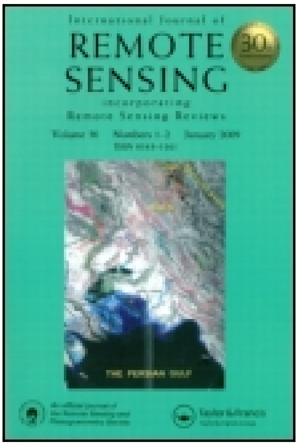

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Dynamics of mountain semi-natural grassland meadows inferred from SPOT-VEGETATION and field spectroradiometer data

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Permanent semi-natural grassland meadows (*lameiros*) are characteristic of the mountain rural landscapes in northeast Portugal and represent the main fodder resource for livestock production. Furthermore, these meadows are recognized for their environmental, historical, cultural and visual landscape value. A monitoring study based on remote-sensing data was implemented to understand the impacts of management practices on the *lameiros* vegetation dynamics and to analyse changes in vegetation dynamics over the period 1998–2008 in response to inter-annual climatic variability. Ten-day SPOT-VEGETATION (VGT) image composites from this period were used to examine the annual temporal profile using the normalized difference vegetation index (NDVI) and their relationship with ground-based observation of vegetation growth and reflectance inferred with a spectroradiometer. Results show that the NDVI profile fits well the characteristic vegetation growth dynamics and associated management practices in the region. For the period from July 2007 to December 2008, the variation in vegetation height explains 46 to 52% of the variation in NDVI derived respectively from spectroradiometer and VGT data. NDVI referring to dates of specific stages of the vegetation dynamics and management practices in *lameiros* was tested against climatic variables, for the period 1998–2008. More than 57% of the inter-annual variability of the average NDVI during the *lameiros* development period can be explained by the mean temperature, and 53% of the variability on the date of occurrence of maximum vegetation development (MVD) can be explained by the mean temperature during the spring period. These results support the analysis of *lameiros* responses to different scenarios of climate and water management and may support the implementation of more efficient farm activities.

1. Introduction

The mountain landscape of northeast Portugal greatly shows the influence of the traditional agricultural systems of the region. Among the most important and characteristic elements of this mountain rural landscape are the permanent semi-natural

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grassland meadows, locally called *lameiros*. These meadows are generally located above the elevation of 700–800 m, in areas of high water availability and loamy soils.

The origin of *lameiros* is attributed to the Middle Ages, when populations settled in the mountains of the region; hence it has high historical and patrimonial value (Taborda 1932). For hundreds of years, they have been representing the main fodder resource for livestock production, which is the first economic input to the local farmers and the main activity supporting rural development. These meadows are exploited for grass and hay. Grazing is practised from late winter to mid-spring, when cattle are not allowed to graze in order to allow vegetation to grow for hay cutting (HC) in early summer. Following VRG, livestock is returned to grazing by the end of summer and it remains until winter. *Lameiros* are irrigated all year round, either to satisfy the crop water requirements during late spring and summer months or to protect the crop against frost during winter and early spring seasons. Water is derived from the mountain watercourses and/or springs, conveyed through small earth canals and spread over the fields through a cascade of small contour ditches (Pereira and Sousa 2006, Pôças *et al.* 2009). Large amounts of water are applied; excessive water is reutilized successively in fields located down the hill, or returns to the watercourses or percolates into the groundwater with a non-degraded quality; therefore, water losses are minimal.

