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Abstract

Adaptive Multi-Paddock (AMP) is a grazing system which combines intensive, rapid grazing livestock rotation with relatively short grazing periods and 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 vs Grassland) with a remote sensing approach based on the time-series analysis of Normalized Difference Vegetation Index (NDVI) from remote sensing through 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.

Keywords: Adaptive Multi-Paddock grazing; TIMESAT; grazing management; grassland phenology; remote sensing

1 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 favourable 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). The 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.*, 2013b; Pulido *et al.*, 2018), soil degradation and erosion (Ibáñez *et al.*, 2007; Pulido *et al.*, 2017), and lack of tree regeneration (Carmona *et al.*, 2013a; Rossetti and Bagella, 2014).

The 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 and forage crops and grasslands. The 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 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, 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 the Mediterranean silvopastoral grazing systems, this study hypothesized that adopting rotational grazing under different land covers (wooded grasslands and grasslands) can have a positive impact on pasture phenology and forage spatial variability using NDVI time series from 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.

2 Materials and methods

2.1 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 Alentejo region (Vale del 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 hot, dry summer and cold, rainy winter. According to Global Climate Monitor (<https://www.globalclimatemonitor.org/>) in 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 out 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 of three main functional plant groups: grasses, forbs and legumes, with relative cover around of 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., *Trifolium 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: Wooded Grassland (WG) and Grassland (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) in 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.

2.2 Remote sensing data collection

Landsat images were collected from the United States Geological Survey (USGS, <https://earthexplorer.usgs.gov>) web service. Landsat Level-2 images with less than 10% of cloud cover were collected among those available (every 16 days) by Landsat-5 TM and Landsat-7 ETM from January 2010 to March 2013 and by Landsat-8 OLI/TIR from April 2013 to December 2020. Images from both satellites had 30 m x 30 m spatial resolution per pixel. For this study, red and NIR bands of both 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) 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 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:

$$NDVI = \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + \rho_{red}}$$

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 harmonise 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.

2.3 *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 description 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 in phenological stages as follows: Green stage, when NDVI was higher than 80% of the maximum NDVI; Regreening stage, from the start of the season (SOS) to the beginning of the Green stage; Drying stage, from the end of the Green stage to the end of the season (EOS) estimated by the algorithm; 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 stages identification is reported in Figure 3.

2.4 *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 vs. WG) and grazing scheme (subfactor, AMP vs. 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-which correlation structure, through which the random effect of main plots (farm x land cover) and seasons was computed. The analysis of variance (anova) was performed to test the significance of factors and their interaction. 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.

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-tails 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 two-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 (Pineiro *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).

3 Results

3.1 NDVI dynamics

The NDVI dynamics within each farm before and after the AMP adoption in WG and GR are summarised 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.

3.2 *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 der_1 ($P = 0.0445$) 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.

3.3 NDVI variability

The F values calculated as the NDVI variance ratios between 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).

4 Discussion

4.1 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 grassland and wooded grasslands in the Mediterranean environment. The inter-annual dynamics of NDVI observed before and after the AMP adoption in both open and wooded grassland 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 than con (TP). 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, can result under AMP also because pastures remained ungrazed for longer periods. Nevertheless, a share of uncertainty on 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 (*len*). 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 along 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.

4.2 *The effect of land cover and management on NDVI 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.

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 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 $1.7 \text{ LSU ha}^{-1} \text{ yr}^{-1}$), which in turn led to no changes in utilization rates (e.g., Schmitz and Isselstein, 2020). These findings can suggest that a positive role of rotational grazing in reducing spatial variability of biomass can be mostly highlighted under low stocking rates, as commonly occurred in the extensively managed silvopastoral systems of the Mediterranean environment. We hypothesize that the most critical effect of rotational grazing resulted in different grazing behaviour leading to lower forage species selection by animals. The 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).

5 Conclusions

The results from the study confirmed the experimental hypotheses that adopting rotational grazing systems such as the AMP under different land covers (wooded grasslands and grasslands) 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 the end of the season, suggesting that this may imply a higher forage availability for grazing animals. Furthermore, a reduction of 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 utilisation 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.

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Table 1. Farm location and surface of the pasturelands (ha) within Grassland (GR) and Wooded Grassland (WG) land cover under Adaptive Multi Paddock (AMP) and continuous (CON) 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

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 SOS	val_start	NDVI	value of the function at the time of the start of the season
value of EOS	val_end	NDVI	value of the function at the time of the end of the season
value of TP	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

Table 3. Minimum, maximum, and mean value and standard deviation of NDVI within each farm before and after the AMP grazing system adoption under Grassland (GR) and Wooded Grassland (WG) land cover in continuously grazed areas (CON) and in areas where rotational grazing was implemented (AMP).

