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ASSESSMENT OF ADAPTIVE MULTI-PADDOCK GRAZING UNDER MEDITERRANEAN AGRO-SILVOPASTORAL SYSTEMS

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Abstract

Agroforestry activities such as silvopastoral systems can represent an optimal integration between the need for land use and the conservation of ecosystem services. Nevertheless, innovative practices and tools are needed to face the loss of profitability of agricultural activities in silvopastoral areas of the Mediterranean basin. Adaptive Multi Paddock (AMP) grazing management is a grazing strategy that combines intensive grazing, rapid rotation of grazing livestock, and managing livestock/grassland with adaptive decision-making. This grazing strategy is typically implemented through a high-intensity rotation of animals on multiple small paddocks to provide periods of short duration followed by adequate grass recovery periods. The AMP grazing system has stimulated long-lasting and still unresolved debates in the bibliography, bringing the generation of different names to the same management. It has been argued that AMP systems can increase productivity in pastures, mainly through the impact of densely grouped animals on primary production. However, the vast majority of experiments do not support the perception that AMP is more effective than continuous grazing. Studies on AMP considering vegetation composition changes, relative frequency and contribution to dry weight of the most desirable and palatable species are not frequent.

This thesis aims to reach a deeper understanding of the AMP impacts on Mediterranean silvopastoral systems. In the first chapter, the impacts of the AMP grazing system adoption in a Mediterranean silvopastoral farm were assessed in a two-year field experiment. The second chapter evaluated the large-scale impacts of AMP adoption through a remote sensing approach within Dehesa farms in a study area located in the Southwestern Iberian peninsula.

The results from the field study partially confirm that the adoption of the AMP grazing system can improve grassland productivity, as grazing management influenced the total biomass production only in autumn grazing areas. Nevertheless, it emerged that introducing a rotational grazing system in Mediterranean silvopastoral systems can enhance the efficiency of forage resource exploitation.

The results from the remote-sensing study partially confirmed the hypothesis that adopting adaptive management can change the patterns of forage availability, as the NDVI response to the AMP grazing system was evident only at the early stages of the growing season. Nevertheless, the overall lower spatial variability of NDVI in AMP than in continuously grazed areas, and the reduced variability after the AMP adoption, can be considered as a reasonable indicator of better exploitation of forage biomass.

The results highlighted that the adoption of adaptive grazing management, in a context of climate change, land degradation, rising costs, and loss of competitivity if agricultural activities in marginal and less productive areas, could represent an effective strategy to enhance the efficiency in forage resources exploitation contrasting the overall land degradation.

Preface

This PhD thesis was designed as a set of experimental studies to test different scientific hypotheses supporting sustainable grazing systems within Mediterranean agro-silvopastoral systems. The relevance of the topic is multiple: (i) grazing is a key activity in Mediterranean silvicultural and pastoral systems, as the absence of grazing or cutting in secondary grasslands triggers ecological successions that under the Mediterranean climate can result in natural disasters (e.g. wildfires); (ii) grazing is an indirect driver of plant biodiversity in silvopastoral systems as it contributes to maintaining the habitat for the grass component of wooded grasslands; (iii) grazing is a driver of ecosystem services including provisioning (e.g. animal productions), regulating (e.g. soil carbon sequestration, pollination) and cultural services (e.g. identity landscapes). While several scientific studies are available about grazing management in grassland systems, the impacts of some emerging grazing management options validated in other environments are not sufficiently investigated in Mediterranean silvopastoral systems. Among these, the Adaptive Multi Paddock grazing was chosen as a focus for this thesis. The work has been carried out in the context and in close collaboration with the Life project “Regenerate”, which has been implemented in Extremadura in Spain and in Sardinia. Agroforestry Systems (AFSs) include different land uses and management options (Sahoo et al., 2020). These systems are well preserved in EU-27, occupying a large surface equivalent to about 5.7% of the territorial area and 14.0% of the utilized agricultural area (den Herder et al., 2017). In this context, AFS represent an optimal integration between the need for land use and the conservation of ecosystem services (Lomba et al., 2020).

Agroforestry Systems (AFS) are complex ecosystems that combine different land uses and management options based on the association of trees, herbaceous crops, and pastures (Sahoo et al., 2020). These systems are well preserved in EU-27, occupying a large surface equivalent to about 5.7% of the territorial area and 14.0% of the utilized agricultural area (den Herder et al., 2017). In this context, AFS represent an optimal integration between the need for agricultural and forest land use and the provisioning of ecosystem services (Lomba et al., 2020).

According to CORINE Land Cover (EEA, 2018), in the Iberian peninsula, AFS cover about 3.14 Mha, which is 2.37 Mha in Spain and 0.77 Mha in Portugal. These peculiar systems are mostly known as *dehesas* and *montados* in Spain and Portugal, respectively. AFS in Italy cover about 1.4 Mha (Paris et al., 2019), of which some 167,000 ha are located in Sardinia (EEA 2018). Although AFS characterize almost all Mediterranean landscapes, the percentage of AFS-covered land in Sardinia is higher than the average European coverage (6,9 vs 5,7%), as well as the area covered in the Iberian peninsula (5,3 %).

These complex ecosystems can contribute to diversifying and increasing agricultural production whereas conjointly providing land users with different economic, social, and environmental advantages (Sahoo et al., 2020). Nevertheless, their role in agricultural and forestry systems is not always recognized, even though they increasingly cover large areas following agricultural abandonment and rural exodus (Rolo, 2019). A high proportion of the scientific literature available on AFS in Mediterranean Europe focuses on large-scale AFS in Spain and Portugal, with studies on support services, among which biodiversity and plant intake are the most investigated (e.g. Torralba et al., 2016; Moreno et al., 2018; Torralba et al., 2018; Velamazán et al., 2020). Much less literature is available on AFS based on silvopastoral systems in other Mediterranean areas such as Sardinia (e.g. Bagella et al., 2020).

Silvopastoral activities within Mediterranean wooded grassland establish complex social-ecological systems, generally characterized by multifunctional low-intensity management and extensive production systems, successfully integrating shelter and forage for grazing animals and production of a variety of woodland products (Torralba et al. 2018; Freitas et al. 2020). Agro-silvopastoral farms are inherently semi- natural ecosystems, as they are characterized by diversification in terms of products, management, structure, and current socio-economic interest (Moreno et al., 2018, Lomba et al., 2020;). Silvopastoral systems provide a wide range of ecosystem services (Latham et al., 2014; Briske, 2017; Bagella et al., 2020). The provisioning services depend on ecological processes such as primary production and nutrient cycling and are intimately related to biological diversity (Briske, 2017). Grasslands support most of the world's livestock production - with about 91% of the surface devoted - and are among the most widely distributed terrestrial biomes globally, with about 52.54 million km^2 for 40.5% of the global land area without permanent ice cover (Bellocchi et al., 2020; Reed, 2008; White et al. 2000).

Managing agricultural landscapes to support biodiversity and ecosystem services is a crucial aim of sustainable agriculture (Martin et al., 2019). The objective of sustainable grazing management in AFS is to obtain a distribution of livestock that reduces grazing selectivity to balance the plant species composition giving key species some rest (Briske et al., 2008; Sollenberger et al., 2020). Grazing intensity is the key issue to obtaining the best economic outcomes without compromising the system's sustainability (Carvalho et al., 2010a). The Adaptive Multi Paddock grazing system (AMP) is a grazing strategy that combines intensive grazing, rapid rotation of grazing livestock, and managing livestock/grassland with adaptive and holistic decision-making (Savory 1998; Gosnell et al., 2020). However, this definition has stimulated long-lasting and still unresolved debates in rangeland ecology and management, also because the original definition of Savory (Holistic Planned Grazing) in research activities is known by different names (Table 1). Moreover, sometimes additional terms are used for the same system or the same term is used for other systems (Mann and Sherren, 2018; Briske et al., 2011).

Many Savory's writings lack specifics that could be used for quantitative, scientifically valid studies. Carter et al. (2014) report that the claims of the benefits of AMP grazing should be validated by scientific testing, as Savory's studies present ecological controversy and are not generalizable across all ecosystems. An accurate and efficient assessment of herbage mass is essential for testing different grazing systems in terms of forage provisioning capacity, optimizing grass utilization, and increasing feed production for pasture farming systems worldwide (Murphy et al., 2020; López-Díaz et al., 2011). Non-destructive measurements of pasture production in grasslands are statistically acceptable when the measurement system is proportionate to the work scale, available resources, and precision required. These methods include manual and electronic pasture meters and remote sensing (López-Díaz et al., 2011).

Table 1. Alternate terms for Holistic Planned Grazing or adaptive grazing in research activities (Mann and Sherren, 2018).

Rapid Rotation Grazing	High Frequency-Short Duration Grazing
Time-Controlled Grazing	Season-Long Grazing
Planned Grazing	High-Intensive Short-Duration Grazing
Prescribed Grazing	Adaptive Multi-Paddock Grazing
Management-Intensive Grazing	Savory Grazing
Rest-Rotation Grazing	Cell Grazing
Deferred Rotation Grazing	Swath Grazing
Grazing Management	Managed Grazing
Adaptive Grazing	Short Duration Grazing
Intensive Rotational Grazing	Holistic Resource Management
Strategic Planned Grazing	Savory Grazing Method

The HFRO sward-stick (Barthram, 1984) is a manual pasture meter used for *in situ* non-destructive measurements. This tool can be used in heterogeneous grasslands to measure the sward height and, at the same time, make a survey of surface botanical composition, but multi-temporal measurements of herbage mass are needed for seasonal calibrations equations between sward stick height (cm) and dry matter (DM, kg ha^{-1}) biomass (Litherland et al., 2008; L'Huillier et al., 1988).

Remote sensing is a powerful tool for building multi-temporal series of data over time in grasslands, especially over areas that are difficult to access and in large geographic domains (Gómez-Giráldez et al., 2020). Remote sensing for vegetation monitoring is based not only on SAR sensor systems - that send a signal and receive the complex information back-detected - but also on optical sensors - that require sunlight- as reported in Figure 1 (Reinermann et al., 2020).

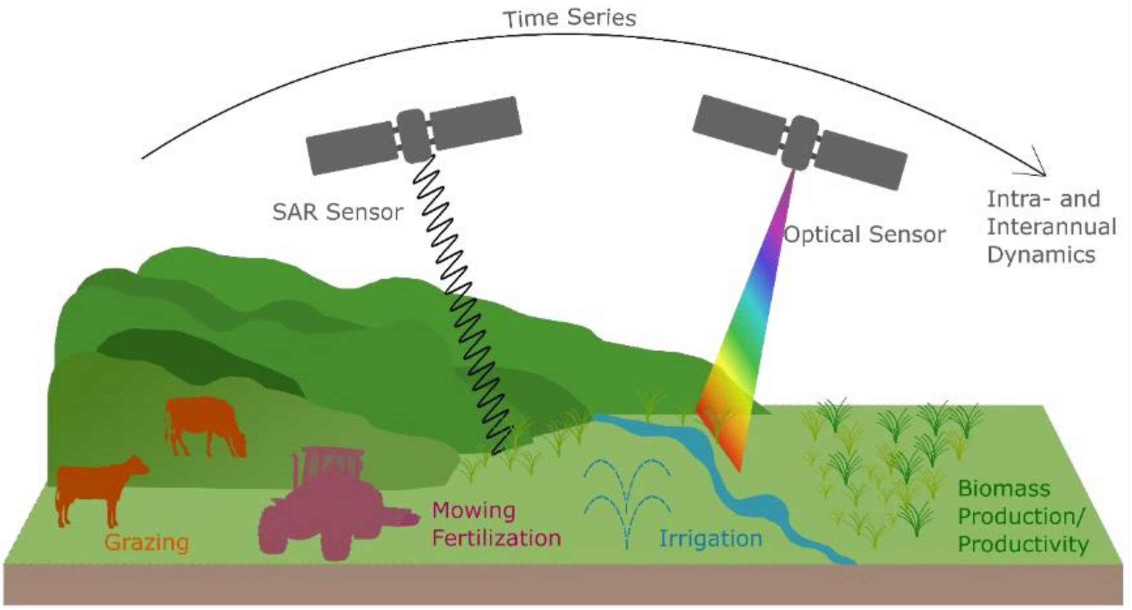

Figure 1. Overview of satellite remote sensing of most important drivers and processes in grassland management (Reinermann et al., 2020).

Since the Landsat satellite was launched in the early 1970s, medium-resolution remote sensing imagery (15–30 m resolution) such as Thematic Mapper (TM) and Landsat Operational Land Imager (OLI) have been widely used for examining ecosystem changes (Phiri and Morgenroth, 2017). The sensors aboard each Landsat satellite were designed to acquire data in different frequencies along the electromagnetic spectrum (https://www.usgs.gov) (Table 2).

A wide range of indices from remote-sensed spectral data has been developed to monitor vegetation status. Nevertheless, the Normalized Difference Vegetation Index (NDVI) has been the most frequently used within the remote sensing family (Gao et al., 2020; Xue et al., 2017).

Many studies demonstrate strong correlations between NDVI, which is strongly related to the fractional absorbed photosynthetically active radiation, and grassland production (Wang et al., 2005; Myneni et al., 1995).

Table 2. Summary of different types of Landsat images indicating spatial, temporal, radiometric and spectral resolution (https://www.usgs.gov)

LANDSAT 4-5 Thematic Mapper (TM) 1975-2013			LANDSAT 8-9 Operational Land Imager (OLI) Thermal Infrared Sensor (TIRS) 2013 to Present		
Temporal 16 days	Radiometric 8 bits		Temporal 16 days	Radiometric 12 bits	
Band Name	Spectral (µm)	Spatial (m)	Band Name	Spectral (µm)	Spatial (m)
Band 1 – Blue	0.45-0.52	30	Band 1 – Coastal aerosol	0.43-0.45	30
Band 2 – Green	0.52-0.60	30	Band 2 – Blue	0.45-0.51	30
Band 3 – Red	0.63-0.69	30	Band 3 – Green	0.53-0.59	30
Band 4 – NIR	0.76-0.90	30	Band 4 – Red	0.64-0.67	30
Band 5 – SWIR 1	1.55-1.75	30	Band 5 – NIR	0.85-0.88	30
Band 6 – TIR	10.40-12.50	120	Band 6 – SWIR 1	1.57-1.65	30
Band 7 – SWIR 2	2.08-2.35	30	Band 7 – SWIR 2	2.11-2.29	30
			Band 8 – Panchromatic	0.50-0.68	15
			Band 9 – Cirrus	1.36-1.38	30
			Band 10 – TIRS 1	10.6-11.19	100
			Band 11 – TIRS 2	11.50-12.51	100

The overall objective of this thesis is to reach a deeper understanding of the AMP impacts on Mediterranean silvopastoral systems. The thesis is divided into two chapters consisting of specific objectives aiming to assess:

1. The impacts of the AMP grazing system adoption in a Mediterranean silvopastoral farm in a two-year field experiment;
2. the large-scale impacts of the AMP adoption within D*ehesa* farms in a study area located in the South-Western Iberian peninsula through a remote sensing approach.

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1 Chapter I

Short-terms effects of Adaptive Multi-Paddock Grazing on Agroforestry Systems under Mediterranean conditions

Abstract

Context, The role of the adaptive multi-paddock (AMP) grazing system, which typically uses a high-intensity rotation of animals on multiple small paddocks to provide periods of short duration followed by adequate grass recovery periods, in improving the ecosystem services provision is still debated.

Objectives The aim of this study is to assess the impact of grazing management within different typologies of land uses on herbage production and grassland resource utilization by grazing animals. Therefore, the hypothesis is that the AMP may be more effective than current grazing systems in using pastures in different vegetation conditions of Mediterranean agroforestry systems.

Methods A two-year experiment was conducted on a farm located in central-eastern Sardinian Island under two Land-Use typologies (i) Permanent Grassland (PG) and Wooded Grassland (WG). Eight paddocks (0.6-1-2 ha in size) in the highland WG and PG and another eight paddocks (0.3 ha each) in the lowland PG were identified to perform the AMP system. A continuous grazing (business as usual) area was also identified in both highland and lowland pastures under the same vegetation type. The forage production was monitored from the beginning to the end of the grazing periods by measuring the sward height with the HFRO sward stick, seasonally calibrated against herbage biomass, considering a different calibration for grasses, legumes and forbs. The pasture utilization factor (UF, %) was calculated as the ratio between the grazed and the available herbage.

Results The interaction between the year and the grazing management in mountain areas significantly influenced the biomass productivity, which was mainly associated with higher grams production in wooded grassland (1.15±0.08 Mg ha^{-1} of DM in the first year), but with other unpalatable species in permanent grassland (1.38±0.07 Mg ha^{-1} during the second year). In spring grazing areas, no significant effect of grazing on total production was observed. The grazing management always influenced the utilization rates in EU_WG and SB_PG, especially for grams in the first (44% in AMP vs 27% in CG) and legumes (45% vs 11%) for the second area. The results partially confirm that the adoption of the AMP grazing system can improve grassland productivity. Nevertheless, the hypothesis that adaptive grazing can improve the pasture utilization rate is confirmed, so introducing a rotational grazing system in Mediterranean silvopastoral systems can enhance the efficiency of the forage resource exploitation.