Lameiros play a relevant role in the conservation of plant and animal biodiversity, the conservation of water and soil resources, including the control of erosion risks in sloping areas, and the prevention of forest fires because they often act as buffer zones. However, changes that have occurred in the region in the past decades affect the sustainability of *lameiros*, with consequences on the landscape equilibrium. The decrease in rural population and ageing since the 1950s are the main problems in the region and have put at risk the agricultural activities and hence the preservation of *lameiros* management practices. Furthermore, although traditional irrigation systems in *lameiros* are environmentally appropriate, the foreseen increase in the competition for water may lead to reduced availability of irrigation water. These limitations to the conservation of *lameiros* and their traditional management practices may result in the loss or deterioration of several ecological services related to biodiversity and resource conservation and in the impoverishment of the concerned landscape and agricultural systems. Similar cases have been observed in other ancient meadows in Europe (Ihse and Lindahl 2000). Furthermore, climate variability may lead to modifications on the management practices, including those related to vegetation growth and the crop calendar (Lavalle *et al.* 2009, Opam *et al.* 2009). Hence, conservation measures for *lameiros* should consider these impacts. The identification and quantification of vegetation responses to the inter-annual climate variability, mainly referring to years of higher temperatures or lower precipitation, could help in understanding how to cope with those impacts.

Systematic data collection integrating *lameiros* response to management practices is expected to provide for developing conservation strategies and to support regional and environmental planning. However, field surveys for the monitoring of vegetation dynamics, mainly in relation to crop phenology and management practices, although useful, are difficult, time consuming and expensive. Hence, alternative and reliable approaches for the monitoring of vegetation dynamics must be considered and tested, in particular those related to remote sensing. With a view to improve the knowledge and understanding of the ecological behaviour of *lameiros* and their dynamics in traditional agriculture, and featuring the mountain landscapes of northeast Portugal, a monitoring study based on remote sensing was implemented.

Remote-sensing techniques have been widely used for monitoring biotopes (Bock 2003), land use and land changes (e.g. Sawaya *et al.* 2003, Marçal *et al.* 2005, Hill *et al.* 2008, Phua *et al.* 2008, Zomeni *et al.* 2008), crop phenology (Fisher *et al.* 2006, Xiao *et al.* 2006), vegetation dynamics (Telesca and Lasaponara 2006, Martínez and Gilabert 2009, Verbesselt *et al*. 2010) and agricultural land-cover mapping (Lucas *et al.* 2007), as well as discriminating differences in grassland types and related management practices (Price *et al.* 2001). Data acquired by Earth Observation Satellites (EOSs) provide a synoptic and repetitive coverage of large areas through several years, which make it interesting for monitoring studies.

Vegetation indices (VIs) derived from EOS data have been widely used for vegetation monitoring due to their scalable relations with vegetation dynamics or phenology, leaf area index (LAI), roughness lengths for turbulent transfer, emissivity, albedo and related evapotranspiration processes, crop productivity and the fraction of photosynthetically active radiation absorbed by a canopy (Payero *et al.* 2004, Xiao *et al.* 2004, 2006, Nagler *et al.* 2005, Pettorelli *et al.* 2005, Glen *et al.* 2008, Tao *et al.* 2008, Cunha *et al.* 2010a,b). These VIs represent the spectral transformation of two or more bands of the electromagnetic spectrum in order to highlight specific plant properties. They are mostly derived from reflectance data of red and near infrared (NIR) bands, thus operating by contrasting intense chlorophyll pigment absorption in the red band against high reflectance of leaf cellular structure in the NIR band (Maselli *et al.* 1998, Haboudane *et al.* 2004). In the past few years, many VIs extracted from hyperspectral imagery have been used for evaluating vegetation growth and/or pigmentation (e.g. Haboudane *et al.* 2004, Wang *et al.* 2007, Wu *et al.* 2008). Nevertheless, the normalized difference vegetation index (NDVI), first formulated by Rouse *et al.* (1973), is still the most used vegetation index because it is a sensitive indicator of the vegetation cover. Also, the NDVI is considered to be a robust index to describe green vegetation because its formulation allows a normalization of the red/NIR ratio, thus minimizing the effects of variations of atmospheric conditions in those bands (Holben *et al.* 1990, Cayrol *et al.* 2000).