PERIOD	FARM	LAND COVER	GRAZING	minNDVI	maxNDVI	meanNDVI	sdNDVI
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

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 (\pm standard error) of each seasonal phenology parameter estimated with the TIMESAT (version 3.3) software after the rotational grazing adoption. P-values < 0.05 are highlighted in bold. 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).

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

Table 5. Average values across seasons of seasonal phenological parameters under Grassland (GR) and Wooded Grassland (WG) land covers before and after the rotational grazing adoption under Adaptive Multi-Paddock (AMP) and continuous (CON) grazing systems. The asterisks indicate that the mean of the differences (n = 3) between parameter values after and before the AMP adoption were different than 0 according to a two-tails 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

Figures

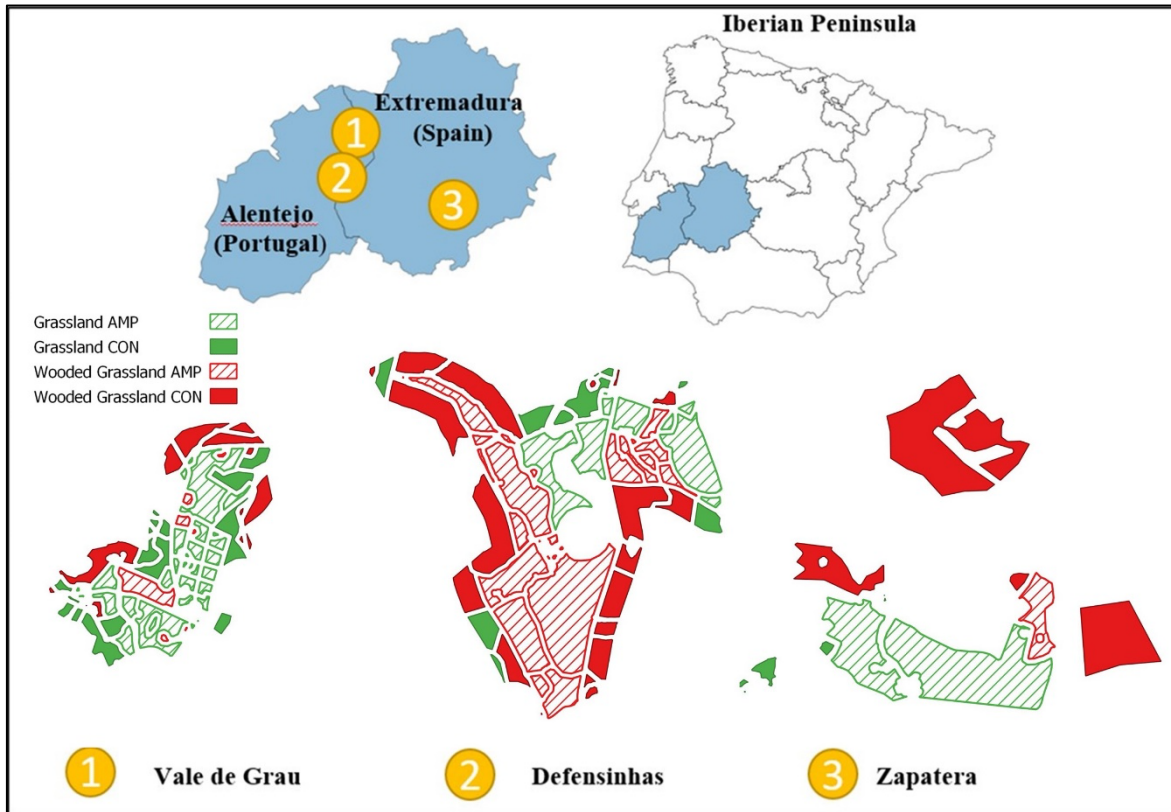


Figure 1. Maps of the three farms in Alentejo (Portugal) and Extremadura (Spain) regions of the Iberian Peninsula. The red areas represent the Wooded Grassland, and the green areas the Grassland land cover. Solid areas represent the field in which continuous grazing occurred throughout the study period (2010-2021), while striped areas indicate fields in which the Adaptive Multi-Paddock grazing system has been implemented since 2014-2016.