Keywords: herbage growth, herbage production, herbage utilization, calibration, functional groups.

1.1 Introduction

In Mediterranean environments, agroforestry systems such as silvopastoral farms have gradually been recognized as a multifunctional pattern of sustainable development (Santoro et al., 2020), which provides a wide range of ecosystem services, including supporting and provisioning services, such as primary productivity and feed production for grazing animals (Bullock at al., 2011).

Plant communities of grasslands within Mediterranean silvopastoral farms result from morphogenetic responses to the interactions between plants and grazing pressure. Grazing systems are different in animal species and livestock management, and their complexity can vary in time and space, thus differently influencing grassland dynamics (Laca et al., 2000). Current environmental issues related to animal production and vegetation management require studies for expanding knowledge related to grazing management. Conventional grazing methods such as the Continuous Grazing (CG) are effective, but it is necessary to fully incorporate the spatial and temporal heterogeneity of supply and demand of forage into dynamic models and methods (Laca, 2009).

The rotational grazing systems have proved to be an effective management scheme to improve forage resource exploitation, but their effectiveness in enhancing grassland productivity and animal performance is still debated (Briske et al., 2008; Hawkins, 2017). Among rotational grazing schemes, the Adaptive Multi Paddock (AMP) grazing system (Savory et al., 2016; Butterfield et al., 2019) has been proposed as a model to achieve better performance in terms of ecosystem services provision with respect to CG. The AMP combines very high instantaneous stocking rates with short grazing events and long restoring periods within a rotational scheme of "adaptive" paddocks in terms of surface, grazing animals, and management decision-making (Frith, 2020; Gosnell et al., 2020). Several studies highlighted the effectiveness of AMP in enhancing grassland productivity and quality (e.g. Teague *et al.*, 2011), as well as animal performances (e.g. Teague *et al.*, 2013) and soil fertility (Park *et al.*, 2017). However, contrasting evidence emerges from the literature on AMP's reliability in achieving better production performances, forage exploitation and quality, and overall improvement of ecosystem services provision (Nordborg et al., 2016; Teague et al., 2013). Mann et al. (2018) claim that, although the methods and outcomes of AMP remain controversial, researchers have indicated that its emphasis on adaptivity may make it a valuable tool for helping farmers deal with complexity, especially in agroforestry system contests. In fact, understanding of AMP grazing management effects on agroforestry systems has slowly advanced as manipulative studies conducted at the scale of ranching operations are challenging to implement (Hawkins et al., 2017; Teague et al., 2017).

In the context of a sustainable intensification paradigm, AMP could increase forage production and simultaneously face challenges such as increasing forage utilization *in situ* and avoiding additional costs for supply with external inputs to silvopastoral farms. The hypothesis of this study is that the AMP grazing systems can be more effective than the CG in ensuring higher grassland productivity and better forage resource exploitation in a Mediterranean silvopastoral farm characterized by vertical transhumance within different land uses. The aims of this study were to assess the short-term effects of AMP on grassland growth rates and production, herbage utilization rates and consumption by grazing animals in a multifunctional Mediterranean silvopastoral farm.

1.2 Materials and methods

1.2.1 Study site

The study site was on a silvopastoral private farm in central-western Sardinia, Italy (40°8'N, 8°35'E). The principal livestock activities are beef cattle (Sardo-Modicana and Charolais breed) and milking goats breeding. The whole farm is located in two distinct main areas within the same municipality at 850 m (Elighes Uttiosos, EU) and 400 m a.s.l. (Sas Bogadas, SB), respectively (Figure 1.1). The livestock activities within the study areas are representative of a Mediterranean silvopastoral farm. Both beef cattle and goats are fed by combining forage grazed directly in open and wooded grasslands and woodlands with farm-produced hay supply and external feed to integrate the nutritional requirements of animals. Following both the seasonal availability of herbage to graze and the nutritional need of animals related to their physiological stages, cattle follow a vertical transhumance scheme from mountain (EU, summer and autumn grazing) to valley (SB, winter and spring) areas.

1.2.2 Experimental layout

The experimental activities were carried out from August 2018 to June 2020. Two land use typologies were identified: i) Wooded Grassland (WG) and ii) Permanent Grassland (PG). Since August 2018, an AMP grazing scheme has been implemented within the farm in the context of the LIFE-Regenerate project (https://regenerate.eu/en/). At EU, eight paddocks (4 for both WG and PG, sizes from 0.1 to 2.2 ha) were identified, aiming to perform the AMP grazing. Furthermore, a zone where animals grazed continuously was identified as a control area (about 6.3 ha at WG and 3.2 ha at PG areas, respectively). At SB, the AMP area was divided into eight paddocks (size of about 0.4 ha) in the first year and four paddocks (about 0.8 ha) in the second year. The continuous grazing was performed within a control area of about 4.8 ha. Paddocks were subdivided with electric fencing, which allowed the animals access. In each paddock, animals graze for a few days (average seven days) depending on forage availability and paddock size with high instantaneous stocking (Livestock Units, LSU) rates (up to about 20.6 LSU ha^{-1} year) followed by long resting periods, while in the control areas grazing will occur according to a continuous scheme with lower stocking rates (up to 1.5 LSU ha^{-1} year). The exact grazing periods and dates and the stocking rate (LSU ha^{-1} year) are shown in Figure 1.2.

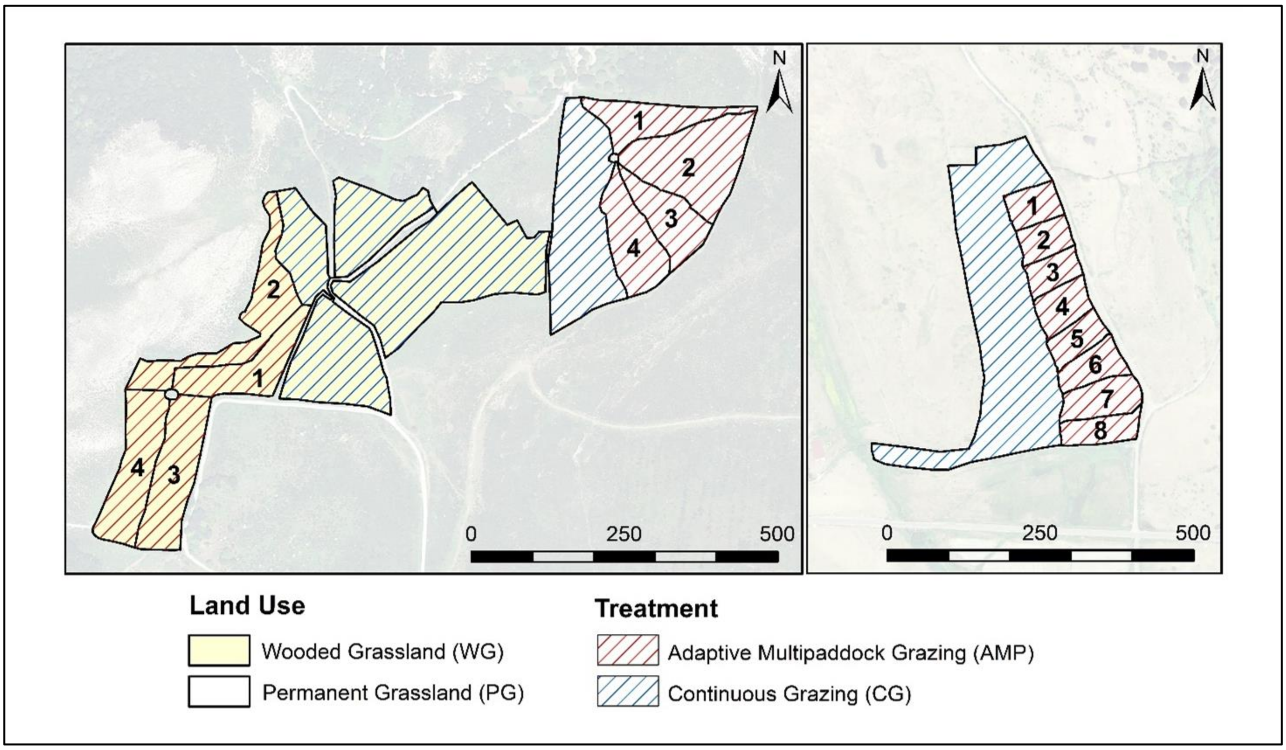
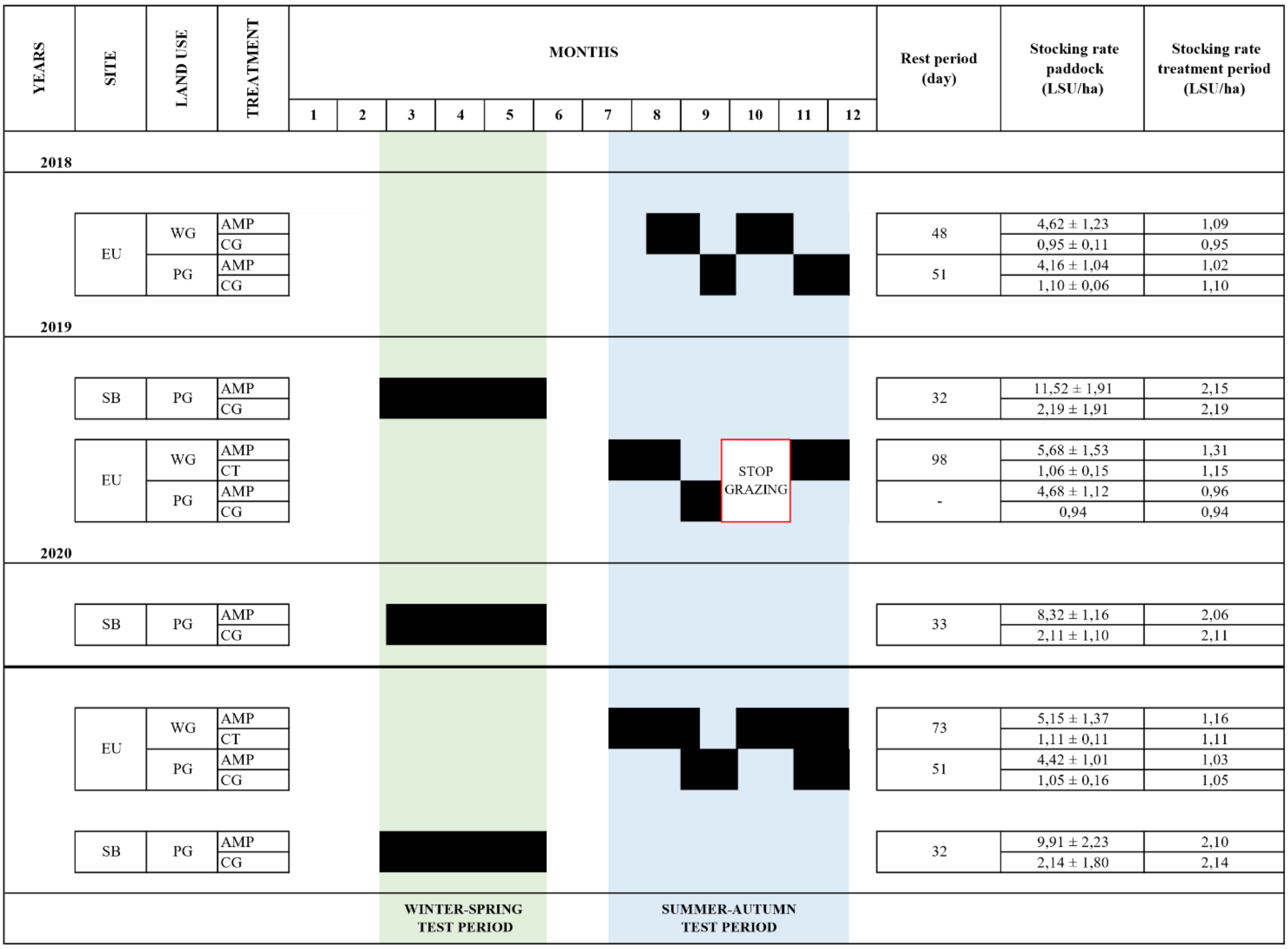


Figure 1.1. Study areas and experimental design



YEARS	SITE	LAND USE	TREATMENT	Rest period (day)	Stocking rate paddock (LSU/ha)	Stocking rate treatment period (LSU/ha)
2018	EU	WG	AMP	48	4,62 ± 1,23	1,09
			CG		0,95 ± 0,11	0,95
		PG	AMP	51	4,16 ± 1,04	1,02
			CG		1,10 ± 0,06	1,10
2019	SB	PG	AMP	32	11,52 ± 1,91	2,15
			CG		2,19 ± 1,91	2,19
	EU	WG	AMP	98	5,68 ± 1,53	1,31
			CT		1,06 ± 0,15	1,15
		PG	AMP	-	4,68 ± 1,12	0,96
			CG		0,94	0,94
2020	SB	PG	AMP	33	8,32 ± 1,16	2,06
			CG		2,11 ± 1,10	2,11
	EU	WG	AMP	73	5,15 ± 1,37	1,16
			CT		1,11 ± 0,11	1,11
		PG	AMP	51	4,42 ± 1,01	1,03
			CG		1,05 ± 0,16	1,05
	SB	PG	AMP	32	9,91 ± 2,23	2,10
			CG		2,14 ± 1,80	2,14

Figure 1.2. Paddocks, stock movements, number of days of rest, duration of grazing periods, and instantaneous stocking rates during grazing periods under AMP and CG areas between August 2018 and June 2020. Black boxes highlight grazing events in both AMP and CG areas

1.2.3 Measurements

In order to characterize the study areas, a floristic survey was carried out in autumn 2018 and 2019 and spring 2019 and 2020 to explore the highest spatial and temporal variability according to the biology and phenology of species composing the floristic communities.

Grassland biomass production in continuously grazed areas was assessed through the mobile exclusion cages method (Frame, 1993). Moreover, the dynamics of biomass production were estimated by measuring the herbage height through the HFRO sward stick (Barthram, 1984). The sward height was measured at both AMP and control areas after and before each grazing event. At each AMP CG area, 25 m transects (n=4) evenly distributed were identified, within which 50 height measurements (about 0.50 m between measures) were carried out. Along with sward height, the functional group of each species touched by the sward-stick was recorded, distinguishing grasses (GRAM), legumes (LEG), other pabular species (OT_PB), and unpabular (OT_NP) species or weeds in general. The sum of GRAM, LEG, OT_PB, and OT_NP results in total biomass (TOT). Periodically throughout the growing season, herbage samples were randomly collected in fields before measuring the sward-stick heights according to the identified functional groups. Biomass was sampled by cutting the sward in areas from 0.0625 m^2 to 0.50 m^2 before height measurements. The sampled biomass was then oven-dried at 65 °C until constant weight reaching to assess the DM content (Mg ha^{-1}). The relationships between the sward-stick height and the biomass DM were used to calibrate the sward stick and thus estimate the herbage offered, growth rates and grassland productivity.

Mobile grazing exclusion cages (1 m × 1 m × 1 m) were established in control areas (n =4 for CG areas) to monthly measure the grassland production under continuous grazing by cutting inside (IN) and outside (EX) each cage 0.5 m^2 surface to collect biomass samples, from which DM biomass was determined as described above. The biomass production (Mg ha^{-1} of DM) between two sampling dates was determined as reported by Seddaiu *et al.* (2018), calculating the difference between the IN biomass at the sampling date (t1) and the EX biomass at the previous sampling date (t0), as follows:

$$DM = IN_{t_1} - EX_{t_0}$$

The sward-stick heights were collected just before cutting the biomass to calibrate the sward-stick and then to average and upscale the data using heights and functional groups frequencies, which were sampled as described above.

The biomass growth rates (kg ha^{-1} d^{-1} of DM) were determined in AMP plots as the difference between the standing biomass just before a grazing event and the standing biomass at the same plot just after the end of the previous grazing turn, divided by the number of days that consist of the restoring period. In CG plots, growth rates were estimated from average biomass data from mobile exclusion cages and sward-stick heights.

The total biomass production (Mg ha^{-1} of DM) was determined as the sum of the daily biomass growth rates. The total biomass production was calculated at each site, distinguishing the WG and the PG at the EU site, for which the autumn biomass production was considered, and the PG at the SB area, for which the winter-spring biomass production was calculated.

The biomass consumption by grazing animals (Mg ha^{-1} of DM) was calculated in AMP plots as the difference between the standing biomass at the end of each grazing event and the sum of the biomass growth during the grazing period at the same plot. The biomass consumption in CG areas was calculated from mobile cages as the difference between the IN and the EX biomass at the same sampling time.

The utilization rate or biomass utilization factor (UF, %) was calculated as the ratio between biomass consumption and total biomass production.