The plant structure and associated pigment assemblage vary significantly following the crop growth stages, hence influencing the values of the NDVI or other VIs (Lunetta *et al.* 2002). Thus, remote-sensing monitoring of vegetation dynamics associated with seasonal and annual weather patterns requires multi-temporal measurements. The identification and quantification of intra-annual NDVI variability allows understanding of the relationships between vegetation dynamics and abiotic factors such as summer dryness and winter freezing, as well as meadows management (Price *et al.* 2001, Telesca and Lasaponara 2006). NDVI-based time series derived from high temporal resolution images are then fundamental in remote-sensing studies of vegetation phenology and vegetation dynamics (Pettorelli *et al.* 2005, Martínez and Gilabert 2009). Remote-sensing techniques based on time series have also been used in the analysis of gradual changes related with inter-annual climate variability, land management or land degradation (Fabricante *et al.* 2009, Zhou *et al.* 2009, Verbesselt *et al*. 2010). However, these NDVI-based time series are only available at low and medium spatial resolution. Although sensors such as SPOT (Visible High-Resolution (HRV), Visible and Infrared High-Resolution (HRVIR), High Resolution Geometric (HFR)) and Landsat (TM (Thematic Mapper) and ETM+ (Enhanced Thematic Mapper)), with spatial resolution between 10 and 30 m, are adequate for collecting information with high spatial detail (Pôças *et al.* 2008), their temporal coverage of 16 days (Landsat) and 26 days (SPOT HRV, HRVIR and HGR, at nadir) may not be enough to follow rapid in-season vegetation changes. The use of time series of VIs provided by sensors of coarse resolution (e.g. MODIS (Moderate resolution Imaging Spectroradiometer), Medium Resolution Imaging Spectrometer (MERIS), AVHRR (Advanced Very High Resolution Radiometer) and SPOT-VEGETATION), but having a high revisiting rate (1–3 days), is limited to extensive areas with contiguous vegetation of similar characteristics. Among other mountain areas where semi-natural meadows cover large contiguous areas, Montalegre in northeast Portugal was selected for this work because *lameiros* are the main croplands there.

Ground data obtained using a spectroradiometer can be integrated with data from satellite sensors to investigate how different spatial and temporal scales may impact the monitoring of *lameiros*. Handheld spectroradiometers allow the measurement of reflectance in a broad range of the electromagnetic spectrum, thus making it possible to derive VIs. These devices facilitate the collection of multi-date measurements at the field scale, therefore with large spatial detail, which can be integrated into multi-scale monitoring and modelling efforts (Price *et al.* 2001). Although, this methodology is highly time consuming and applies to small areas, its use can be of great value mostly aiming at validating large-scale, remote-sensing information.

The main goal of this study was to evaluate the capability of the SPOT-VEGETATION sensor to provide quality spectral, spatial and temporal data to identify and assess the *lameiros* vegetation growth patterns. Ten-day SPOT-VEGETATION image composites from 1998 to 2008 were used to examine the annual temporal profile in the NDVI. For the years 2007 and 2008, they were also used to assess their relationship with ground-based observation of vegetation growth and reflectance inferred by a handheld spectroradiometer. The information derived from this study is intended to improve the understanding of the impacts of management practices on vegetation dynamics and the inter-annual variation of vegetation dynamics in response to climatic variability.

2. Material and methods

2.1 *Study area*

This study was carried out in the mountain region of Montalegre, northeast Portugal (figure 1). This region is characterized by irregular relief, with plateau and mountain zones reaching 1200–1500 m in altitude. These mountain formations constitute a barrier to the Atlantic influence, favouring cold winters with a large number of frost days and hot and dry summers. Nevertheless, the Atlantic influence is still important, favouring high precipitation, averaging 1531 mm year^{-1}, mainly occurring from the autumn to the spring (figure 2). Mean monthly temperatures range from 3.5°C to 17.2°C (figure 2). *Lameiros* and other permanent pasture lands represent 68% of the agricultural area (34 417 ha), and bovine livestock production is the main agricultural activity (INE 2001).

