, and dry phases. Under WG, the average log(F) values were in all stages lower than 0 (Figure 4).

Table 4. Analysis of variance (F values) reporting the effects of land cover, grazing system, and the interaction between land cover and grazing and estimated marginal mean (±standard error) of each seasonal phenology parameter estimated with the TIMESAT (version 3.3) software after the rotational grazing adoption.

Parameter	p			GR		WG	
	Land cover	Grazing	LxG	AMP	CON	AMP	CON
SOS (doy)	0.0848	0.0876	0.1999	292±9	305±9	290±9	292±9
EOS (doy)	0.2406	0.1023	0.8173	162±12	173±12	156±12	165±12
TP (doy)	0.1095	0.0219	0.5402	56±8	66±8	52±8	58±8
len (days)	0.9344	0.6968	0.4946	235±13	233±13	231±13	237±13
val_start (NDVI)	<0.0001	0.0013	*0.0125*	0.27±0.01[b]	0.25±0.01[c]	0.31±0.01[a]	0.31±0.01[a]
val_end (NDVI)	*<0.0001*	*0.0045*	0.0937	0.27±0.01	0.24±0.01	0.31±0.01	0.30±0.01
val_peak (NDVI)	0.9542	0.0243	0.1493	0.64±0.04	0.57±0.04	0.61±0.04	0.59±0.04
val_base (NDVI)	<0.0001	0.0040	*0.0427*	0.18±0.01[b]	0.16±0.01[c]	0.24±0.01[a]	0.23±0.01[a]
ampl (NDVI)	*0.0004*	0.0823	0.2832	0.46±0.04	0.41±0.04	0.37±0.04	0.36±0.04
der_l	*0.0105*	0.1391	0.6956	0.026±0.004	0.023±0.004	0.021±0.004	0.019±0.004
der_r	0.0136	0.3526	0.6984	0.036±0.006	0.033±0.006	0.028±0.006	0.027±0.006
integ_large	0.2548	*0.0409*	0.0763	16.9±1.2	14.7±1.2	16.6±1.2	16.4±1.2
integ_small	*0.0009*	0.0562	0.1743	10.63±1.01	9.055±1.011	8.3±1.011	8.031±1.011

p<0.05 are highlighted in italics. [a,b,c]When the effect of the interaction between factors is significant, different lowercase letters after means indicate different means according to Tukey's test (p<0.05). AMP, adaptive multi-paddock; CON, continuous grazing; GR, grassland; WG, wooded grassland; SOS, start of the growing season; EOS, end of season; TP, time peak; len; length of season; val_start, value of the start of the growing season; val_end, value of the end of season; val_peak, value of time peak; val_base, base level; ampl, amplitude; NDVI, normalized difference vegetation index; der_l, rate of increase; der_r, rate of decrease; integ_large, large integrated value; integ_small, small integrated value.

Table 5. Average values across seasons of seasonal phenological parameters under grassland and wooded grassland covers before and after rotational grazing adoption, under adaptive multi-paddock and continuous grazing systems. The asterisks indicate that the mean of the differences (n=3) between parameter values after and before the adaptive multi-paddock adoption was different than 0 according to a 2-tail Student's paired *t* test (p<0.05).

Parameter	GR			WG		
	Before	After		Before	After	
		AMP	CON		AMP	CON
SOS	295±21	292±10	305±14	284±7	290±4	292±6
EOS	174±8	162±4	173±5	168±9	156±9	165±13
TP	67±13	56±5	66±2	60±9	52±6	58±5
len	243±14	235±14	233±11	249±10	231±13	237±17
val_start	0.23±0.03	0.27±0.03*	0.24±0.06	0.27±0.02	0.31±0.02*	0.30±0.03
val_end	0.24±0.04	0.27±0.02	0.24±0.06	0.28±0.02	0.31±0.02*	0.30±0.03
val_peak	0.57±0.06	0.64±0.05*	0.57±0.15	0.55±0.03	0.61±0.03	0.59±0.03
val_base	0.15±0.03	0.18±0.02*	0.16±0.04	0.20±0.02	0.24±0.02*	0.23±0.03
ampl	0.43±0.04	0.46±0.03	0.41±0.12	0.35±0.01	0.37±0.02	0.36±0.01
der_l	0.022±0.003	0.026±0.002*	0.023±0.005	0.019±0.003	0.021±0.003	0.019±0.001
der_r	0.035±0.002	0.036±0.002	0.033±0.007	0.028±0.003	0.028±0.001	0.027±0.002
integ_large	15.4±3.0	16.9±2.1	14.7±4.4	16.0±1.3	16.6±1.8	16.4±2
integ_small	10.1±1.7	10.6±1.2	9.1±3.0	8.4±0.5	8.3±0.8	8.0±0.4