1.2.4 Data analysis

The relationships between the DM biomass and the sward-stick heights were assessed by a stepwise procedure looking for the significant linear regression distinctly by functional group, site, and season. The significance of the linear regressions between DM and height was assessed through the ANOVA (anova) of fitted linear models (lm). The effect of the interaction between sampling date and grazing management within each site on biomass growth rate was assessed by fitting a Linear Mixed-Effect Model (lme), setting up as a random (position) factor each sampling transect and a constant variance function structure within each sampling date (e.g. Onofri *et al.*, 2016). The effect of the interaction between year and grazing management within each site on biomass production, biomass ingestion, and UF was assessed by fitting a Linear Mixed-Effect Model (lme), setting up a random (position) factor each sampling transect. The significance of experimental factors and their interaction was assessed by performing the ANOVA (anova) of the fitted lme. The estimated marginal means (emmeans) were computed on significant experimental factors or interactions to compare means within each significant level. The significance of the statistical computation was evaluated at $P<0.05$ unless otherwise stated. The lm, anova, lme (Pinheiro *et al.*, 2018), and emmeans (Lenth, 2018) computations were performed using the RStudio application of R software (version 4.0.5) (RCoreTeam, 2018).

1.3 Results

1.3.1 Weather

The studied system showed a grassland grow typical of the seasonal meteorological pattern in Mediterranean conditions. The weather conditions for the experimental period are shown in Figure 1.3. The mean annual rainfall is 1292 mm and 1120 mm in EU (2006-2018) and SB (2006-2018) areas, respectively, about 75% of which falls in the autumn-winter seasons (from October to March). The annual average air temperature is 11.5 °C and 14.6 °C in EU and SB, respectively.

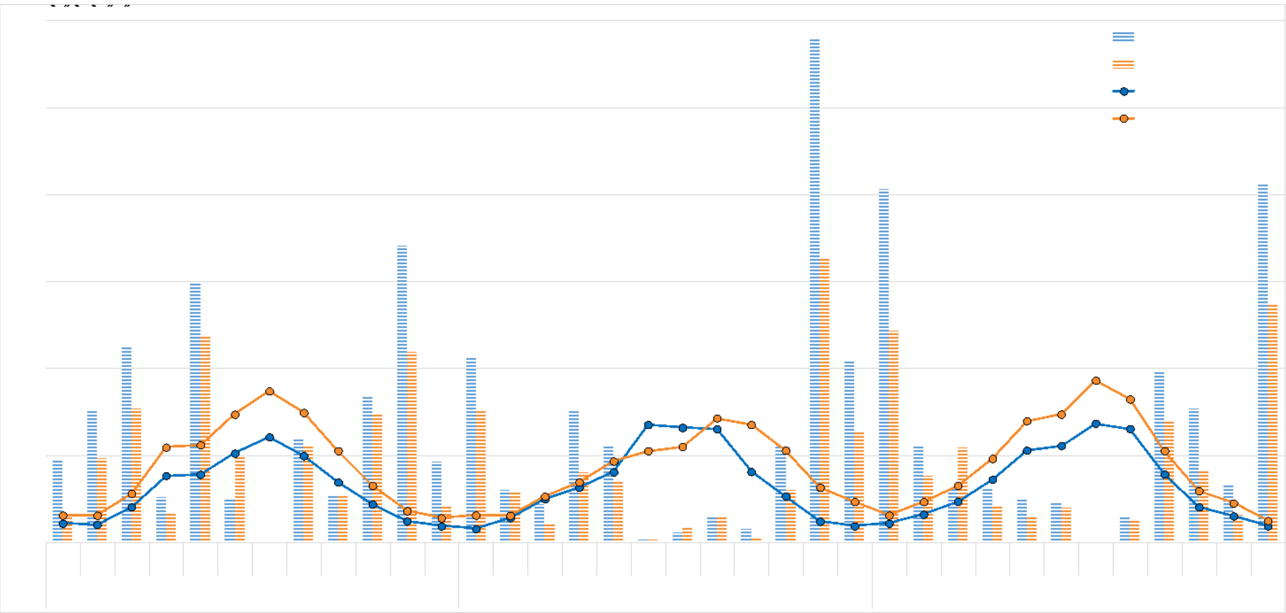
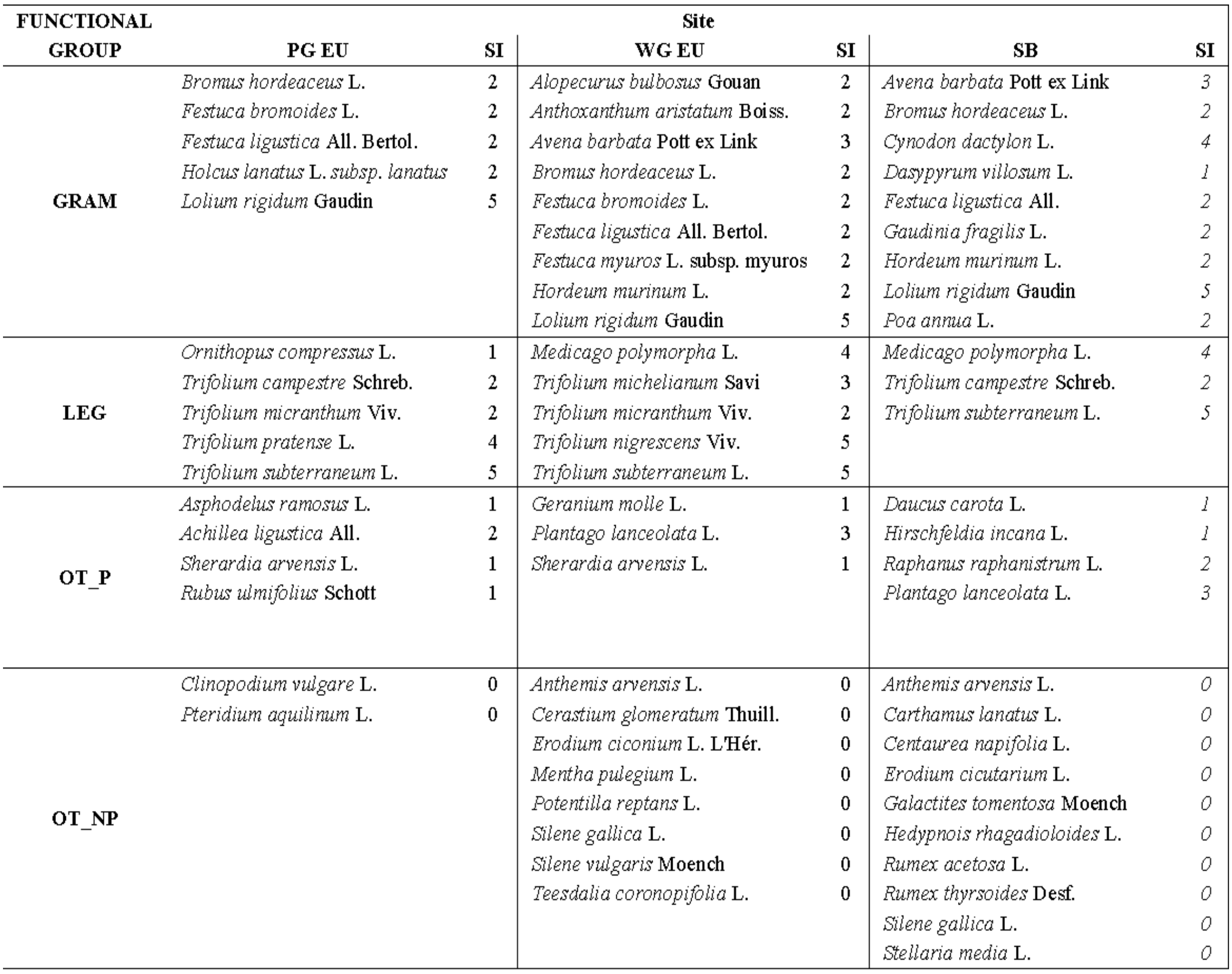


Figure 1.3. Rainfall and ET(0) dynamics in ELIGHES UTTIOSOS (Blue) and SAS BOGADAS (Orange), from ARPAS (Agenzia Regionale per la Protezione dell'Ambiente della Sardegna)

1.3.2 Floristic surveys

The results of the floristic surveys are reported in Table 1.1. Species richness among grassland sites ranged from 61 to 84 species. The principal palatable families available and contributing to grassland production were the Poaceae, Fabaceae and Asteraceae, while Dennstaedtiaceae (especially for the site EU-PG), Asteraceae, *Pteridium aquilinum* L. and *Anthemis arvensis* L., for unpalatable production. The differences in floristic composition between the sites (SB and EU) are associated with the different altitudes and the different types of pasture (WG and PG).

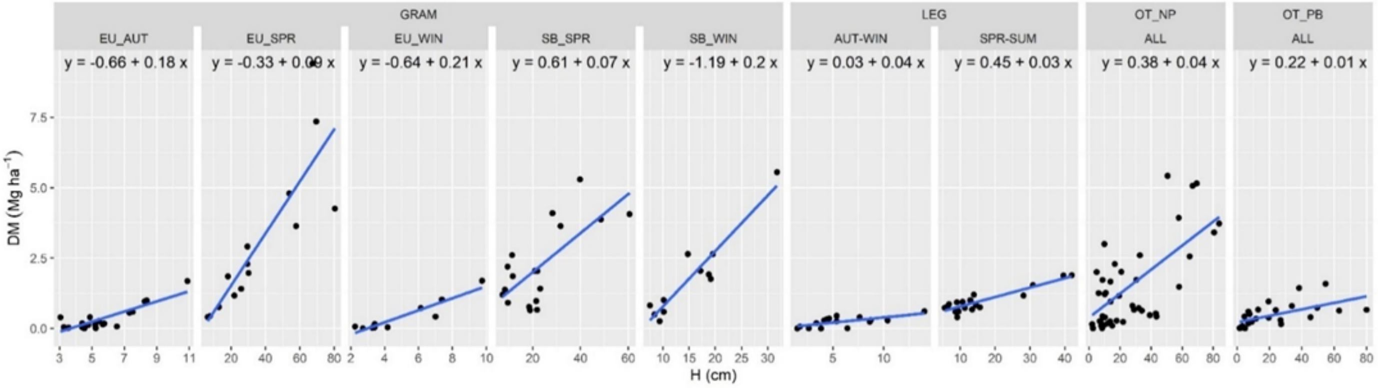
Table 1.1. List of the main species contributing more than 50% of the species frequency in each functional group for site; SI= Specific index from "integrated analysis to assess the grazing value of Mediterranean rangelands" (Roggero, at al., 2002).



FUNCTIONAL	Site					
GROUP	PG EU	SI	WG EU	SI	SB	SI
GRAM	*Bromus hordeaceus* L.	2	*Alopecurus bulbosus* Gouan	2	*Avena barbata* Pott ex Link	3
	Festuca bromoides L.	2	*Anthoxanthum aristatum* Boiss.	2	*Bromus hordeaceus* L.	2
	Festuca ligustica All. Bertol.	2	*Avena barbata* Pott ex Link	3	*Cynodon dactylon* L.	4
	Holcus lanatus L. *subsp. lanatus*	2	*Bromus hordeaceus* L.	2	*Dasypyrum villosum* L.	1
	Lolium rigidum Gaudin	5	*Festuca bromoides* L.	2	*Festuca ligustica* All.	2
			Festuca ligustica All. Bertol.	2	*Gaudinia fragilis* L.	2
			Festuca myuros L. subsp. myuros	2	*Hordeum murinum* L.	2
			Hordeum murinum L.	2	*Lolium rigidum* Gaudin	5
			Lolium rigidum Gaudin	5	*Poa annua* L.	2
LEG	*Ornithopus compressus* L.	1	*Medicago polymorpha* L.	4	*Medicago polymorpha* L.	4
	Trifolium campestre Schreb.	2	*Trifolium michelianum* Savi	3	*Trifolium campestre* Schreb.	2
	Trifolium micranthum Viv.	2	*Trifolium micranthum* Viv.	2	*Trifolium subterraneum* L.	5
	Trifolium pratense L.	4	*Trifolium nigrescens* Viv.	5		
	Trifolium subterraneum L.	5	*Trifolium subterraneum* L.	5		
OT_P	*Asphodelus ramosus* L.	1	*Geranium molle* L.	1	*Daucus carota* L.	1
	Achillea ligustica All.	2	*Plantago lanceolata* L.	3	*Hirschfeldia incana* L.	1
	Sherardia arvensis L.	1	*Sherardia arvensis* L.	1	*Raphanus raphanistrum* L.	2
	Rubus ulmifolius Schott	1			*Plantago lanceolata* L.	3
OT_NP	*Clinopodium vulgare* L.	0	*Anthemis arvensis* L.	0	*Anthemis arvensis* L.	0
	Pteridium aquilinum L.	0	*Cerastium glomeratum* Thuill.	0	*Carthamus lanatus* L.	0
			Erodium ciconium L. L'Hér.	0	*Centaurea napifolia* L.	0
			Mentha pulegium L.	0	*Erodium cicutarium* L.	0
			Potentilla reptans L.	0	*Galactites tomentosa* Moench	0
			Silene gallica L.	0	*Hedypnois rhagadioloides* L.	0
			Silene vulgaris Moench	0	*Rumex acetosa* L.	0
			Teesdalia coronopifolia L.	0	*Rumex thyrsoides* Desf.	0
					Silene gallica L.	0
					Stellaria media L.	0

1.3.3 Relationships between plant height and biomass

The results of the stepwise analysis performed to identify significant regressions between sward-stick height and DM biomass are reported in Figure 1.4. The sward-stick height significantly explained the variability of the standing biomass ($P<0.001$) as follows: GRAM species, distinguishing at the EU site the autumn ($R^2=0.75$), spring ($R^2=0.72$), and winter ($R^2=0.87$) seasons, and at SB site in spring ($R^2=0.50$) and winter ($R^2=0.88$); LEG species, distinguishing a model for autumn-winter ($R^2=0.46$) and spring-summer ($R^2=0.81$) seasons; OT_PB species ($R^2=0.36$); OT_NP species ($R^2=0.43$). Functional groups frequencies by period sampled are reported in Figure 1.4.



n°	Funtional Grou	Site	Time	H (cm)			DM (Mg)			Linear equation			p-value	R²
				Mean	Min	Max	Mean	Min	Max	a	b	g.l.		
1	GRAM	EU	WIN	4,95	2,25	9,75	0,42	0,00	1,70	-0,62	0,21	9	>0,01	0,87
2	GRAM	EU	AUT	5,43	3,05	10,88	0,29	0,00	1,68	-0,60	0,16	23	>0,01	0,64
3	GRAM	EU	SPR	36,47	6,43	80,24	3,05	0,41	9,41	-0,33	0,09	13	>0,01	0,72
4	GRAM	SB	WIN	15,14	7,50	31,75	1,79	0,26	5,55	-1,19	0,20	10	>0,01	0,88
5	GRAM	SB	SPR	22,95	7,38	60,50	2,20	0,65	5,30	0,61	0,07	17	>0,01	0,50
6	LEG	EU-SB	AUT-WIN	5,80	1,50	14,00	0,24	0,00	0,61	0,03	0,04	31	>0,01	0,46
7	LEG	EU-SB	SPR-SUM	15,82	5,50	42,00	0,97	0,40	1,89	0,45	0,03	37	>0,01	0,81
9	OT_NP	EU-SB	ALL	24,25	2,00	83,75	0,94	0,01	5,42	0,38	0,04	34	>0,01	0,30
8	OT_PB	EU-SB	ALL	22,40	1,50	80,00	0,48	0,01	1,58	0,22	0,01	24	>0,01	0,36

Figure 1.4. Linear regressions between the aboveground biomass (DM, Mg ha^{-1}) and the sward-stick height (H, cm) of grams (GRAM), legumes (LEG), other pabular (OT_PB) and unapalatable (OT_NP) species in autumn (AUT), spring (SPR), winter (WIN) periods or considering the whole (ALL) growing season.

1.3.4 Productivity

Overall, growth rates follow bimodal dynamics, for which the highest rates were observed in autumn and spring. The growth rate dynamics in EU_PG, EU_WG (both summer-autumn grazing) and SB_PG (winter-spring grazing) are reported in Figure 1.5.

In the EU_WG site, the interaction date x grazing management significantly influenced biomass growth rates (kg ha^{-1} d^{-1}) of GRAM ($P<0.0001$), LEG ($P=0.009$), while grazing management influenced the TOT biomass growth rates ($P=0.03$). The sampling data significantly affected the growth rates of OT_PB ($P=0.05$) and OT_NP ($P<0.0001$). The GRAM growth rates were significantly higher under AMP grazing from the end of November 2018 to the end of autumn 2018 and at the beginning of autumn 2019. The LEG growth rates were significantly higher in CG on only one date at the beginning of October 2018. The average TOT growth rates were higher in AMP (10.2±0.6 kg ha^{-1} d^{-1}) than in CG (8.1±0.6 kg ha^{-1} d^{-1}). In the EU_PG site, the interaction date x grazing significantly influenced biomass growth rates of GRAM ($P=0.002$), OT_NP, and TOT ($P<0.0001$). No significant effects of experimental factors were observed in LEG and OT_PB. The GRAM growth rates were higher under AMP (11.1±0.2 kg ha^{-1} d^{-1}) than CG (4.2±0.2 kg ha^{-1} d^{-1}) in mid-November 2018, when maximum growth rates occurred, and at the beginning of 2019, grazing season. The OT_NP growth rates were higher in CG in the late summer of 2018, when the highest rates of 27.3±1.0 kg ha^{-1} d^{-1} and 16.5±1.0 kg ha^{-1} d^{-1} under respectively CG and AMP were observed, while they were higher in AMP (18.3±1.0 kg ha^{-1} d^{-1}) than CG(12.2±1.0 kg ha^{-1} d^{-1}) during the same period in 2019. This results in similar dynamics in TOT growth rates (Figure 1.5).