2.2 *Test sites*

The pixel size of SPOT-VEGETATION images (1 km^2) determines the criteria for selection of test sites, which have to include large contiguous areas with *lameiros* fields. Two suitable test sites were selected in Montalegre municipality: Paredes do Rio (PRR;

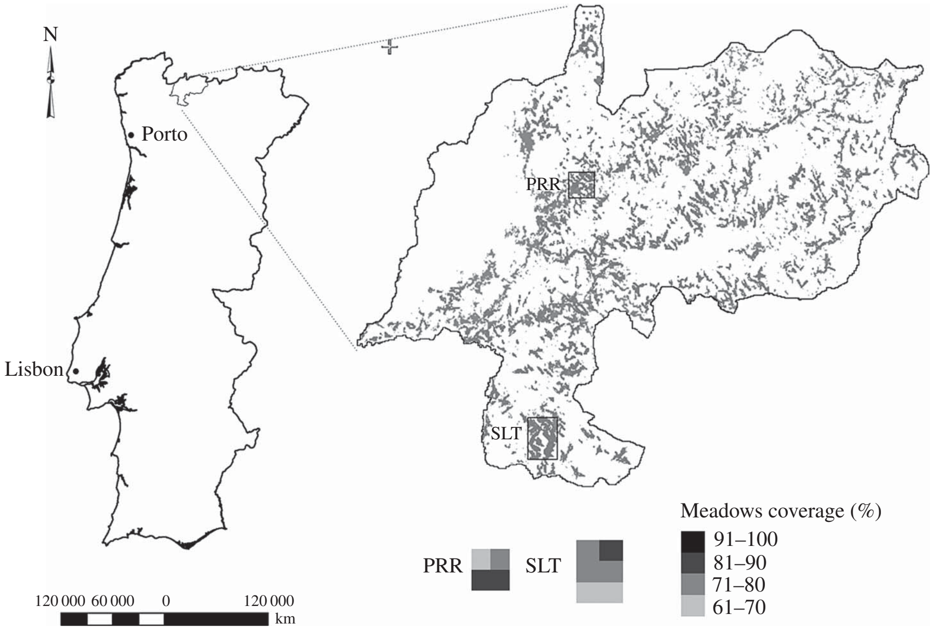

Figure 1. Location of the study area (Montalegre) and test sites (Paredes do Rio – PRR and Salto – SLT) in northeast Portugal, showing the meadow coverage in Montalegre (in grey). Details of meadow coverage per pixel in each test site are also given as percentages.

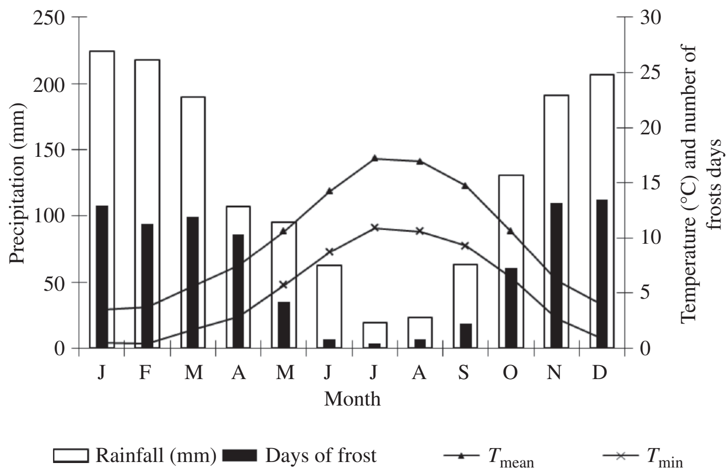

Figure 2. Average weather data (1951–1980) at Montalegre: precipitation (mm); number of frost days per month; mean temperature (°C); and minimum temperature (°C) (INMG 1991).