GR, grassland; WG, wooded grassland; AMP, adaptive multi-paddock; CON, continuous grazing; SOS, start of the growing season; EOS, end of season; TP, time peak; len, length of season; val_start, value of the start of the growing season; val_end, value of the end of season; val_peak, value of time peak; val_base, base level; ampl, amplitude; der_l, rate of increase; der_r, rate of decrease; integ_large, large integrated value; integ_small, small integrated value.

Discussion

The effect of land cover and grazing regime on seasonal vegetation parameters

The NDVI dynamics observed in the study areas comply with those reported by other studies (*e.g.*, Alcaraz-Segura *et al.*, 2008; Evrendilek and Gulbeyaz, 2008; Catorci *et al.*, 2021) under both GR and WG in the Mediterranean environment. The inter-annual dynamics of NDVI observed before and after the AMP adoption in both open and wooded grasslands are linked to the grassland and tree species' photosynthetically active period (Migliavacca *et al.*, 2017), which varied among phases during the season. The observed differences between GR and WG in parameters estimating the start and the base value of NDVI (val_start, val_base) are associated with the effect of the evergreen tree species (mostly *Q. ilex* and *Q. suber*) characterizing the Dehesa ecosystems on NDVI (Arenas-Corraliza *et al.*, 2020).

Under AMP after the rotational grazing adoption, the higher values of parameters estimating NDVI at the beginning of the growing season (val_start, val_base) and its maximum value (val_peak, val_peak, integ_large) suggested that the AMP system can stimulate the autumn restart, leading to higher production at the season peak, which came on average earlier under AMP than CON. The rotational scheme (higher instantaneous stocking rates and longer resting periods) may have stimulated productivity (*e.g.*, Behcet *et al.*, 2010), survival of plant species (Donaghy *et al.*, 2021), forage production (Teague *et al.*, 2011; Díaz de Otálora *et al.*, 2021), even under similar productivity rates, and can result under AMP also because pastures remained ungrazed for longer periods. Nevertheless, a share of uncertainty about the actual effect of AMP emerged from the lack of significance of the effect of grazing on seasonal parameters describing the length of the season. In a regional-scale analysis conducted across South African grasslands, Venter *et al.* (2019) reported little impact of rotational grazing with high stoking rates on grassland forage productivity, vegetation cover, and NDVI. In fact, in their study, under the high frequency of defoliation occurring under AMP, the NDVI increased only in fertile soil with high levels of nutritive elements. Similarly, Briske *et al.* (2008) observed enhanced grassland productivity when appropriate conditions in terms of soil water availability occur throughout the season. On the other hand, Ma *et al.* (2019) observed a reduction of grass species, thus grazing biomass, in tallgrass prairie landscapes under very high stocking rates and drought conditions. Under semiarid Mediterranean conditions, in a saltbush-based grazing system, Norman *et al.* (2010) observed similar uncertainty patterns due to little rotational grazing effects on grassland productivity and length of the season.

The effect of land cover and management on normalized difference vegetation index variability

The evidence emerging from the analysis of NDVI variability confirmed the hypothesis that rotational grazing could reduce the spatial variability of pasture biomass.

The higher spatial variability of NDVI under CON grazing can be attributed to the less efficient exploitation of grassland forage resources. This can result in a loss of pasture quality, *i.e.*, loss of legumes and other palatable species, and then soil fertility. Nevertheless, even if adopting continuous grazing can lead to an overall reduction of pasture quality, rotational grazing can reduce the overall biomass intake by grazing animals, thus compromising animal performances, as Savian *et al*. (2014) observed in Italian ryegrass grasslands.