In the SB_PG site, the interaction date x grazing significantly influenced biomass growth rates of OT_PB ($P=0.0002$), OT_NB ($P<0.0001$), and TOT ($P=0.01$). The sampling date significantly influenced the growth rates of GRAM and LEG ($P<0.0001$). The highest GRAM growth rates were observed between the second half of April and the first week of May in both 2019 and 2020 (19.3±1.6 kg ha^{-1} d^{-1}), while the lowest growth rate (5.6±2.3 kg ha^{-1} d^{-}1) were observed and the end of winter 2020. The highest LEG growth rates were observed between the second half of March and the first 20 days of April in both 2019 and 2020 (6.0±1.7 kg ha^{-1} d^{-1}) were observed. The lowest rates were observed at the end of grazing seasons (late May) of both 2019 and 2020, when LEG growth rates became negligible (<0.2 kg ha^{-1} d^{-1}). The OT_PB growth rates were higher under AMP (highest rate 2.4±0.4 kg ha^{-1} d^{-1}) than CG only in the second half of April 2019. The OT_NP growth rates were higher under AMP (highest rate 16.7±2.8 kg ha^{-1} d^{-1}) than CG (highest rate 8.0±2.8 kg ha^{-1} d^{-1}) from the second half of April to the end of May in both 2019 and 2020. The TOT growth rates were higher under AMP (highest rate 36.4±2.1 kg ha^{-1} d^{-1}) than CG (highest rate 25.6±2.1 kg ha^{-1} d^{-1}) in both 2019 and 2020 from the second half of April to the first half of May.

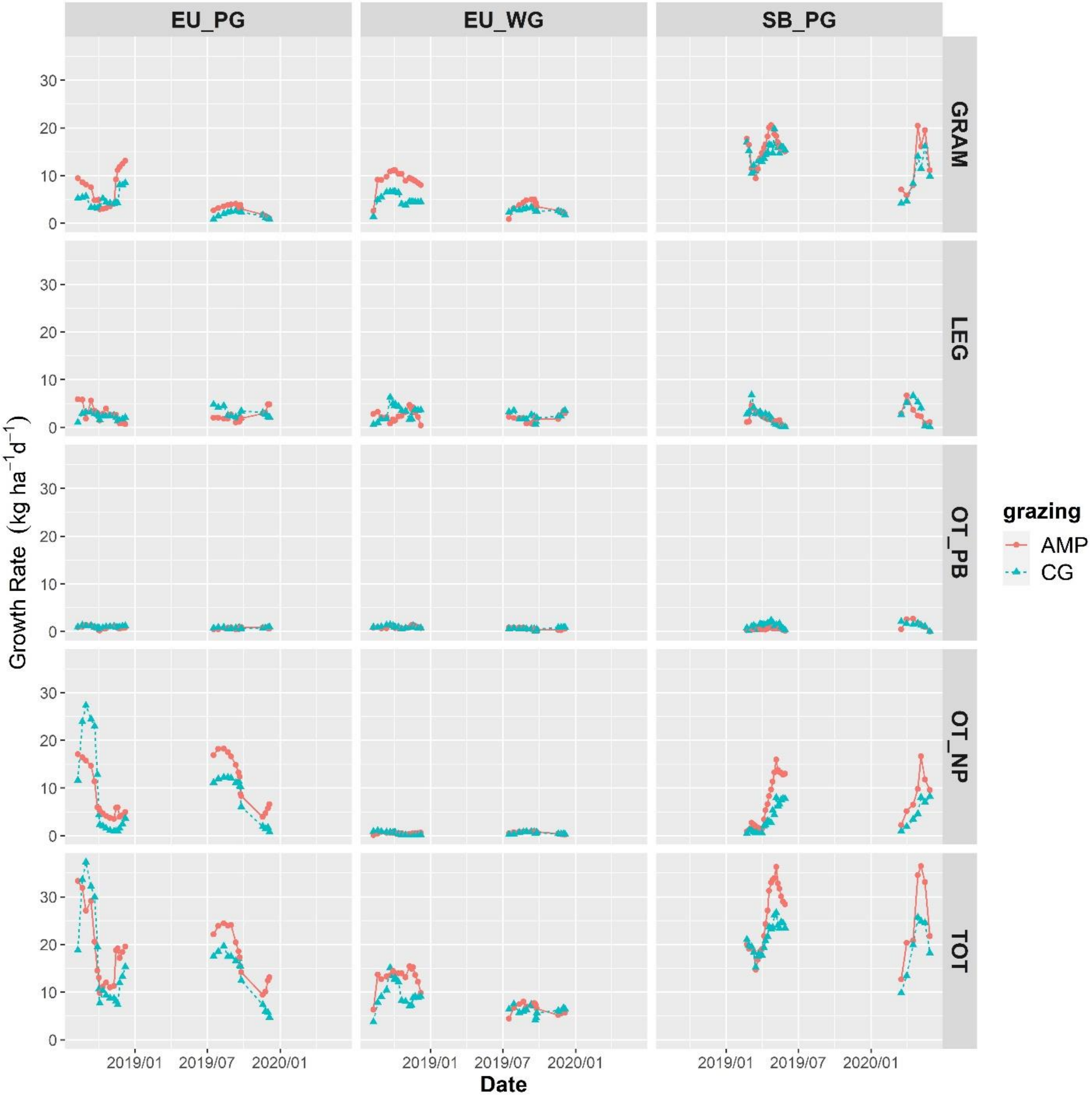


Figure 1.5. Aboveground biomass Growth Rates (kg ha^{-1} d^{-1} of DM) from July 2019 to June 2020 of grams (GRAM), legumes (LEG), other pabular (OT_PB) and other unpalatable (OT_NP) species in the three areas. Red lines and dots represent the growth rates under rotational grazing (AMP, Adaptive Multi Paddock grazing), blue lines and dots under continuous grazing management (CG, continuous grazing). EU = Elighes Uttiosos; SB = Sas Bogadas; PG = permanent grassland; WG = wooded grassland

1.3.5 Biomass production and utilization rates

The aboveground biomass production in EU_PG, EU_WG (both summer-autumn grazing) and SB_PG (winter-spring grazing) is reported in Figure 1.6.

In the EU_PG site, the interaction year x grazing significantly influenced the biomass production (Mg ha^{-1}) of OT_PB, OT_NP ($P<0.05$), and TOT ($P=0.05$). The year and the grazing system significantly influenced the biomass production of LEG ($P<0.01$). No significant effects of experimental factors were observed in GRAM. The biomass LEG production was on average higher in the second year (0.39±0.01 Mg ha^{-1} of DM) than in the first (0.26±0.01 Mg ha^{-1}), and on average in AMP (0.38±0.01 Mg ha^{-1}) than in CG (0.38±0.01 Mg ha^{-1}). The biomass production of OT_PB was significantly higher in AMP (0.11±0.01 Mg ha^{-1}) than in CG (0.094±0.01 Mg ha^{-1}) in the second year, while no significant differences between AMP and CG were observed in the first year. The OT_NP biomass production was significantly higher in AMP (1.38±0.07 Mg ha^{-1}) than CG (0.96±0.07 Mg ha^{-1}) in the second year, while in the first year no significant differences were observed between CG (1.26±0.07 Mg ha^{-1}) and AMP (0.99±0.07 Mg ha^{-1}). The TOT biomass in the second year was significantly higher in AMP (2.48±0.11 Mg ha^{-1}) than in CG (1.86±0.11 Mg ha^{-1}), while the biomass production in AMP and CG in the first year was not significantly different than both AMP and CG at year 2.

In the EU_WG site, the interaction year x grazing significantly influenced the biomass production (Mg ha^{-1}) of GRAM ($P=0.04$), LEG ($P<0.05$), OT_PB ($P<0.0001$), and TOT ($P<0.05$), while no significant effects of both year and grazing were observed in OT_NP. The GRAM biomass production was significantly higher in the first year of AMP (1.15±0.08 Mg ha^{-1}) than in the other interaction levels. The LEG biomass production was significantly higher in the first year of AMP (0.33±0.04 Mg ha^{-1}) than CG (0.11±0.04 Mg ha^{-1}), while both AMP and CG in the second year were not different from the first-year values. The OT_PB biomass production was higher in AMP (0.11±0.01 Mg ha^{-1}) than CG in the first year, while it was higher in CG (0.08±0.01 Mg ha^{-1}) than AMP in the second year. Overall, the TOT biomass production was significantly higher in the first-year AMP (1.65±0.11 Mg ha^{-1}) than in the other levels of interaction.

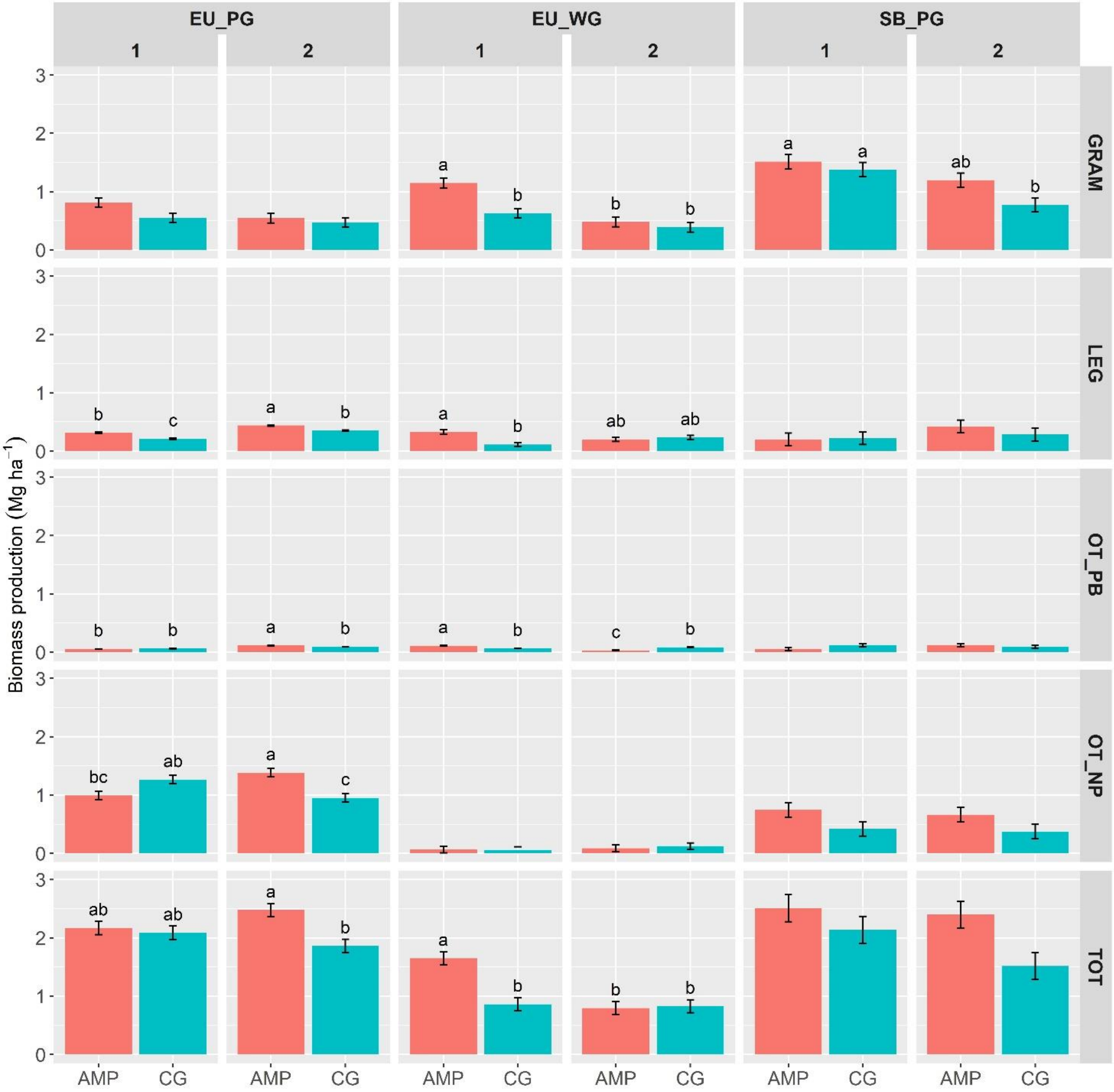


Figure 1.6. Aboveground biomass production (Mg ha^{-1} of DM) in the two years of the experiment of grams (GRAM), legumes (LEG), other pabular (OT_PB) and other unpalatable (OT_NP) species in the three areas. AMP = Adaptive Multi Paddock; CG = continuous grazing. EU = Elighes Uttiosos; SB = Sas Bogadas; PG = permanent grassland; WG = wooded grassland

The UF (kg kg^{-1} of DM) of functional groups, including pabular species (GRAM, LEG, OT_PB) in EU_PG, EU_WG (both summer-autumn grazing) and SB_PG (winter-spring grazing), are reported in Figure 1.7.

In the EU_PG site, the interaction year x grazing significantly influenced the UF of OT_PB ($P<0.01$), while year significantly affected the UF of LEG ($P<0.01$). No significant effects of year and grazing on UF of GRAM (on average 0.28±0.07 kg kg^{-1}) were observed. The UF of LEG was higher in the first year (on average 0.30±0.02 kg kg^{-1} of DM) than in the second (0.16±0.02 kg kg^{-1}).

In the EU_WG site, year significantly affected UF of LEG ($P<0.01$) and OT_PB ($P<0.01$), while grazing significantly influenced only GRAM ($P<0.01$). The UF of GRAM was on average higher in AMP (0.44±0.03 kg kg^{-1}) than CG (0.27±0.03 kg kg^{-1}). The UF of LEG was higher in the first year (on average 0.51±0.03 kg kg^{-1}) than in the second (0.36±0.03 kg kg^{-1}), as well as for OT_PB (0.42±0.02 kg kg^{-1} and 0.25±0.02 kg kg^{-1} in the first and second year, respectively).

In the SB_PG site, grazing significantly influenced the UF of GRAM ($P<0.01$), while both year ($P<0.01$) and grazing ($P<0.01$) significantly affected the UF of OT_PB. The interaction year x grazing significantly influenced the UF of LEG ($P<0.01$). The UF of GRAM was on average higher in AMP (0.38±0.02 kg kg^{-1}) than CG (0.15±0.02 kg kg^{-1}). The UF of LEG was significantly higher in the first-year AMP (0.45±0.03 kg kg^{-1}) than CG (0.11±0.03 kg kg^{-1}), while no significant differences between AMP and CG were observed in the second year. The UF of OT_PB was significantly higher in AMP (on average 0.46±0.02 kg kg^{-1}) than CG (0.23±0.02 kg kg^{-1}), and in the second year (0.42±0.02 kg kg^{-1}) than the first (0.27±0.02 kg kg^{-1}).