2 pixels × 2 pixels) and Salto (SLT; 2 pixels × 3 pixels). The coordinates (Datum WGS84) of the upper-left corner of each site are (i) PRR: 7° 55′ 04″ W, 41° 48′ 32″ N and (ii) SLT: 7° 57′ 33″ W, 41° 38′ 25″ N (figure 1). Each test site was established over a contiguous area of *lameiros* fields, therefore in compact groups of contiguous satellite pixels. Both test sites included two fields used for ground measurements. The two fields included seven plots of *lameiros* in PRR and two plots of *lameiros* in SLT.

The vegetation of *lameiros* in test sites essentially consists of permanent herbaceous species from the Molinio-Arrhenatheretea class, e.g. *Holcus lanatus*, *Plantago lanceolata*, *Dactylis glomerata*, *Anthoxanthum odoratum*, *Cynosurus cristatus* and *Trifolium* spp. (Teles 1970). The test sites were selected within areas of well-preserved and managed *lameiros* fields, explored for both grass and hay, and whose vegetation was similar to the surrounding areas, thus being representative of the *lameiros* characteristic in the region. However, because the study area is within a mountain region, variations in aspect and slope occur between and within test sites, which influence vegetation conditions and growth, as well as management practices. Differences due to management may be larger than desired because fields were managed by the farmers without interference from the researchers.

2.3 *SPOT-VEGETATION data*

A ten-day NDVI synthesis ('S10-composite') images data set from SPOT-VEGETATION (VGT) were used to produce temporal NDVI profiles for each test site. The S10 composites have spatial resolution of 1 km and are corrected for radiometric, geometric and atmospheric effects. In S10 composites, the surface reflectance for each pixel is processed according to maximum value compositing (MVC) (Holben 1986, VITO 2008). The VGT S10-composites are provided on 10 possible regions of interest. One of these pre-defined regions is 'Europe', covering an area between 25° N and 75° N and between 11° W and 62° E (VITO 2008). The software CROP VGT (Griguolo 2008) was used to crop a section from the satellite images covering the northeast region of Portugal. The final image set refers to a period of 11 years, from 1998 to 2008, with 36 images from each year.

The VGT sensor acquires data in four spectral bands in the visible and NIR, ranging from 0.43 to 1.75 μm (VITO 2008). NDVI values were computed from the extracted pixel values as (Rouse *et al.* 1973):

$$\mathrm{NDVI} = \frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{red}}}{\rho_{\mathrm{NIR}} + \rho_{\mathrm{red}}}, \qquad (1)$$

where ρ_{NIR} is the reflectance at the NIR wavelength band and ρ_{red} is the reflectance at the red waveband. The widths of the red and the NIR bands in the VGT sensor correspond to 0.61–0.68 μm and 0.78–0.89 μm, respectively.

The process of MVC applied to the S10-composite data set was not enough to eliminate unrealistic variability of the NDVI. Hence, NDVI values outside the interval 0.05–0.92 were rejected and replaced by the median value derived from the NDVI data from two dates before and after the concerned date.

As each NDVI image was obtained by merging data from 10 consecutive days, the whole test site was considered as a unit, instead of using a pixel-by-pixel approach. This was done to prevent misregistration and errors from other sources; these errors could contaminate the temporal profiles. The pixels of each test site were averaged to create the NDVI value for each time period.