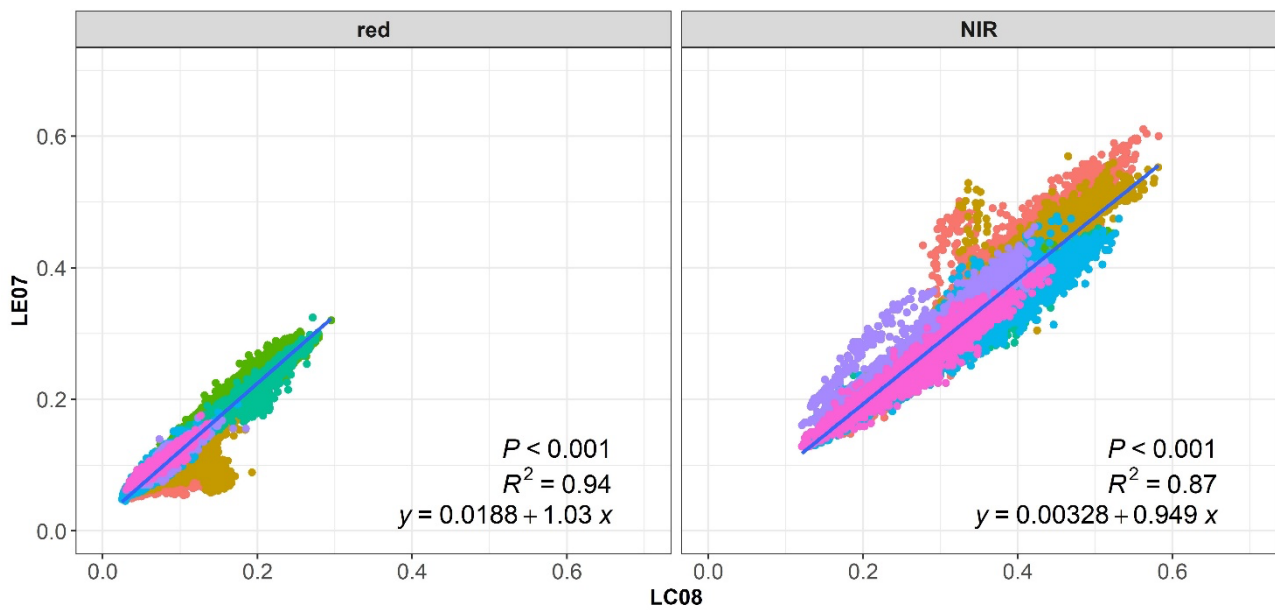


Figure 2. Relationships between the spectral reflectance at the red (left) and NIR (right) bands detected with LC08 (Landsat-8 OLI) and LE07 (Landsat-7-ETM) and linear regression equation. Different colours represent different groups of sensing dates.