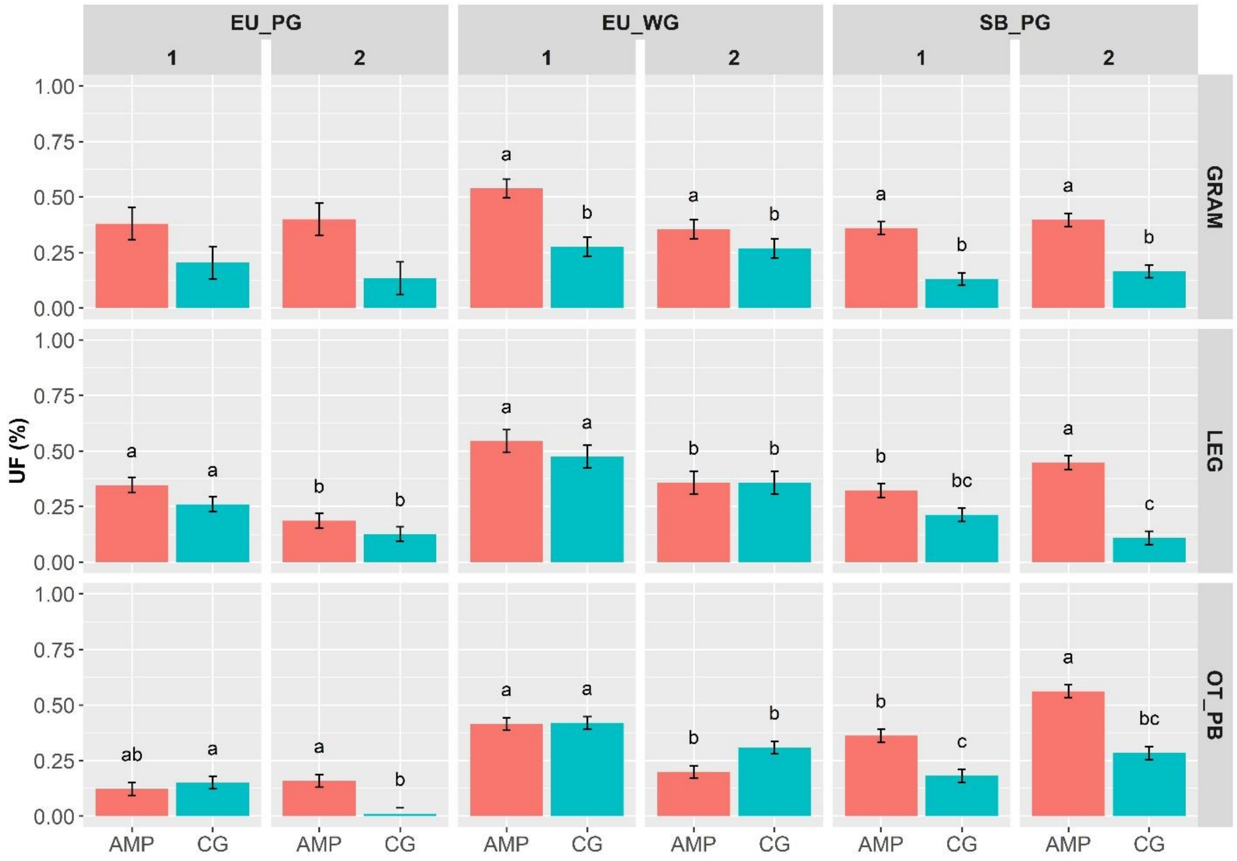


Figure 1.7. Biomass Utilization factor (UF, kg kg^{-1} of DM) in the two years of the experiment of grams (GRAM), legumes (LEG), and other pabular (OT_PB) species in the three areas. AMP = Adaptive Multi Paddock; CG = continuous grazing. EU = Elighes Uttiosos; SB = Sas Bogadas; PG = permanent grassland; WG = wooded grassland

The estimated biomass consumption as ingestion (Mg ha^{-1} of DM) of functional groups, including pabular species (GRAM, LEG, OT_PB), is reported in Figure 1.8**.**

In the EU_PG site, the interaction year x grazing significantly only influenced the biomass ingestion of OT_PB ($P<0.01$), while grazing significantly influenced the ingestion of GRAM ($P=0.04$), LEG ($P<0.01$), and TOT ($P<0.05$). In the EU_WG site, the interaction year x grazing significantly influenced the biomass ingestion of GRAM ($P<0.01$), LEG ($P<0.01$), OT_PB ($P<0.01$), and TOT ($P<0.01$). In the SB_PG site, grazing significantly influenced the ingestion of GRAM and the TOT ($P<0.01$), while the year x grazing interaction significantly influenced the ingestion of OT_PB ($P<0.05$). No significant effects of experimental factors on LEG ingestion were observed.

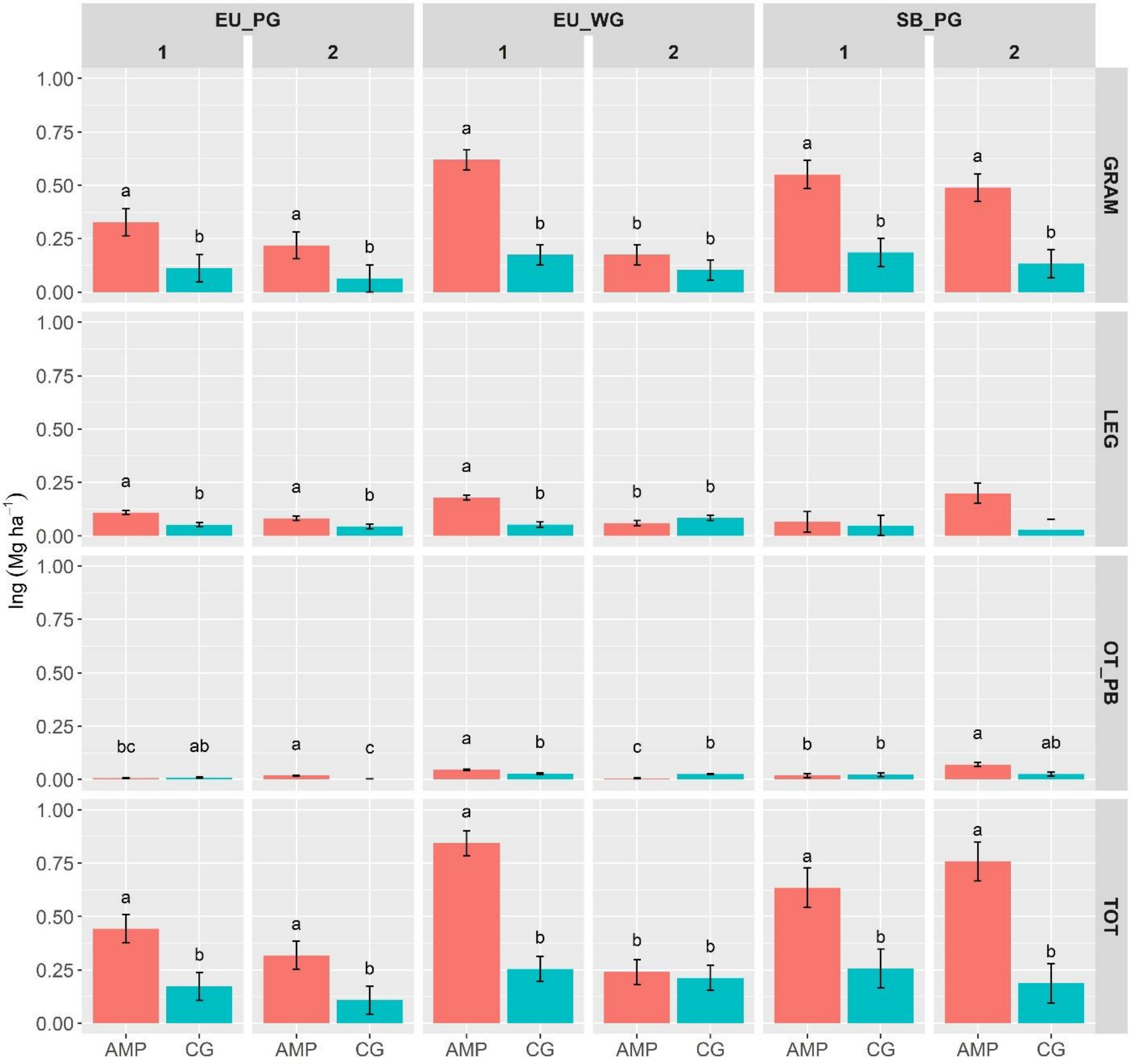


Figure 1.8. Biomass Ingestion (Ing, Mg ha^{-1} of DM) in the two years of the experiment of grams (GRAM), legumes (LEG), and other pabular (OT_PB) species in the three areas. AMP = Adaptive Multi Paddock; CG = continuous grazing. EU = Elighes Uttiosos; SB = Sas Bogadas; PG = permanent grassland; WG = wooded grassland

1.4 Discussions

1.4.1 Grazing, weather patterns and productivity

The observed vegetation types and floristic composition were in line with other works done on Sardinia's hill and mountain landscape (e.g. Bagella et al., 2013; Seddaiu et al., 2018). The biomass productivity showed dynamics over the monitoring period associated with the weather patterns. In fact, in Mediterranean grazing systems, the seasonal distribution of rainfall and temperature is the primary constraint determining herbage growth (Pineda et al., 1987; Calanca et al., 2016). On average, DM production of AMP pasture areas was higher than that of CG areas, although significant differences emerged only in one of the grazing seasons in permanent and wooded grasslands. These results agree with several authors highlighting a negligible impact of the AMP grazing system compared to CG on pasture production (e.g. Briske et al., 2008) or even a minimal effect (e.g. Holechek et al., 2000). Nevertheless, most of the studies available in the literature relate production in absolute terms, while considering the impact of rotational grazing systems on distinct vegetational groups is a concern which is addressed less frequently (Nordborg, 2016), even if the impacts of grazing management practices on functional groups are quite explored (Lavorel et al., 1999; McIntyre and Lavorel, 2001; Pillar, 1999; Nygaard and Ejrnaes, 2004).

During the first growing seasons, a higher biomass production under AMP grazing than CG was observed in EU_WG. This higher forage availability was associated with the interaction between the grazing management and the extraordinary rainfall events in the late summer and early autumn that compensated for the ET deficit commonly occurring in that period. A favourable rain distribution patterns in the late summer and early autumn combined with long periods of restoration within a rotational grazing pattern lead to the higher efficiency of AMP in promoting growth rates and then total biomass production, especially gram pabular species (e.g. *Avena barbata* Pott ex Link - in wooded areas). These results align with Teague et al. (2008), according to which AMP can enhance grassland productivity when appropriate conditions in terms of soil water availability occur along the season, particularly during the grazing resting period. In fact, a fundamental tenet of adaptive, multi-paddock grazing is that long rest periods are vital for enhancing vegetation conditions (Gosnell et al., 2020).

The higher unpabular biomass production in the AMP than in the CG areas observed during the second year in the permanent mountain grassland was mainly associated with a higher cover of the unpalatable species *Pteridium aquilinum* L. Even if an overall higher utilization rate of biomass was observed under AMP and a consequent reduction of the selective behaviour of grazing animals, this is not always valid when invasive an potentially poisonous species such as *P. aquilinum* are present, as in the case of the EU_PG mountain areas. In this case, the rotational grazing could have induced better conditions for *P. aquilinum* growth thanks to the water stress that annual pabular species suffer in summer, reducing the intraspecific competition favouring *P. aquilinum* growth. Due to its clonal propagation strategy, longevity and persistence, *P. aquilinum* can produce a dense canopy of fronds that may dominate for decades (Karjalainen 1989). Such dense *P. aquilinum* L. may effectively compete for water and nutrients and reduce the growth of other species (Gray, 2022; Richardson, 1993).

It is probable that, in Mediterranean grasslands, gradual accumulative changes in productivity due to different grazing regimes are masked, on a short time scale, by the variability in rainfall patterns. In addition, the evaluations should bear in mind that the recording with the sward stick method probably resulted in a subtle bias towards the tall species and an underestimation of the short prostrate species, particularly in paddocks at higher pasture heights.

1.4.2 Biomass consumption as ingestion

The higher utilization rates observed on average in AMP than in CG areas were associated with higher stoking rates, leading to higher forage consumption (Milton et al., 1994; Smart et al., 2010). This can improve the ability to use forage resources in rangelands (Hirschfeld et al. 1996), even if under Mediterranean conditions, not always paddock subdivision and increased stock density reduce selectivity and intensity of utilization (e.g. Steffens et al., 2009). The stocking rate drives the animals' ability to select plant species over time for that period and, therefore, can be changed through management. Grazing behaviour and, consequently, biomass consumption are also influenced by the vertical distribution of morphological components of sward biomass (Carvalho et al., 2009, Fonseca et al., 2012). As grazing progresses, vertical and horizontal constraints alter the animal's consumption behaviour and the short-term herbage intake rate (Burns and Sollenberger, 2002). Therefore, structural changes could influence rotational plots compared to CG areas during the grazing period. Even if the disappearance rate of forage increases with stocking density, controlling the length of the grazing period can stop usage at any desired level (Steffens et al., 2009; Barnes, 2009). At the global level, in grassland-based livestock farming systems, the improvement of pasture availability through the increase in biomass production and its utilization efficiency can significantly reduce the conflict between feed and food production (Mottet et al., 2017).

1.5 Conclusions

The results of this study only partially confirm that the adoption of the AMP grazing system can improve the overall productivity and then the aboveground biomass production under Mediterranean silvopastoral systems. Enhanced biomass production was observed for gram species, especially under non-limiting water conditions in autumn, but also for unpalatable and invasive species in the summer-autumn permanent grassland, in which the AMP could have promoted the vegetative vigour of an invasive species such as the *Ptedirium aquilinum* L. Nevertheless, the hypothesis that adaptive grazing can improve the pasture utilization rate is confirmed, so introducing a rotational grazing system such as the AMP in this context of extensive management can enhance the efficiency of the forage resource exploitation. These results highlighted the potential of the AMP as a grazing system contrasting the loss of pasture quality associated with undergrazing. Therefore, the large-scale implementation of rotational grazing could represent a strategy facing the land degradation associated with rangelands under exploitation, thus the abandonment trends.

Future insights on large-scale grazing systems analysing the effect of innovative grazing management such as the AMP require a multi-factorial and predictive approach through the integration of field data and digital technologies such as models and data from remote sensing aiming to explore the wider environmental (meteorological dynamics, soil, microbiological activity, and other factors with influence on plant production) and management variability (stocking rate, animal species, field size, time, food integration and other factors affecting animal production). This approach could represent the basis for building effective decision support systems that allow users to make decisions under the different environmental and social conditions that characterize Mediterranean silvopastoral systems.

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2 Chapter II

Suitability of the Landsat-NDVI Time-Series for a posteriori grassland dynamics evaluation of Adaptive Multi-Paddock Grazing in Iberian agroforestry systems

Abstract

Context. Grazing management plays a crucial role in inter-annual vegetation changes and provides a wide range of ecosystem services. Adaptive Multi-Paddock grazing system (AMP) is a flexible methodology that combines intensive, rapid rotation of grazing livestock to provide relatively short grazing periods with moderate plant use and adequate recovery time after grazing.

Objectives. In this study, a remote sensing approach based on a 6-year (between 2010 and 2019) time-series analysis of Normalized Difference Vegetation Index (NDVI) data, derived from Landsat-5 TM/8 OLI Sensors (30 x 30 m spatial resolution) and processed with GIS free software, was applied on silvopastoral systems in south-western Iberian Peninsula to assess the impacts of the adoption of the AMP grazing systems in Mediterranean wooded grasslands.

Methods. A time-series of NDVI from Landsat images in three silvopastoral farms of the Iberian peninsula was analysed. In these farms, the effect of the interaction between Land Use (Wooded Grassland and Grassland) and grazing Management (AMP and continuous grazing) on NDVI was tested, both before and after the AMP adoption, in four different grassland phenophases of the annual growing season.

Results. Land Use significantly influenced the NDVI in the Regreening, Drying, and Dry phenophases (WG>GR) during the PRE period, while in the POST period, Land Use significantly influenced the NDVI at the Regreening, Drying, and Dry phenophases. The management (AMP>CON) influenced the NDVI at the Regreening stage. Overall, under GR land use, the spatial variability tended to decrease from PRE to POST, while under WG, little changes from PRE to POST period were observed in the Green and Dry stages. While there is a clear effect of land use on NDVI in the early and late stages of the growing season associated with the presence of trees in wooded grasslands, little evidence emerged on the impacts of AMP adoption, suggesting potential better exploitation of forage resources promoting autumn restart and biomass availability in autumn.

Keywords: vegetation indices; grazing management; grassland phenology; remote sensing

2.1 Introduction

Mediterranean silvopastoral farms are characterized by multifunctional and extensive management, integrating forage provision for grazing animals and forestry (Torralba et al., 2018; Freitas et al., 2020). In the Iberian peninsula, these systems, covering about 3.14 Mha (EEA, 2018), are mainly managed wooded grasslands known as Dehesas and Montados in Spain and Portugal, respectively (Hausner et al., 2015).

The grassland vegetative cycle of Mediterranean wooded grasslands is characterized by seasonal variations in plant species composition and productivity, which are, in turn, linked to the seasonal variability in rainfall and temperatures (Lumbierres et al., 2017). The grassland 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 both increasing temperature and water availability establishes the conditions for increasing pasture productivity in spring. In summer, the lack of precipitation and high temperatures are linked to the final stages of the pasture vegetative cycle (Serrano et al., 2018a; Serrano et al., 2018b). The forage availability during the grazing season is also influenced by grazing management (Tesk et al., 2018). In these silvopastoral systems, 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.

The Adaptive Multi-Paddock grazing system (AMP) combines 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 bibliography. Catalan et al. (2019) 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. On the other hand, other studies (Briske et al., 2008; 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, agroforestry systems' shape, complexity, and heterogeneity make remote sensing more difficult than in distinct and homogeneous land cover types, such as forests and open grasslands (Weiss et al., 2020). The level of analysis complexity increase when remote sensing tools are used to determine the phenological phases and variations as these systems combine herbaceous and shrubby understory with a low-density tree cover, constituting a severe challenge for remote sensing studies (Martín et al., 2020). 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; Rossi M 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., 2020).

In a context of little scientific knowledge as well as disagreement and uncertainty emerging from the literature on the impacts of the adoption of AMP as a solution to improve the suitability of forage resources in grasslands under silvopastoral farms, it becomes crucial to assess the greatest extent as possible in terms of grazing area the effects over time of grazing management changing from continuous to AMP. In a context of increasing demand for innovative tools to support the assessment of impacts of management practices on forage production and availability of extensive grazing systems, the NDVI from remote sensing from satellite images can represent an effective tool to properly explore the quantity and variability of forage availability over time (Blanco et al., 2009).