Figure 3 presents the coefficient of variation (CV) for the inter-annual change of NDVI within test sites, considering different periods of the year. Related data show that CV was less than 0.05 in 81–100% of the cases (figure 3). In both test sites, lower CV is related to the summer images. The autumn images of Paredes do Rio have the highest CV, with CV greater than 0.15 in 8% of the cases. The next highest CV was

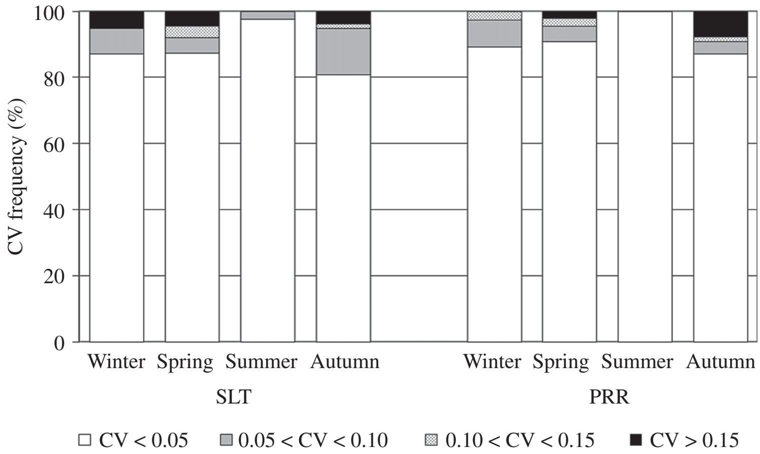

Figure 3. Histogram of the seasonal pattern of the coefficient of variation for the inter-annual change of NDVI relative to the period 1998–2008 for pixels at both test sites.

observed for the winter images of Salto. The higher CVs are likely due to high atmospheric humidity during autumn and winter (Kobayashi and Dye 2005), which, in contrast, is generally low in the summer dry season. In mountain regions, this effect of atmospheric vapour is less negligible due to the acceleration of air streams passing over the mountains because of the Venturi effect and the impacts of drag due to undulating topography, therefore differently affecting the atmospheric transmissivity throughout the study area (Allen *et al.* 2008).

2.4 *Ground-based measurements*

Reflectance measurements were performed using a handheld spectroradiometer (ASD FieldSpec UV/VNIR, ASD Inc., Boulder, CO, USA) with a conic instantaneous field of view (IFOV) of approximately 25° and a reflectance data capture between 325 and 1075 nm of the electromagnetic spectrum. Ground-based reflectance measurements were performed in each of 17 points at SLT and 15 points at PRR, in two fields in each test site. The fields were selected to include varying conditions of orography (aspect and slope) and irrigation water availability, thus representing the overall conditions of the areas where test sites were located. A similar approach was adopted when selecting the measurement points throughout each field. The reflectance measurements were performed 30 cm above the vegetation surface, and the spectroradiometer was set to an integration time of 136 ms, and 10 reflectance files were saved. To account for atmospheric changes, these reflectance files were automatically compared with a white reference measurement taken over a reference calibration panel where the reflectance all over the electromagnetic spectrum is close to 100%. Reflectance data of the red and NIR bands of the electromagnetic spectrum were used to compute NDVI. The red and NIR band widths used to compute the NDVI corresponded to the widths of the VGT bands.

Eighteen campaigns of reflectance measurements were carried out from July 2007 to December 2008, thus sampling all phenological stages of *lameiros*. All measurements were performed in sunny and cloudless days between 11.00–13.00 (local time) on 10 July 2007, 20 July 2007, 8 August 2007, 11 September 2007, 20 October 2007, 23 November 2007, 27 December 2007, 29 January 2008, 22 February 2008, 13 March 2008, 5 April 2008, 18 June 2008, 9 July 2008, 5 August 2008, 13 September 2008, 23 October 2008, 26 November 2008 and 18 December 2008.

The remotely sensed vegetation dynamics was evaluated considering the information on vegetation conditions and phenology and agricultural practices inferred from field surveys. For each measurement point and all the above referred campaigns, the vegetation height was measured and the phenological stage was recorded. The records of phenological stage were determined by the stage observed in more than 50% of the plants in a square of area 1 m^2 over each measurement point. The phenological growth stages were those described by the extended Biologische Bundesanstalt, Bundessortenamt and CHemical (BBCH) scale (Meier 2001). Four phenological stages were recorded for Grasses (Gramineae) – first leaves, tillering, stem elongation and heading – and three for Legumes – rosette growth, booting and flowering.