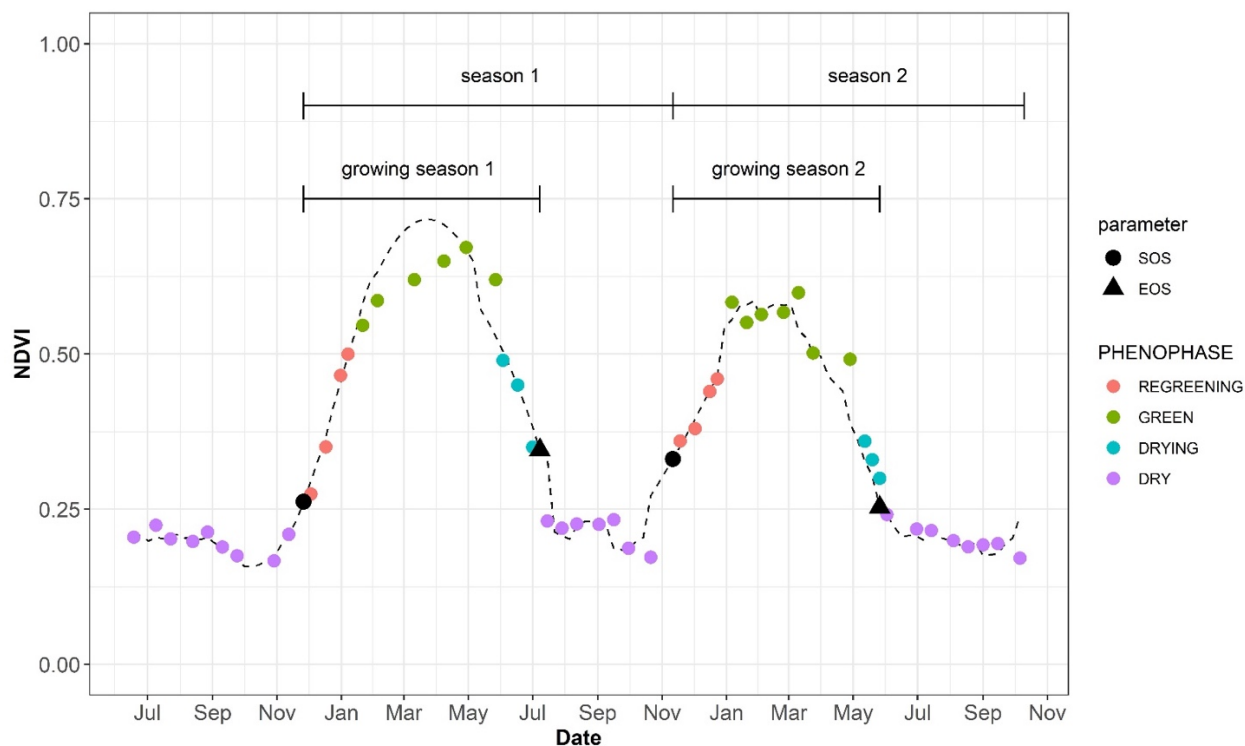


Figure 3. Schematic representation of phenological stages identification over two years. The coloured dots represent the average NDVI observed in a sensing date within a plot; the black dots and triangles represent the Start of the Season (SOS) and the End of the Season (EOS) estimated through the TIMESAT software; the dashed line represents the fitted NDVI values obtained through the Savitzky-Golay smoothing method.

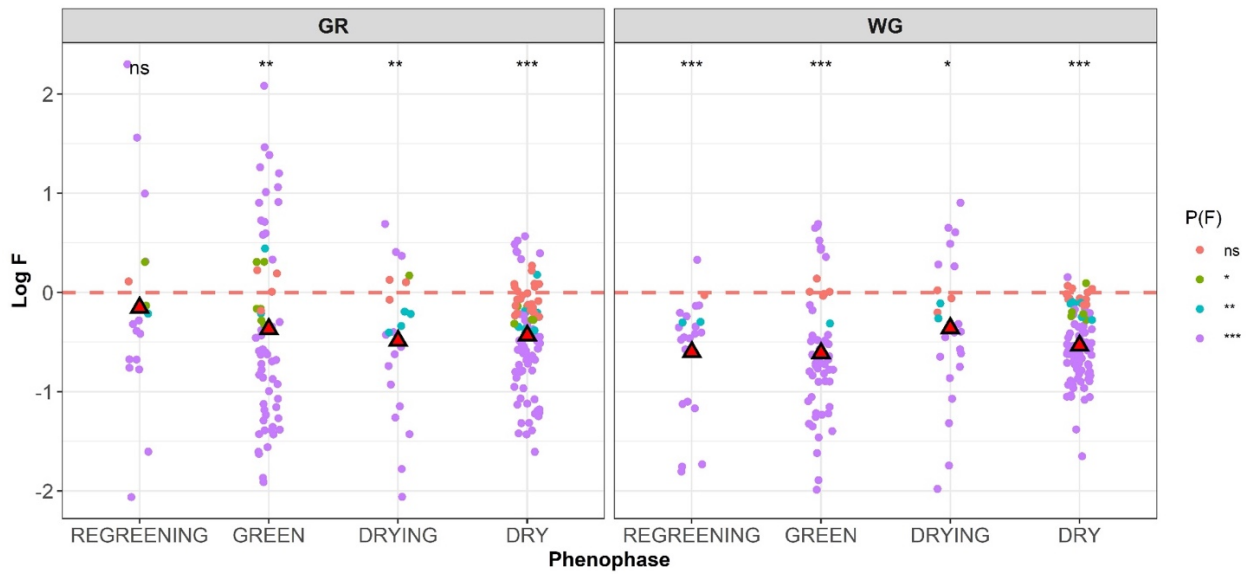


Figure 4. F ratios values at the log-scale calculated for each sensing date and divided per phenological stages after the rotational grazing adoption as the ratio between the NDVI variance in AMP and CON areas in the Grassland (GR) and Wooded Grassland (WG) land covers. Orange dots indicate no significant 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.