The hypothesis of this study was that the Mediterranean silvopastoral agroforestry systems, the NDVI, as a proxy of forage availability, can be influenced by the interaction of land use, phenophase, and grazing management before and after the AMP adoption within different farms. The aims of the study were to assess the effect of time, land use, grassland phenophase, and grazing management on 1) NDVI dynamics and 2) NDVI variability under the Mediterranean silvopastoral systems of the Iberian Peninsula.

2.2 Materials and methods

2.2.1 Study site

The study area was located in the South-Western Iberian peninsula (Figure 2.1), within three livestock farms located between 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 study area has a typical Mediterranean climate with long, hot, and dry summers and mild, wet winters. 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 (Figure 2.2). The whole experimental area was about 2250 ha, distinguishable according to CORINE Land Cover as agroforestry silvopastoral land use (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* genus (e.g. *Quercus ilex* L. subsp. *ballota).* The herbaceous layer covered almost all of the study area and was composed of a wide variety of annual grassland species. The grassland areas within these livestock farms were grazed by cattle, sheep, goats and Iberian pigs. The areas were traditionally managed with continuous grazing and low stoking rates.

2.2.2 Study layout and experimental design

The methodology is summarized in Figure 2.3. The AMP grazing system was introduced between 2014 and 2016 in some parts of each farm to improve grazing management, thus identifying a period before AMP adoption (PRE, before 2014), a transition period (2014-2016), and a period after which the AMP grazing system was well established within farms (POST, 2016-2019). According to the CORINE land cover classes, the AMP at the farm level was implemented in different fields identified as Wooded Grassland (WG) and Grassland (GR). Furthermore, the experimental period was subset according to the grassland growing season, distinguishing the yearly growth seasons (from October to September) and four growth phases within each growing season, according to grassland physiological and phenological stages: Regreening phase (from October to December), Green (from January to April), Drying (May and June), and Dry (from July to September). The experimental layout was set as a two-level factorial design, where factors and respective levels are defined as follows: 1) Land Use classes, with two levels (Wooded Grassland, WG, and Grassland, GR); 2) grazing management (Adaptive Multi Paddock, AMP, and continuous grazing as control - CON). The different Land Uses and Grazing management schemes within each farm are described in detail and reported in the maps given in Figure 2.4.

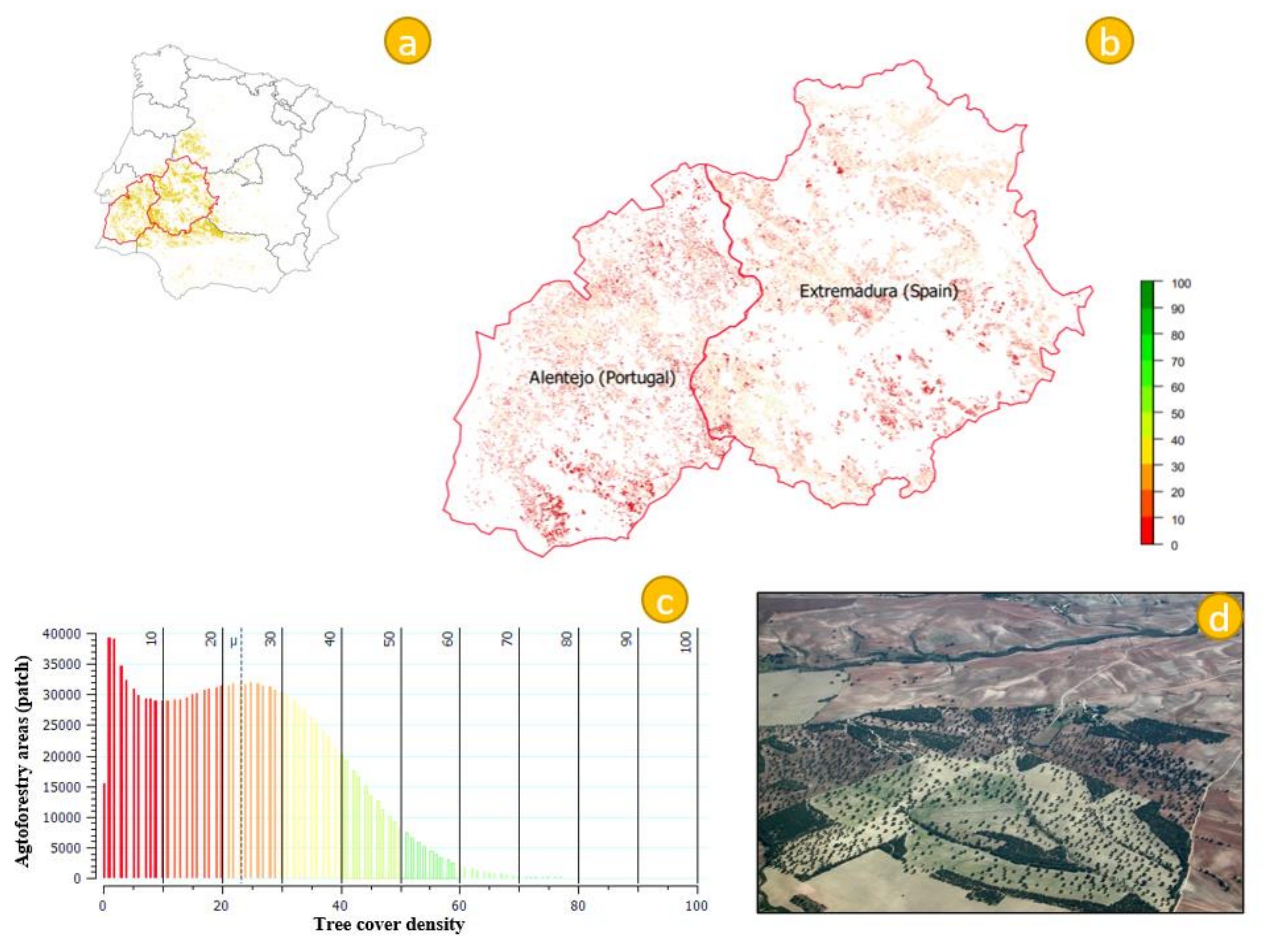
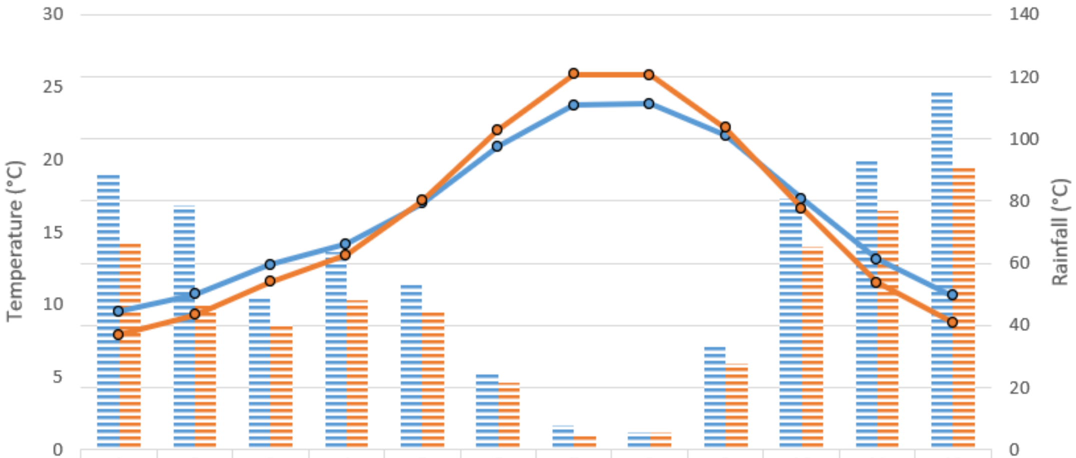


Figure 2.1. Agroforestry areas (code:244) within the Iberian peninsula according to CORINE Land Cover (2018); b. Agroforestry areas within Extremadura (Spain) and Alentejo (Portugal) regions according to both CORINE Land Cover (2018) and European Land Monitoring Service (http://land.copernicus.eu/). c. Frequency of tree cover density within agroforestry systems of Extremadura and Alentejo regions;. d). Agroforestry area near Madrid (ES-MD) (photo: Gy. Büttner).



	1	2	3	4	5	6	7	8	9	10	11	12
Rainfall (mm) - Portugal	89,33	78,79	48,68	63,59	53,89	25,14	8,1	5,59	33,31	81,07	93,17	115,33
Rainfall (mm) - Spain	66,93	46,3	40,4	48,33	43,96	21,78	4,59	5,55	27,66	65,46	76,95	90,76
Temperature (°C) - Portugal	9,52	10,71	12,74	14,2	16,98	20,9	23,73	23,83	21,68	17,3	13,13	10,64
Temperature (°C) - Spain	7,93	9,3	11,59	13,43	17,15	22,04	25,87	25,85	22,18	16,63	11,54	8,76

Figure 2.2. Average Monthly Temperature and Rainfall (from Global Climate Monitor)

2.2.3 Data collection

Landsat remote-sensed 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 from January 2010 to March 2013 and by Landsat-8 OLI/TIR from April 2013 to December 2019 (Table 2.1). 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 (band 3 and 4 of Landsat 5 and Landsat 8, respectively), and 0.76-0.90 µm and 0.85-0.88 µm for NIR (band 4 and 5 of Landsat 5 and Landsat 8, respectively).

2.2.4 Data processing

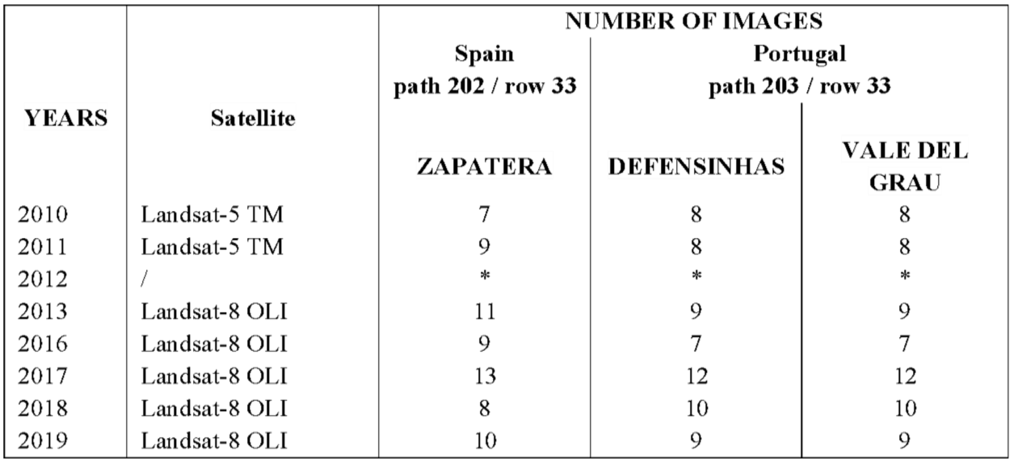
The QGIS software (version 3.14.1.) was used to process Landsat satellite images, referencing them at WGS 84 /UTM zone 29 (EPSG:32629) and WGS 84 /UTM zone 30 (EPSG:32630) coordinate systems for Portuguese and Spanish sites, respectively.

The atmospheric correction was performed to remove any atmosphere effect on reflectance resulting in remotely sensed images to correct reflectance values at pixel level using the semi-automatic classification plugin (Congedo, 2016). 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, the study plots were limited to 30 m from the internal border of polygons. The NDVI was calculated at pixel level starting from reflectance of NIR and Red bands as follows:

$$NDVI = (NIR-red)/(NIR+red)$$

where NIR was the near-infrared band reflectance value and red was the Red band reflectance value.

Table 2.1. Frequency by year of all available Landsat data years.*no available images



YEARS	Satellite	NUMBER OF IMAGES		
		Spain path 202 / row 33	Portugal path 203 / row 33	
		ZAPATERA	DEFENSINHAS	VALE DEL GRAU
2010	Landsat-5 TM	7	8	8
2011	Landsat-5 TM	9	8	8
2012	/	*	*	*
2013	Landsat-8 OLI	11	9	9
2016	Landsat-8 OLI	9	7	7
2017	Landsat-8 OLI	13	12	12
2018	Landsat-8 OLI	8	10	10
2019	Landsat-8 OLI	10	9	9

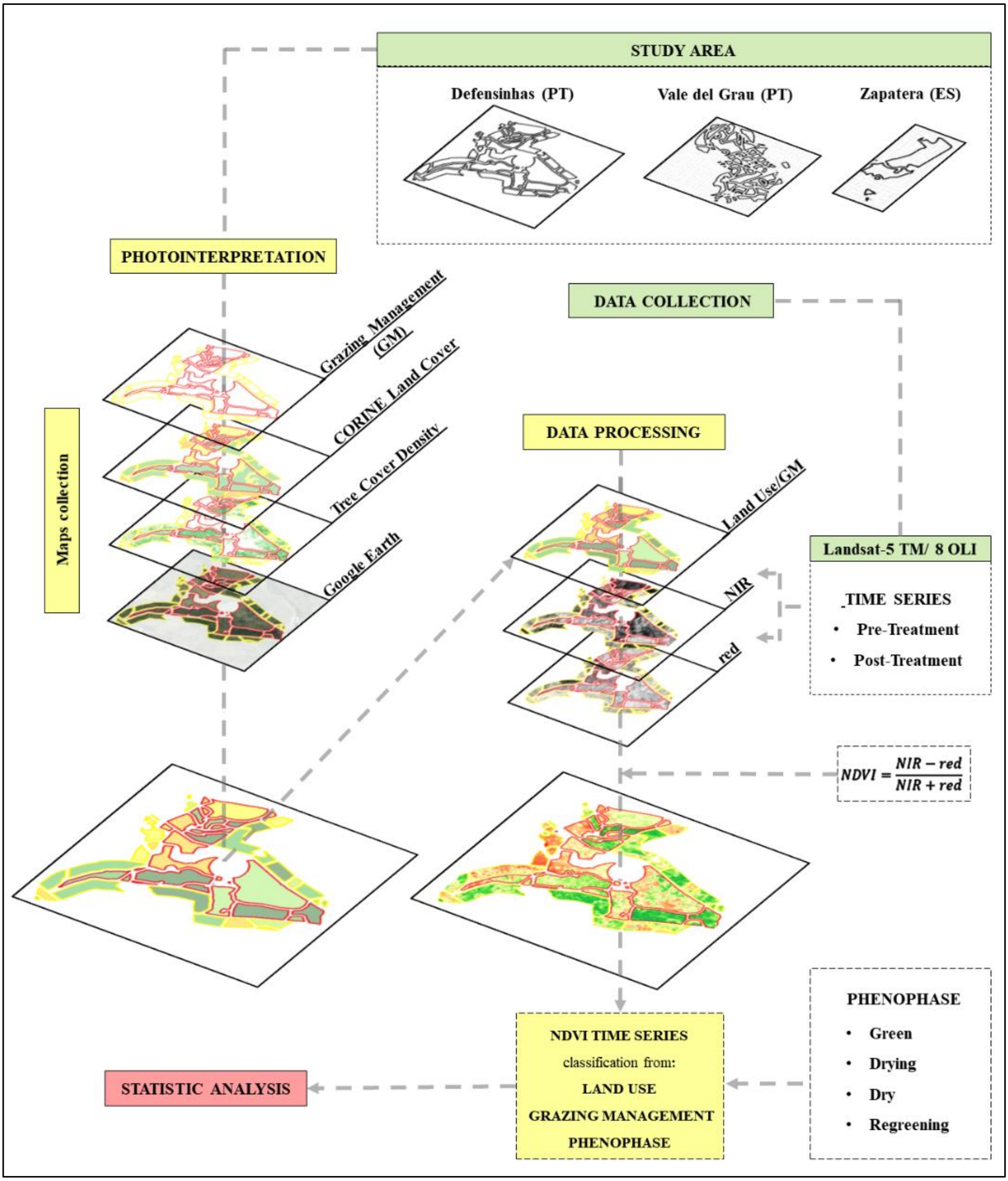


Figure 2.3. Methodology: Pre-processing (green), Processing (yellow) and Post-processing (red).