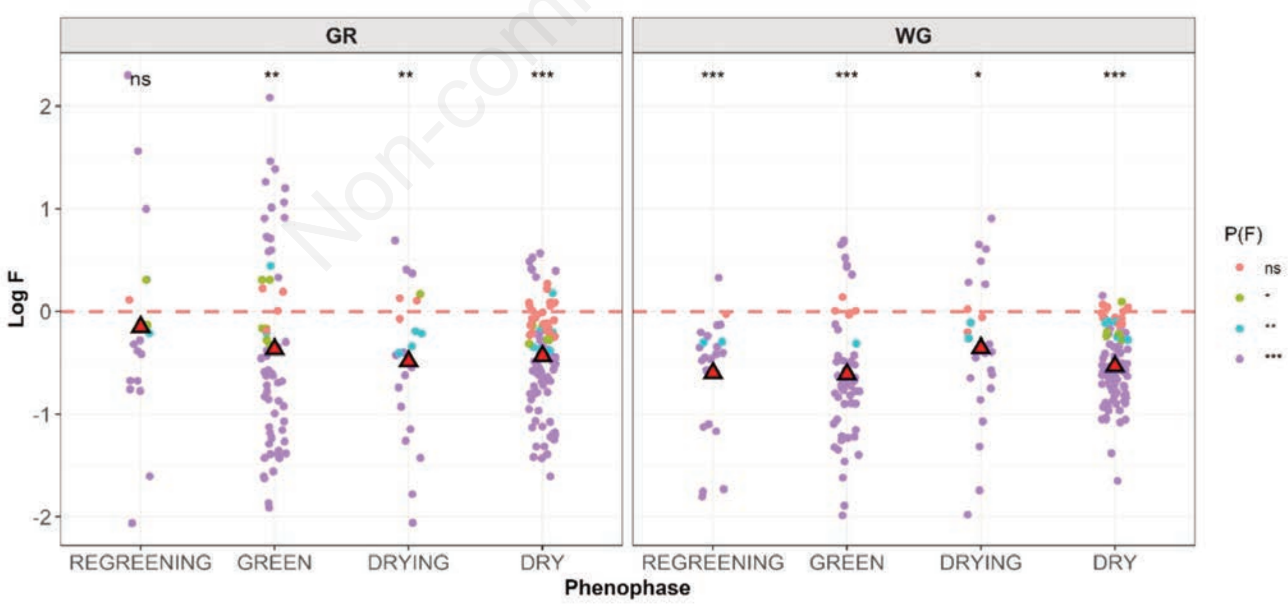

Figure 4. F ratio values at the log-scale calculated for each sensing date and divided per phenological stages after the rotational grazing adoption as the ratio between the normalized difference vegetation index variance in the adaptive multi-paddock and continuous grazing areas in the grassland and wooded grassland land covers. Orange dots indicate no significant differences between variances (ns, p>0.05), green, blue and purple dots indicate a p(F)<0.05 (*), <0.01 (**), and <0.001 (***), respectively. The red triangles indicate the average log(F) values across dates. Symbols in the upper boxes report the significance of the Student's *t* test comparing the average log(F) values to 0. GR, Grassland; WG, Wooded Grassland.

On the other hand, the overall lower spatial variability of NDVI observed under rotationally grazed areas after the AMP adoption suggested a positive role of the AMP system in enhancing the ability of forage resource exploitation by grazing animals with respect to continuous grazing (Augustine *et al.*, 2020), as observed under WG across phenological stages in the whole season. Under GR, the lower spatial variability of NDVI under AMP, which was observed from the green to the dry stage, suggested better and more uniform forage resource exploitation from the peak to the end of the growing season. Oates *et al*. (2011) reported comparable patterns of spatial variability, which observed, under continental climate, a lower sward height variability at the end of the first growing season under rotational grazing with high stocking rates than continuously grazed areas. Conversely, in a study conducted in a mountain semi-natural pastureland with a shorter growing season, Ravetto Enri *et al.* (2017) reported that rotational grazing did not affect the variability of sward height, attributing this to the high homogeneity of grassland in terms of floristic composition and the relatively high average stocking rates (more than 1.7 LSU ha^{-1} y^{-1}), which in turn led to no changes in utilization rates (*e.g*., Schmitz and Isselstein, 2020). These findings suggest that a positive role of rotational grazing in reducing spatial variability of biomass can be mostly highlighted under low stocking rates, as commonly occurs in the extensively managed silvopastoral systems of the Mediterranean environment. We hypothesize that the most critical effect of rotational grazing resulted in different grazing behaviors, leading to lower forage species selection by animals. Better forage exploitation, combined with a clearing action (Barbaro *et al.*, 2001; Hadar *et al.*, 2009) from the less desired species due also to the higher stoking rates, may have caused better conditions for the grassland autumn restart of both annual and perennial species (Kemp *et al.*, 2000; Sanford *et al.*, 2003).

Conclusions

The results from the study confirmed the experimental hypotheses that adopting rotational grazing systems such as the AMP under different land covers (WG and GR) might significantly affect seasonal NDVI parameters describing the pasture phenology and NDVI spatial variability as a proxy of forage distribution.

Although a positive effect of rotational grazing emerged only for a subset of parameters, the NDVI time series analysis revealed a significant and positive effect of the AMP grazing system on pasture phenology. In the short term (4-5 years), the introduction of the AMP schemes has already started to show positive effects on the estimated NDVI values at the beginning, at the peak, and at the end of the season, suggesting that this may imply a higher forage availability for grazing animals. Furthermore, a reduction in the spatial variability of NDVI, which persists over time, emerged after adopting the rotational grazing scheme. This finding suggests higher exploitation of forage resources by grazing animals, which leads to counting rotational grazing as a strategy to improve biomass utilization under low stocking rates in extensively managed silvopastoral systems.

The study evidenced that the multitemporal satellite data from Landsat, combined with the methodological approach for processing spectral information, can represent a valuable tool to compare the impacts of grazing management and land cover on spatial and temporal vegetation patterns in the Mediterranean silvopastoral systems. However, the low spatial and temporal resolution of Landsat products compared with those available, *e.g*., from Sentinel2 satellites, can represent a limitation in understanding phenological patterns under contrasting management schemes and land covers. Furthermore, ground observations can help to interpret and confirm seasonal dynamics and provide more accurate information about biomass availability and distribution.

Further insights on the impacts of rotational grazing can be reached thanks to the availability of high-spatial and temporal-resolution open-source images. Combining high-resolution data with field observation on forage productivity and quality can represent a tool to improve scientific knowledge on the impacts of grazing practices in Mediterranean silvopastoral systems.

References

Alcaraz-Segura D, Cabello J, Paruelo J, 2008. Baseline characterization of major Iberian vegetation types based on the NDVI dynamics. Plant Ecol. 202:13-29.

Arenas-Corraliza I, Nieto A, Moreno G, 2020. Automatic mapping of tree crowns in scattered-tree woodlands using low-density LiDAR data and infrared imagery. Agroforest. Syst. 94:1989-2002.

Augustine DJ, Derner JD, Fernández-Giménez ME, Porensky LM, Wilmer H, Briske DD, 2020. Adaptive, multipaddock rotational grazing management: a ranch-scale assessment of effects on vegetation and livestock performance in semiarid rangeland. Rangeland Ecol. Manag. 73:796-810.

Barbaro L, Dutoit T, Cozic P, 2001. A six-year experimental restoration of biodiversity by shrub-clearing and grazing in calcareous grasslands of the French Prealps. Biodivers. Conserv. 10:119-35.

Behcet KIR, Demiroglu G, Avcioglu R, Hikmet S, 2010. Effects of grazing on some yield and quality traits of a rotation pasture mixture under Mediterranean environmental conditions. Turk. J. Field Crops 15:133-6.

Blanco LJ, Ferrando CA, Biurrun FN, 2009. Remote sensing of spatial and temporal vegetation patterns in two grazing systems. Rangeland Ecol. Manag. 62:445-51.

Briske DD, Derner JD, Brown JR, Fuhlendorf SD, Teague WR, Havstad KM, Gillen RL, Ash AJ, Willms WD, 2008. Rotational grazing on rangelands: reconciliation of perception and experimental evidence. Rangeland Ecol. Manag. 61:3-17.

Byrnes RC, Eastburn DJ, Tate KW, Roche LM, 2018. A global meta-analysis of grazing impacts on soil health indicators. J. Environ. Qual. 47:758-65.