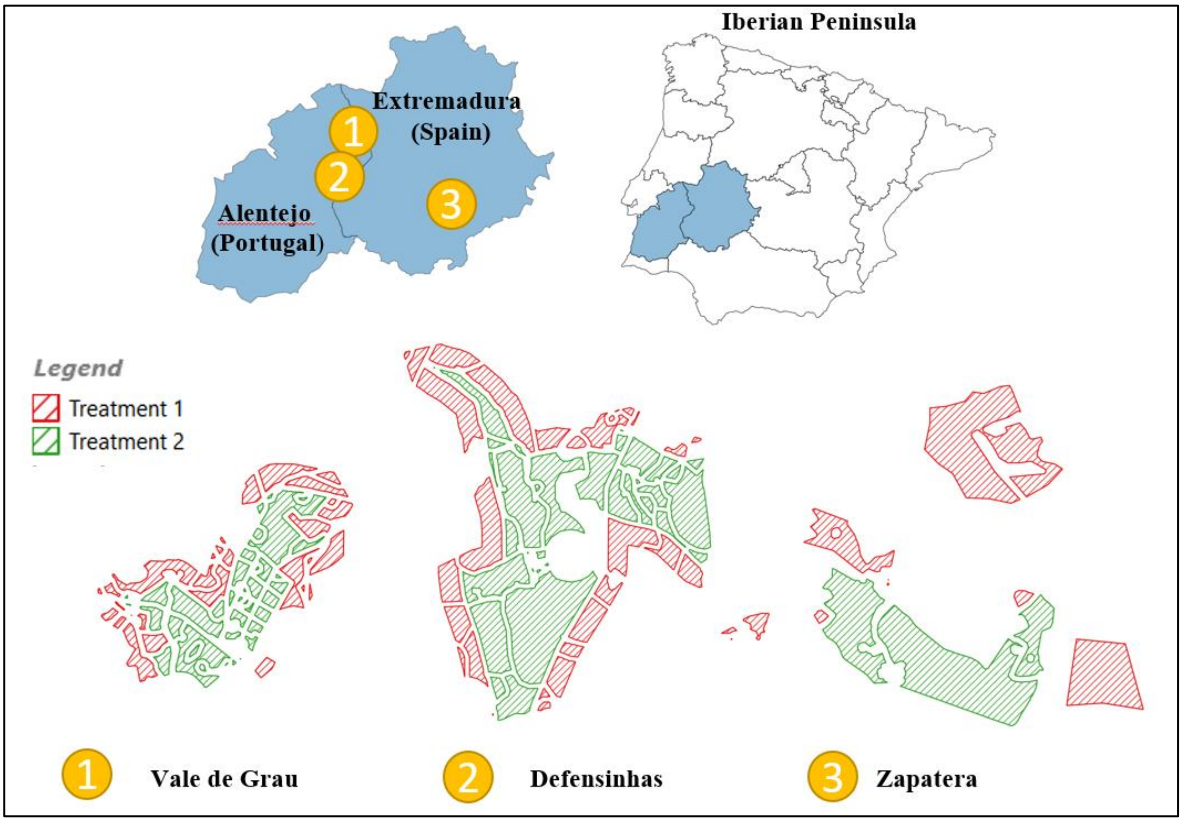


Figure 2.4. Experimental farms within the study area in the Iberian Peninsula. Treatment 1 = CG; Treatment 2 = AMP.

2.2.5 Data analysis

A set of descriptive statistics (mean, standard deviation) and the NDVI dynamics were computed starting from the raw dataset reporting NDVI value at the pixel level.

The statistical inference was performed by running an averaged NDVI dataset at the sensing date level. The effect of the interaction between land use and grazing management) on NDVI in PRE and POST periods at each phenophase (Regreening, Green, Drying, and Dry) was tested by fitting a Generalized Least Squares model (gls). The gls models were fitted with different structures of variance-covariance matrices, according to Onofri et al. (2016), to identify the best model for making an 'a posteriori' selection based on the Akaike Information Criterion (AIC). The analysis of variance (anova) was performed to test the significance of factors and their interaction. The estimated marginal means (emmeans) of the fitted gls models were computed to compare means.

The effect of Grazing on NDVI variance within sensing dates was tested with a two-tails F-test through which the ratios AMP/CTRL variances were tested. To assess the temporal variability, the null hypothesis for which the average log-transformed F ratios at Phenophase levels within Land Use 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 lme (Pinheiro et al., 2018), emmeans (Lenth, 2018), and anova computations were performed by using the RStudio application of the R environment (version 4.0.3; R Core Team, 2018).

2.3 Results

2.3.1 NDVI dynamics

The mean, standard deviation, minimum, and maximum NDVI values, the number of pixels and sensing dates within each site, both PRE and POST the AMP adoption are reported in Table 2.2 and Table 2.3. The NDVI dynamics are reported in Figure 2.5. The NDVI in the PRE period ranged between 0.06 and 0.31 under GR and from 0.05 to 0.34 under WG. The NDVI in the POST period ranged from 0.06 to 0.38 in GR and from 0.06 to 0.41 in WG. Under GR, the lowest NDVI value occurred in the dry season (0.2±0.02 and 0.23±0.03 in PRE and POST periods, respectively), with NDVI values of 0.18±0.04 and 0.24±0.03, respectively, in PRE AMP and POST AMP). Under WG Land-Use, the lowest NDVI values occurred in the dry season (whit NDVI values of 0.26±0.03 and 0.29±0.03 in PRE and POST periods, respectively) and the autumn season (whit NDVI values of 0.23±0.04 and 0.3±0.04, respectively in PRE and POST).

The effects of the interaction between Land Use and Management on the NDVI in PRE and POST periods for each growth stage are reported in Table 2.4. During the PRE period (Figure 2.6), Land Use significantly influenced the NDVI in the Regreening, Drying, and Dry phenophases (WG>GR), while no significant effects of Management and Land Use x Management interaction were observed in any stage. In the POST period (Figure 2.7), Land Use significantly influenced the NDVI at the Regreening, Drying, and Dry phenophases, while management influenced the NDVI at the Regreening stage. No significant effects of the interaction between factors were observed.

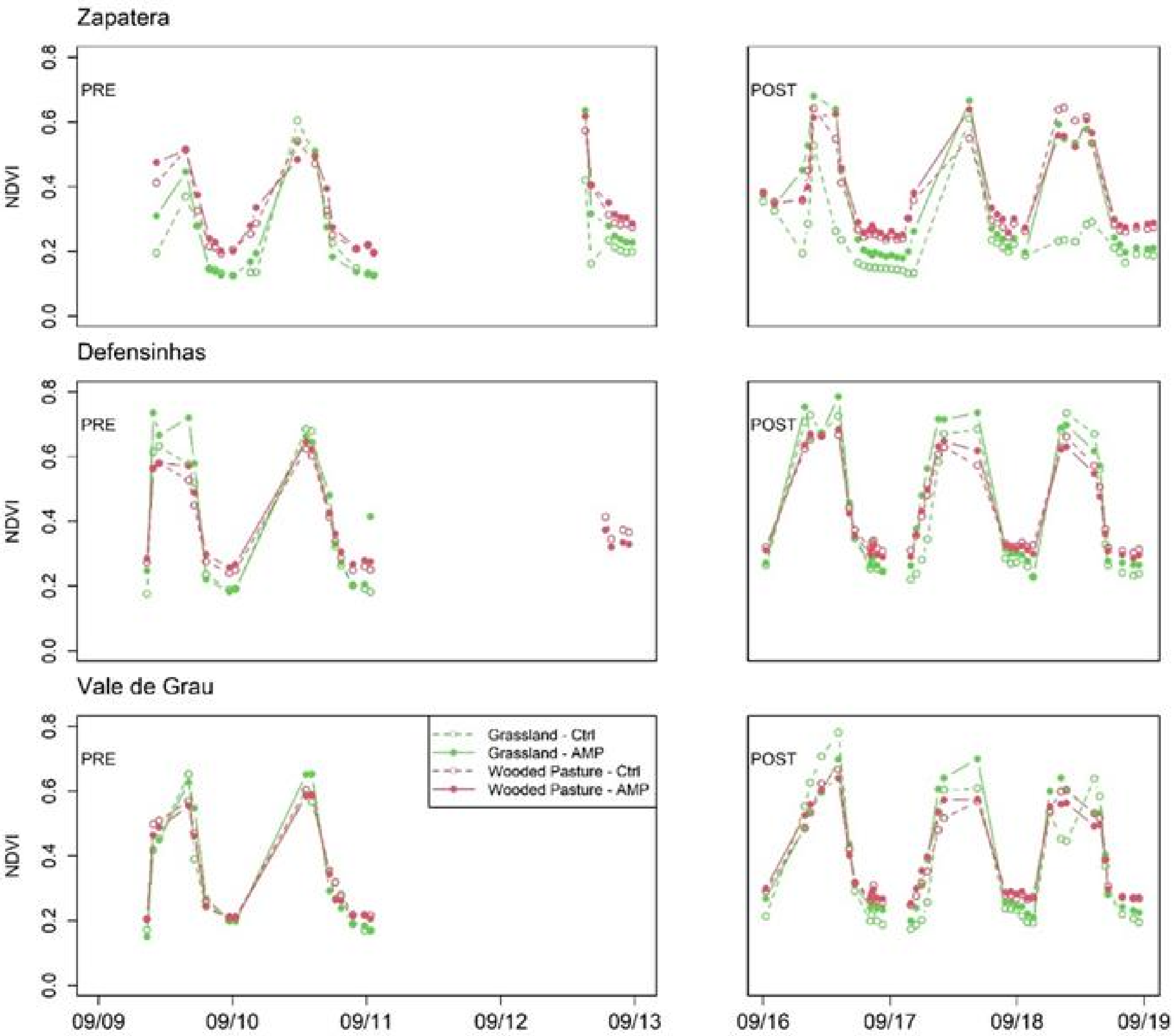


Figure 2.5. NDVI dynamics within study sites before (left boxes, PRE) and after (right boxes, POST) the implementation of the Adaptive Multi Paddock (AMP) grazing system. Green: Grassland land use; Red: Wooded Grassland land use. Filled dots: AMP areas. Empty dots: Control areas

Table 2.2. Pixels and sensing dates within each site both PRE AMP adoption

PRE				AMP	AMP	AMP	AMP	AMP	CTRL	CTRL	CTRL	CTRL	CTRL
SITE	**PHASE**	**Land Use**	**N dates**	**N pixels**	**Mean NDVI**	**St Dev NDVI**	**Min NDVI**	**Max NDVI**	**N pixels**	**Mean NDVI**	**St Dev NDVI**	**Min NDVI**	**Max NDVI**
DEFENSINHAS	**REGREENING**	GR	3	428	0.62	0.07	0.41	0.80	290	0.47	0.08	0.21	0.70
		WG	3	3411	0.65	0.06	0.44	0.86	2178	0.60	0.08	0.23	0.82
	GREEN	GR	5	428	0.59	0.18	0.13	0.81	290	0.56	0.20	0.12	0.77
		WG	5	2201	0.54	0.15	0.10	0.83	2023	0.53	0.14	0.10	0.76
	DRYING	GR	6	397.1666667	0.44	0.19	0.16	0.78	252	0.40	0.15	0.14	0.73
		WG	8	2140.75	0.39	0.11	0.17	0.77	1530	0.38	0.10	0.16	0.71
	DRY	GR	7	428	0.25	0.09	0.15	0.60	290	0.22	0.08	0.13	0.65
		WG	9	2500.555556	0.30	0.07	0.14	0.53	1765	0.28	0.07	0.12	0.53
VALE_DE_GRAU	**REGREENING**	GR	3	678	0.49	0.18	0.20	0.83	406	0.42	0.12	0.18	0.79
		WG	3	364	0.53	0.10	0.23	0.80	645	0.49	0.11	0.18	0.77
	GREEN	GR	5	678	0.46	0.20	0.10	0.80	406	0.44	0.18	0.10	0.82
		WG	5	364	0.47	0.16	0.10	0.81	645	0.48	0.17	0.10	0.81
	DRYING	GR	6	660	0.38	0.17	0.15	0.72	373	0.37	0.16	0.15	0.79
		WG	6	316.8333333	0.37	0.13	0.16	0.71	597	0.38	0.13	0.17	0.81
	DRY	GR	7	678	0.21	0.04	0.10	0.32	406	0.20	0.05	0.09	0.42
		WG	7	364	0.23	0.05	0.12	0.41	645	0.24	0.05	0.13	0.44
ZAPATERA	**REGREENING**	GR	3	1922	0.27	0.11	0.06	0.66	73	0.15	0.05	0.08	0.37
		WG	3	237	0.39	0.08	0.20	0.76	2244	0.37	0.11	0.09	0.70
	GREEN	GR	5	1922	0.49	0.15	0.12	0.83	73	0.42	0.15	0.12	0.76
		WG	5	237	0.52	0.08	0.27	0.74	2244	0.50	0.12	0.09	0.78
	DRYING	GR	6	1922	0.25	0.10	0.08	0.72	73	0.23	0.07	0.05	0.38
		WG	6	237	0.34	0.08	0.15	0.69	2243	0.31	0.09	0.05	0.68
	DRY	GR	13	1922	0.18	0.06	0.06	0.53	73	0.16	0.04	0.05	0.26
		WG	13	237	0.26	0.06	0.13	0.58	2244	0.25	0.06	0.04	0.50

Table 2.3. Pixels and sensing dates within each site POST AMP adoption.

POST				AMP	AMP	AMP	AMP	AMP	CTRL	CTRL	CTRL	CTRL	CTRL
SITE	**PHASE**	**Land Use**	**N dates**	**N pixels**	**Mean NDVI**	**St Dev NDVI**	**Min NDVI**	**Max NDVI**	**N pixels**	**Mean NDVI**	**St Dev NDVI**	**Min NDVI**	**Max NDVI**
DEFENSINHAS	**REGREENING**	GR	4	535	0.58	0.16	0.26	0.83	363	0.46	0.22	0.17	0.81
		WG	4	4264	0.51	0.13	0.21	0.80	2717	0.50	0.14	0.19	0.81
	GREEN	GR	9	569	0.69	0.07	0.29	0.83	385	0.68	0.09	0.23	0.83
		WG	9	4536	0.63	0.09	0.27	0.85	2842	0.63	0.08	0.31	0.85
	DRYING	GR	6	571	0.41	0.15	0.21	0.80	387	0.39	0.14	0.18	0.77
		WG	6	4548	0.39	0.11	0.22	0.80	2904	0.40	0.10	0.19	0.77
	DRY	GR	15	514	0.27	0.03	0.20	0.51	348	0.26	0.05	0.16	0.69
		WG	15	4093	0.31	0.05	0.18	0.57	2614	0.32	0.06	0.16	0.56
VALE_DE_GRAU	**REGREENING**	GR	5	814	0.42	0.17	0.17	0.80	487	0.38	0.21	0.12	0.84
		WG	5	437	0.44	0.13	0.19	0.76	774	0.41	0.16	0.15	0.79
	GREEN	GR	9	892	0.60	0.11	0.21	0.83	530	0.62	0.18	0.13	0.85
		WG	9	473	0.57	0.10	0.25	0.81	844	0.58	0.12	0.25	0.84
	DRYING	GR	6	904	0.39	0.14	0.20	0.82	541	0.36	0.15	0.16	0.79
		WG	6	485	0.37	0.10	0.21	0.80	860	0.38	0.11	0.19	0.75
	DRY	GR	15	814	0.24	0.03	0.16	0.43	487	0.21	0.04	0.13	0.44
		WG	15	437	0.28	0.04	0.17	0.45	774	0.27	0.05	0.15	0.50
ZAPATERA	**REGREENING**	GR	3	1922	0.44	0.16	0.01	0.82	73	0.19	0.07	0.07	0.41
		WG	3	237	0.43	0.11	0.05	0.82	2244	0.45	0.17	0.00	0.85
	GREEN	GR	9	1876	0.57	0.11	0.12	0.87	73	0.33	0.16	0.14	0.74
		WG	9	237	0.55	0.09	0.10	0.84	2186	0.55	0.12	0.10	0.83
	DRYING	GR	5	1922	0.24	0.04	0.12	0.51	73	0.19	0.04	0.12	0.29
		WG	5	237	0.29	0.05	0.20	0.63	2242	0.27	0.06	0.08	0.50
	DRY	GR	18	1921	0.22	0.06	0.02	0.51	72	0.19	0.06	0.01	0.39
		WG	18	237	0.28	0.05	0.18	0.64	2243	0.27	0.07	0.05	0.54

Table 2.4. Analysis of Variance (ANOVA) results on the effects of the interaction between grazing management (AMP vs CON) and Land Use (GR vs WG) on NDVI PRE and POST the rotational grazing adoption in the four grassland growing stages (phenophases). Significant P-values (P<0.05) are highlighted in bold

Phenophase	Factor	P value	
		PRE	POST
Regreening	Management	ns	**0.034**
	Land Use	**0.028**	**0.058**
	Mangement x Land Use	ns	0.127
Green	Management	ns	ns
	Land Use	ns	ns
	Mangement x Land Use	ns	ns
Drying	Management	ns	ns
	Land Use	**0.004**	ns
	Management x Land Use	ns	ns
Dry	Management	ns	ns
	Land Use	**0.010**	**<.0001**
	Mangement x Land Use	ns	ns