Carmona CP, Azcárate FM, Oteros-Rozas E, González JA, Peco B, 2013. Assessing the effects of seasonal grazing on holm oak regeneration: implications for the conservation of Mediterranean dehesas. Biol. Conserv. 159:240-7.

Carmona CP, Röder A, Azcárate FM, Peco B, 2013. Grazing management or physiography? Factors controlling vegetation recovery in Mediterranean grasslands. Ecol. Model. 251:73-84.

Casals P, Garcia-Pausas J, Montané F, Romanyà J, Rovira P, 2010. Root decomposition in grazed and abandoned dry Mediterranean dehesa and mesic mountain grasslands estimated by standard labelled roots. Agric. Ecosyst. Environ. 139:759-65.

Castillo-Garcia M, Alados CL, Ramos J, Moret D, Barrantes O, Pueyo Y, 2022. Understanding herbivore-plant-soil feedbacks to improve grazing management on Mediterranean mountain grasslands. Agric. Ecosyst. Environ. 327:107833.

Catorci A, Lulli R, Malatesta L, Tavoloni M, Tardella FM, 2021.

How the interplay between management and interannual climatic variability influences the NDVI variation in a sub-Mediterranean pastoral system: Insight into sustainable grassland use under climate change. Agric. Ecosyst. Environ. 314:107372.
Chen J, Jönsson P, Tamura M, Gu Z, Matsushita B, Eklundh L, 2004. A simple method for reconstructing a high-quality NDVI time-series data set based on the Savitzky-Golay filter. Remote Sens. Environ. 91:332-44.
Congedo L, 2020. Semi-Automatic classification plugin documentation. Available from: https://semiautomaticclassificationmanual.readthedocs.io/en/latest/.
den Herder M, Moreno G, Mosquera-Losada RM, Palma JHN, Sidiropoulou A, Santiago Freijanes JJ, Crous-Duran J, Paulo JA, Tomé M, Pantera A, Papanastasis VP, Mantzanas K, Pachana P, Papadopoulos A, Plieninger T, Burgess PJ, 2017. Current extent and stratification of agroforestry in the European Union. Agric. Ecosyst. Environ. 241:121-32.
Díaz de Otálora X, Epelde L, Arranz J, Garbisu C, Ruiz R, Mandaluniz N, 2021. Regenerative rotational grazing management of dairy sheep increases springtime grass production and topsoil carbon storage. Ecol. Indic. 125:107484.
Donaghy D, Bryant R, Cranston L, Egan M, Griffiths W, Kay J, Pembleton K, Tozer K, 2021. Will current rotational grazing management recommendations suit future intensive pastoral systems? NZGA 17:225-42.
Eklundh L, Jönsson P, 2017. TIMESAT 3.3 with seasonal trend decomposition and parallel processing - software manual. Available from: https://web.nateko.lu.se/timesat/ docs/TIMESAT33_SoftwareManual.pdf.
Evrendilek F, Gulbeyaz O, 2008. Deriving vegetation dynamics of natural terrestrial ecosystems from MODIS NDVI/EVI data over Turkey. Sensors 8:5270-302.
Flood N, 2014. Continuity of reflectance data between Landsat-7 ETM+ and Landsat-8 OLI, for both top-of-atmosphere and surface reflectance: a study in the Australian landscape. Remote Sens. 6:7952-70.
Global Climate Monitor, 2023. Available from: https://www.globalclimatemonitor.org/.
Golodets C, Sternberg M, Kigel J, Boeken B, Henkin Z, Seligman NG, Ungar ED, 2015. Climate change scenarios of herbaceous production along an aridity gradient: vulnerability increases with aridity. Oecologia 177:971-9.
Gosnell H, Grimm K, Goldstein BE, 2020. A half century of holistic management: what does the evidence reveal? Agr. Hum. Values 37:849-67.
Hadar L, Noy-Meir I, Perevolotsky A, 2009. The effect of shrub clearing and grazing on the composition of a Mediterranean plant. J. Veg. Sci. 10:673-82.
Hawkins HJ, 2017. A global assessment of Holistic Planned Grazing™ compared with season-long, continuous grazing: meta-analysis findings. Afr. J. Range For. Sci. 34:65-75.
Hernández-Esteban A, Rolo V, López-Díaz ML, Moreno G, 2019. Long-term implications of sowing legume-rich mixtures for plant diversity of Mediterranean wood pastures. Agric. Ecosyst. Environ. 286:106686.