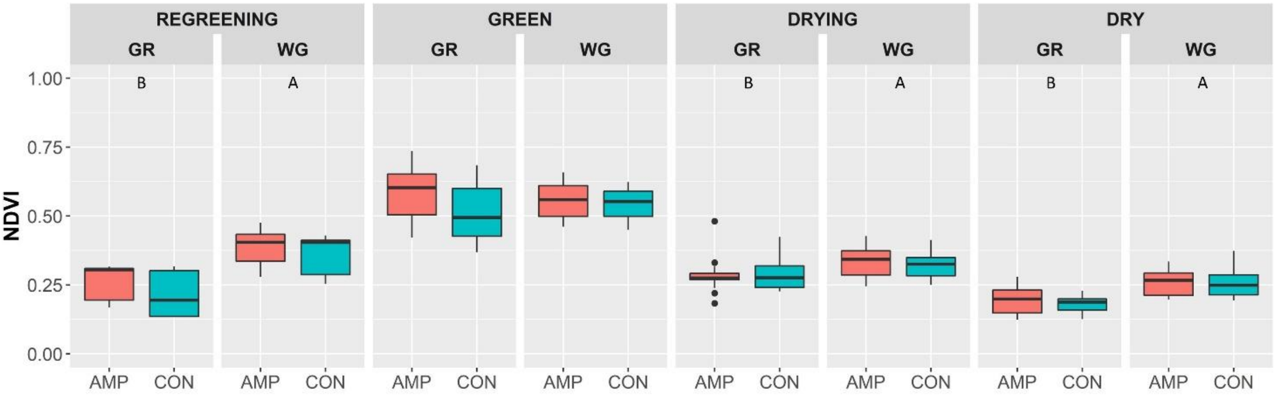


Figure 2.6. NDVI values in the PRE period in the different phenophases and land uses (Grassland, GR, and Wooded Grassland, WG). The red boxplots report the NDVI in areas where the AMP will be implemented in the POST period; the blue boxplots report the NDVI in CON areas. Capital letters in the top indicate different means within Land Use levels (GR and WG) according to Tukey's test (P<0.05)

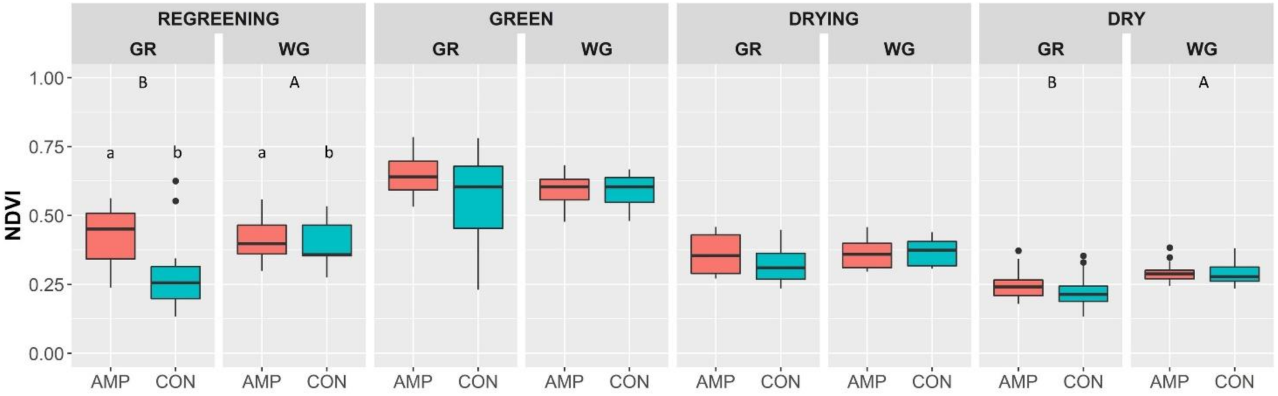


Figure 2.7. NDVI values in the POST period in the different phenophases and land uses (Grassland, GR, and Wooded Grassland, WG). The red boxplots report the NDVI in areas where the AMP were implemented; the blue boxplots report the NDVI in CON areas. Capital letters at the top indicate different means within Land Use levels (GR and WG), and lowercase letters indicate different means within Management levels (AMP, CON) according to Tukey's test (P<0.05)

2.3.2 NDVI variability

The F values (ratios between the NDVI variance ratios between AMP and CTRL areas) within each sensing date are reported (log scale) in Figure 2.8. Under GR during the PRE period, the variance was significantly higher in AMP areas in 100%, 32%, 46%, and 45% of dates in Regreening, Green, Drying and Dry phases, respectively. In the POST period, NDVI variance was significantly higher in CON areas in 55%, 79%, 100%, and 65% of dates in Regreening, Green, Drying and Dry phases. Under WG in the PRE period, the NDVI variance was significantly higher in CON areas in 100%, 77%, 53%, and 74% of dates in Regreening, Green, Drying and Dry phases, respectively. In the POST period, the NDVI variance was higher in CON areas at 100%, 79%, 80%, and 93% of Regreening, Green, Drying and Dry Phases, respectively.

Overall, under GR land use, the average log(F) values tended to decrease from PRE to POST period, changing from not significantly different to lower than 0 in Green, Drying and Dry phases, and from significantly higher to not significantly different than 0 in Regreening phase. Under WG, little changes in the average log(F)value from PRE to POST period were observed in the Green and Dry stages, in which the average log(F) changed from significantly lower than 0 ($P<0.05$) to highly significantly lower ($P<0.001$), as reported in Figure 2.8.

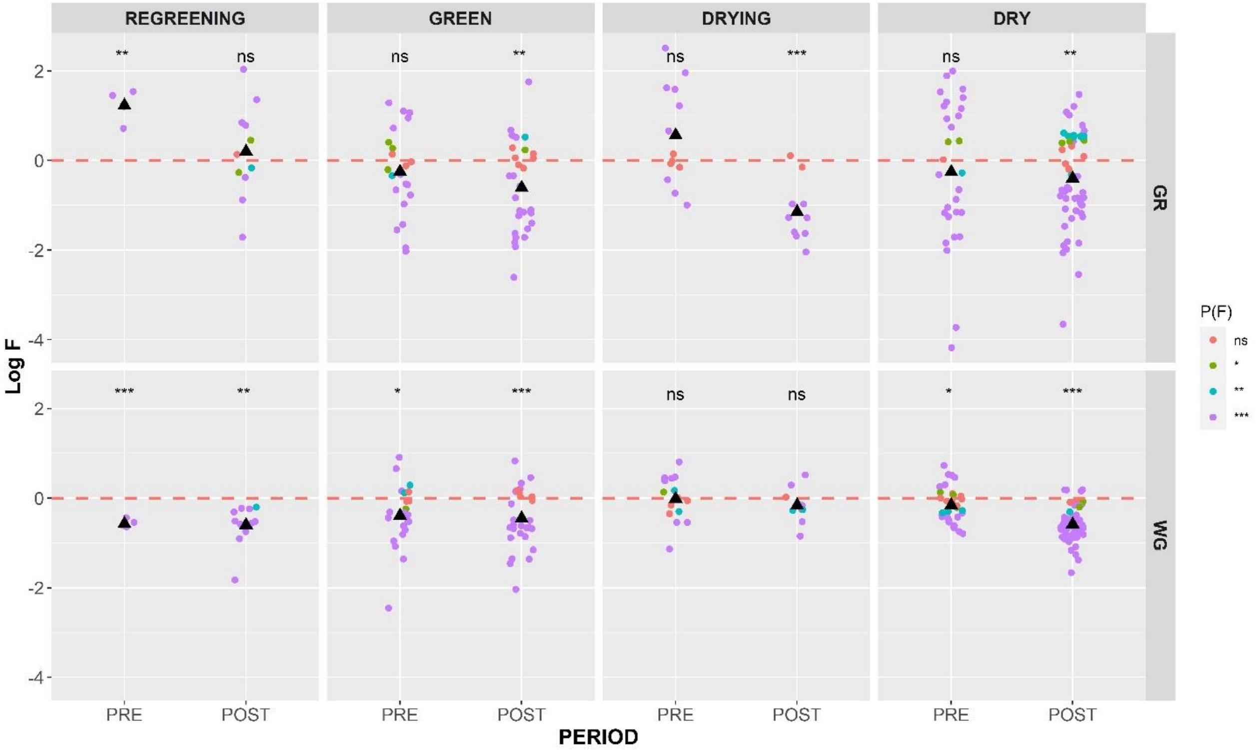


Figure 2.8. F ratios values in log-scale calculated at each date as the ratio between the NDVI variance in AMP and CON areas in the Grassland (GR) and Wooded Grassland (WG) land uses at each phenophase. Red dots indicate no significant differences between variances (ns, P>0.05), green, blue and purple dots indicate a P(F) <0.05 (*), <0.01 (**), and <0.001 (***), respectively. The black 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.

2.4 Discussions

The observed NDVI average values and dynamics within 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 open 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 species' photosynthetically active period (Migliavacca et al., 2017) which varied among phases during the season. The photosynthetic activity of grasslands species starts to increase with the emergence of buds and first leaves at Regreening phase, reaches the highest intensity during the Green period (from winter to spring), and then decreases at the end of spring (Drying) to become null in summer (Dry). In this last period, from the Drying to Dry phase, characterized by depigmentation, leaf yellowing, and then leaf fall under the control of abscission processes, NDVI values decreased, reaching the lowest values during spring.

Before the AMP, only significant differences between GR and WG were found within growth phases due to the effect of the evergreen tree species that characterized WG (Arenas-Corraliza et al., 2020). After the AMP adoption, the higher NDVI observed under the AMP areas at the beginning of the growing season (regreening) suggested that adopting rotational grazing can stimulate the autumn restart and promote higher pasture growth rates. Venter et al. (2019), in a study conducted across South African grasslands, observed that under the high frequency of defoliation occurring under AMP, the NDVI increased only in fertile soil conditions with high levels of nutritive elements. Teague et al. (2008) observed enhanced grassland productivity when appropriate conditions in terms of soil water availability occur along the season. This suggests that the higher NDVI observed in AMP areas in the POST period during the regreening stage could result from the interaction between grazing management and favourable environmental conditions. However, the lack of significance of the effect of the management during the rest of the growing season confirms the findings from a regional-scale analysis by Venter et al. (2019) that reported little overall impact of rotational grazing with high stoking rates on grassland forage productivity, vegetation cover and NDVI, which variability was not explained by the variability of the stoking rates.

The overall lower spatial variability of NDVI observed under AMP in the POST period suggested that rotational grazing can enhance the ability of forage resources exploitation by grazing animals with respect to continuous grazing (Augustine et al., 2020). Changes in this pattern after the AMP adoption are particularly evident under GR land use at the end of the growing season, in the drying and dry stages, suggesting better and uniform forage resource exploitation in the previous stages and generally during the spring. Although little evidence emerged from the effects of management and land use on NDVI during the early stages of the growing season, a positive role of rotational grazing seems to emerge from the lower variability of NDVI observed under AMP in the late season combined with the higher NDVI observed on average in AMP at the regreening stage. We hypothesize that the most critical effect of rotational grazing resulted in different grazing behaviour leading to fewer 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.

2.5 Conclusions

The results from the study partially confirmed our experimental hypothesis that adopting rotational grazing systems such as the AMP may significantly affect the forage availability seasonal patterns in Mediterranean grassland and silvopastoral systems. Only a little evidence of the effect of grazing on forage availability emerges from the analysis of the NDVI from multispectral satellite data. However, the signal coming from the higher NDVI observed under AMP in both GR and WG land uses in the regreening stage, as well as the lower spatial variability under AMP in the late growing season, suggested that the rotational grazing may promote a better autumn restart in terms of biomass productivity.

The study evidenced that the multitemporal satellite data from Landsat-5 TM/8 OLI Sensors) combined with the methodological approach for processing spectral information can represent a useful tool to compare the impacts of grazing management and land use on spatial and temporal vegetation patterns in the Mediterranean silvopastoral systems. However, the resolution of Landsat image products could have limited the possibility of properly detecting the impacts of management under the typical agroforestry landscape of the Iberian Dehesa. In fact, the multispectral signal coming from the evergreen oak, especially in the early and late stages of the growing season, may have masked the effect of grazing management on the derived vegetation index. Nevertheless, the availability of high- spatial and temporal resolution open source images (e.g. Sentinel2) starting from about the last ten years can represent an important tool to set up new remote sensing studies aiming to provide further insights on the effect of grazing practices in silvopastoral systems under the Mediterranean environment.

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3 Overall Conclusions

The PhD thesis aimed to assess the effects of the Adaptive Multi-Paddock grazing system on managed grassland in the Mediterranean environment, focussing mainly on silvopastoral systems. The study contributes to increasing knowledge about the impacts of the adoption of AMP in grazed agrosystems, which effectiveness in improving the overall grassland quality and animal performances is still debated showing often conflicting results.

The two-year field study conducted on a silvopastoral farm in central Sardina highlighted that, overall, little or no significant effects of grazing management on grassland forage production emerged comparing the AMP system with the business as usual continuous grazing. Some benefits in terms of biomass productivity under adaptive management appeared at the beginning of the growing season (autumn) under favourable weather conditions, i.e. rainfall, during which higher productivity of gram species was observed. The main outcome emerging about the effect of the adoption of rotational grazing was the higher utilization rate of forage with respect to continuous grazing, especially during the spring period, when the forage availability is maximum, regardless of the functional group. During the autumn season, in mountain sites and, overall, when the growth rates of forage biomass are lower, the higher consumption under AMP management is evident only for gram species, reasonably as a result of their higher cover with respect to the other species, particularly legumes. Furthermore, this effect is particularly evident in managed wooded grassland, in which the spring mowing for hay production also can have the effect of clearing from the unpalatable species and promoting the autumn restart (both from seed for annual and reserve organs for perennial species) of gams by limiting the competition for resources.

The remote sensing study conducted within silvopastoral farms in the Iberian peninsula partially confirmed the hypothesis that adopting adaptive management can change the patterns of forage availability during the growing season. While the analysis of the NDVI time series was able to detect the differences between the grassland and the wooded grassland land use on the seasonal patterns of the vegetation, little evidence emerged about the effect of grazing management. The NDVI response to the AMP grazing system was evident only at the beginning of the growing season. What was observed can be considered an effect of establishing better conditions for forage species in terms of reducing competition for resources due to rotational grazing. We hypothesize that the AMP system can promote a clearing effect from little shrubs and other unpalatable species with different reproductive strategies or growing cycles. The reduced spatial variability after the introduction of adaptive management support this hypothesis. The overall lower spatial variability of NDVI in AMP than in continuously grazed areas or the reduced variability after the AMP adoption can be considered a reasonable indicator of better exploitation of forage biomass, thus an improved efficiency in forage consumption. Furthermore, the higher efficiency in forage utilization leads to a reduced selectivity that can induce the clearing effect from unpalatable species and reduce the competition for resources at the beginning of the season.

The indication emerging from these studies suggests that adaptive grazing could stimulate grassland productivity in the early stages of the growing season, especially when weather conditions allow adequate rates of grass regrowth. In particular, the species belonging to the grams family showed better responsiveness in terms of productivity and forage availability than other functional groups. Furthermore, adopting a rotational grazing system can represent a strategy to enhance the effectiveness of grazing in exploiting the forage resources thanks to the higher utilization rates, as emerged from the two-year field study. Furthermore, this last evidence can be considered confirmed by the result from the remote sensing study in the Iberian peninsula. In fact, the lower spatial variability observed under rotational than in continuous grazing areas and overall after the AMP adoption suggests a better use of forage resources under adaptive management.

The obtained results highlight that the adoption of adaptive grazing management, in a context of environmental and socio-economics threats for silvopastoral systems such as climate change, land degradation, rising costs, and loss of competitivity of agricultural activities in marginal and less productive areas, could represent an effective strategy to enhance the efficiency in forage resources exploitation contrasting at the same time the adverse effects of undergrazing such as shrubs encroachment, decreasing pasture quality, and the overall land degradation. Nevertheless, even if better forage exploitation could represent a strategy to enhance the general ecosystem service provision and the economic sustainability of silvopastoral farms, potentially reducing feed costs, the large-scale implementation of such grazing patterns can lead in turn to rising costs in terms of labour and infrastructure (e.g. fences and water points). For this reason, further insights are needed to better understand the impacts of adaptive management on other ecosystem services such as soil C sequestration, soil N cycling and quality, biodiversity conservation, livestock performance, and economic benefits at the farm and district scale. Research activities can also be addressed to assess the impact of the adoption of innovative tools to implement adaptive animal management, such as virtual fencing, that allows taking advantage of the agronomic and environmental benefits of rotational grazing, reducing at the same time the costs associated, for example, to labour and fencing.

Further research should focus on understanding the multiple effects of adopting AMP grazing systems on grassland agroecosystems in the context of multidisciplinary project activities and participative approaches involving farmers and local stakeholders.

This typology of studies may require integrating data from multi-factorial field experiments and innovative digital technologies and approaches such as predictive modelling and proximal and remote sensing. Furthermore, it becomes crucial to incorporate information from digital tools and local knowledge to explore the broad environmental and social complexity of such agroecosystems. Moreover, these activities should be oriented to gather helpful information to develop "smart" decision support systems. These innovative tools will be implemented to help farmers and technicians make choices about grazing management, stocking rates, feed integration, and pasture improvement and to effectively face environmental and social threats such as climate change, land abandonment, rising costs of raw materials, and loss of competitiveness. The new scientific knowledge emerging from the integrated research activities could also support local policies aiming to counteract the loss of profitability of agricultural activities in marginal districts triggering abandonment and loss of associated ecosystem services provision, thus guaranteeing the sustainability and the future of human activities in the silvopastoral systems of the Mediterranean basin.