Hijmans RJ, 2020. Raster: geographic data analysis and modeling. R package version 3.4-5. Available from: https://CRAN.R-project.org/package=raster.
Ibáñez J, Martínez J, Schnabel S, 2007. Desertification due to overgrazing in a dynamic commercial livestock–grass–soil system. Ecol. Model. 205:277-88.
Jönsson P, Eklundh L, 2004. TIMESAT - a program for analyzing time-series of satellite sensor data. Comput. Geosci. 30:833-45.
Kemp DR, Michalk DL, Virgona JM, 2000. Towards more sustainable pastures: lessons learnt. Aust. J. Exp. Agr. 40:343-56.
Lenth R, 2018. Emmeans: estimated marginal means, aka least-squares means. Available from: https://CRAN.R-project.org/package=emmeans.
Liu H, Jin Y, Roche LM, O'Geen AT, Dahlgren RA, 2021. Understanding spatial variability of forage production in California grasslands: delineating climate, topography and soil controls. Environ. Res. Lett. 16:014043.
Lumbierres M, Méndez P, Bustamante J, Soriguer R, Santamaría L, 2017. Modeling biomass production in seasonal wetlands using MODIS NDVI land surface phenology. Remote Sens. 9:392.
Ma S, Zhou Y, Gowda PH, Chen L, Starks PJ, Steiner JL, Neel JPS, 2019. Evaluating the impacts of continuous and rotational grazing on tallgrass prairie landscape using high-spatial-resolution imagery. Agronomy 9:238.
Migliavacca M, Perez-Priego O, Rossini M, El-Madany TS, Moreno G, van der Tol C, Rascher U, Berninger A, Bessenbacher V, Burkart A, Carrara A, Fava F, Guan JH, Hammer TW, Henkel K, Juarez-Alcalde E, Julitta T, Kolle O, Martin MP, Musavi T, Pacheco-Labrador J, Perez-Burgueno A, Wutzler T, Zaehle S, Reichstein M, 2017. Plant functional traits and canopy structure control the relationship between photosynthetic CO2 uptake and far-red sun-induced fluorescence in a Mediterranean grassland under different nutrient availability. New Phytol. 214:1078-91.
Moreno G, Gonzalez-Bornay G, Pulido F, Lopez-Diaz ML, Bertomeu M, Juárez E, Diaz M, 2015. Exploring the causes of high biodiversity of Iberian dehesas: the importance of wood pastures and marginal habitats. Agroforest. Syst. 90:87-105.
Norman HC, Wilmot MG, Thomas DT, Barrett-Lennard EG, Masters DG, 2010. Sheep production, plant growth and nutritive value of a saltbush-based pasture system subject to rotational grazing or set stocking. Small Ruminant Res. 91:103-9.
Olea L, San Miguel-Ayanz A, 2006. The Spanish dehesa. A traditional Mediterranean silvopastoral system linking production and nature conservation Proc. 21st General Meeting of the European Grassland Federation.
Park JY, Ale S, Teague WR, 2017. Simulated water quality effects of alternate grazing management practices at the ranch and watershed scales. Ecol. Model. 360:1-13.
Peco B, Sánchez AM, Azcárate FM, 2006. Abandonment in grazing systems: consequences for vegetation and soil. Agric. Ecosyst. Environ. 113:284-94.
Pinheiro J, Bates D, DebRoy S, Sarkar D, RCoreTeam, 2018. Nlme: linear and nonlinear mixed effects models. Available from: http://CRAN.R-project.org/package=nlme.
Plieninger T, Flinzberger L, Hetman M, Horstmannshoff I, Reinhard-Kolempas M, Topp E, Moreno G, Huntsinger L, 2021. Dehesas as high nature value farming systems: a social-ecological synthesis of drivers, pressures, state, impacts, and responses. Ecol. Soc. 26:23.
Porqueddu C, Ates S, Louhaichi M, Kyriazopoulos AP, Moreno G, del Pozo A, Ovalle C, Ewing MA, Nichols PGH, 2016. Grasslands in 'old world' and 'new world' Mediterranean-climate zones: past trends, current status and future research priorities. Grass Forage Sci. 71:1-35.
Pulido M, Schnabel S, Contador JFL, Lozano-Parra J, Gómez-Gutiérrez Á, 2017. Selecting indicators for assessing soil quality and degradation in rangelands of Extremadura (SW Spain). Ecol. Indic. 74:49-61.
Pulido M, Schnabel S, Lavado Contador JF, Lozano-Parra J, González F, 2018. The impact of heavy grazing on soil quality

and pasture production in rangelands of SW Spain. Land Degrad. Dev. 29:219-30.
Pulina A, Ferrise R, Mula L, Brilli L, Giglio L, Iocola I, Ventrella D, Zavattaro L, Grignani C, Roggero PP, 2022. The ability of crop models to predict soil organic carbon changes in a maize cropping system under contrasting fertilization and residues management: evidence from a long-term experiment. Ital. J. Agron. 17.
Pulina A, Rolo V, Hernández-Esteban A, Seddaiu G, Roggero PP, Moreno G, 2023. Long-term legacy of sowing legume-rich mixtures in Mediterranean wooded grasslands. Agric. Ecosyst. Environ. 348:108397.
R Core Team, 2021. R: a language and environment for statistical computing. Available from: https://cran.r-project.org/doc/manuals/fullrefman.pdf.
Ravetto Enri S, Probo M, Farruggia A, Lanore L, Blanchetete A, Dumont B, 2017. A biodiversity-friendly rotational grazing system enhancing flower-visiting insect assemblages while maintaining animal and grassland productivity. Agric. Ecosyst. Environ. 241:1-10.
Reinermann S, Asam S, Kuenzer C, 2020. Remote sensing of grassland production and management - a review. Remote Sens. 12:1949.
Rivas-Martínez S, Rivas-Saenz S, Penas-Merino A, 2011. Worldwide bioclimatic classification system. Glob. Geobot. 1:1-604.
Rossetti I, Bagella S, 2014. Mediterranean Quercus suber wooded grasslands risk disappearance: new evidences from Sardinia (Italy). For. Ecol. Manag. 329:148-57.
Sanford P, Cullen B, Dowling PM, Chapman DF, Garden DL, Lodge GM, Andrew MH, Quigley PE, Murphy SR, King WMG, Johnston WH, Kemp DR, 2003. SGS Pasture theme: effect of climate, soil factors and management on pasture production and stability across the high rainfall zone of southern Australia. Aust. J. Exp. Agr. 43:945-59.
Schmitz A, Isselstein J, 2020. Effect of grazing system on grassland plant species richness and vegetation characteristics: comparing horse and cattle grazing. Sustainability 12:3300.
Seddaiu G, Bagella S, Pulina A, Cappai C, Salis L, Rossetti I, Lai R, Roggero PP, 2018. Mediterranean cork oak wooded grasslands: synergies and trade-offs between plant diversity, pasture production and soil carbon. Agroforest. Syst. 92:893-908.
Stumpf F, Schneider MK, Keller A, Mayr A, Rentschler T, Meuli RG, Schaepman M, Liebisch F, 2020. Spatial monitoring of grassland management using multi-temporal satellite imagery. Ecol. Indic. 113:1-12.
Teague R, Provenza F, Kreuter U, Steffens T, Barnes M, 2013. Multi-paddock grazing on rangelands: why the perceptual dichotomy between research results and rancher experience? J. Environ. Manage. 128:699-717.
Teague WR, Dowhower SL, Baker SA, Haile N, DeLaune PB, Conover DM, 2011. Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tall grass prairie. Agric. Ecosyst. Environ. 141:310-22.
Torralba M, Oteros-Rozas E, Moreno G, Plieninger T, 2018. Exploring the role of management in the coproduction of ecosystem services from Spanish wooded rangelands. Rangeland Ecol. Manag. 71:549-59.
United States Geological Survey, 2023. Available from: https://earthexplorer.usgs.gov.
Venter ZS, Cramer MD, Hawkins H-J, 2019. Rotational grazing management has little effect on remotely-sensed vegetation characteristics across farm fence-line contrasts. Agric. Ecosyst. Environ. 282:40-8.
Weiss M, Jacob F, Duveiller G, 2020. Remote sensing for agricultural applications: a meta-review. Remote Sens. Environ. 236:111402.