2.5 *Data analysis*

To analyse the response of vegetation dynamics inferred from satellite data, a number of basic NDVI metrics were computed for each year (1998–2008) based on three important dates referring to meadows management: green-up (GUP), maximum vegetation development (MVD) and vegetation re-growth after cutting for hay (VRG) (table 1). These basic NDVI metrics were used to derive the following periods (table 1): (i) development period, between GUP and MVD, (ii) dry period, between MVD and VRG and (iii) autumn/winter period, between VRG and GUP_{n+1} (i.e. GUP at next year).

The Pearson correlation was applied to assess the relationship between the NDVI obtained from satellite images ($NDVI_{VGT}$) and that from ground-based observations relative to vegetation growth. A paired *t*-test analysis was performed to determine the significance of the differences in the average values of NDVI metrics (DOY and respective NDVI values) between test sites, considering each year (1998–2008) as a repetition.

The inter-annual $NDVI_{VGT}$ profiles were analysed in relation to weather data, from 1998 to 2008, observed at the weather station of Montalegre (41° 49′ N; 7° 47′ W; 1005 m of elevation), located a few kilometres away from the test sites and at about the same elevation. Correlations between each NDVI metrics (value and day of the year, DOY) (table 1) and the temperature, precipitation and reference evapotranspiration were analysed. The reference evapotranspiration was computed according to the procedure proposed by Allen *et al.* (1998).

3. Results and discussion

3.1 *VGT and ground-based data*

The averages of 10-day VGT data referring to the 11 years of study (1998–2008) were used to examine the *lameiros* NDVI profiles and their relationship with growth dynamics and management practices of the meadows (figure 4).

The NDVI profile derived from VGT data ($NDVI_{VGT}$) follows a similar pattern in both test sites (figure 4) and relates to the characteristic vegetation growth pattern and respective management practices as observed in ground surveys (figure 4 and table 1). Lower NDVI values during the winter reflect the vegetation dormancy or the slow growth rate by this time of the year. NDVI values increase after March when the

Table 1. Procedure to determine the basic and derived NDVI metrics depending upon the conditions for vegetation growth in semi-natural meadows inferred from field survey.

NDVI metric*	Definition	Vegetation conditions and agronomic practices
Basic NDVI metrics		
Green-up (GUP)	NDVI value obtained at the first consecutive increase of NDVI after the winter	Beginning of vegetation growth activity after the winter, by March or April
Maximum vegetation development (MVD)	Maximum NDVI value	MVD, by June or early July
Vegetation re-growth (VRG)	NDVI value obtained at the first NDVI increase after MVD	First vegetation re-growth after the summer cutting for hay, by August
Derived NDVI metrics		
Development period	Between GUP and MVD	Vegetation grows quickly and irrigation is generally applied during all the period. Phenological stages refer to leaf development and stem elongation by March–April, and ear development stage (Gramineae) or flowering (Legumes) by May–June. Meadows are grazed by livestock until early May
Dry period	Between MVD and VRG	By late June, irrigation is cut-off to allow vegetation to slowly dry, thus favouring the quality and conservation of hay. By July, grass is cut for hay, and vegetation growth restarts in the following days
Autumn/winter period	Between VRG and GUP by the next year	Vegetation re-growth starts by mid-summer, and growth rates depend on water availability. By October–November, grasses and legumes are mainly at leaf development phenological stage. Irrigation is then used for thermal regulation, thus to minimize frost impacts. Livestock grazing occurs until rainfall and cool weather makes grazing inappropriate. From December to February, vegetation growth is very slow or grasses enter in dormancy. Irrigation is used for thermal regulation.

Note: *Since the NDVI values correspond to a composite of 10 days, the middle day of each decade was considered.

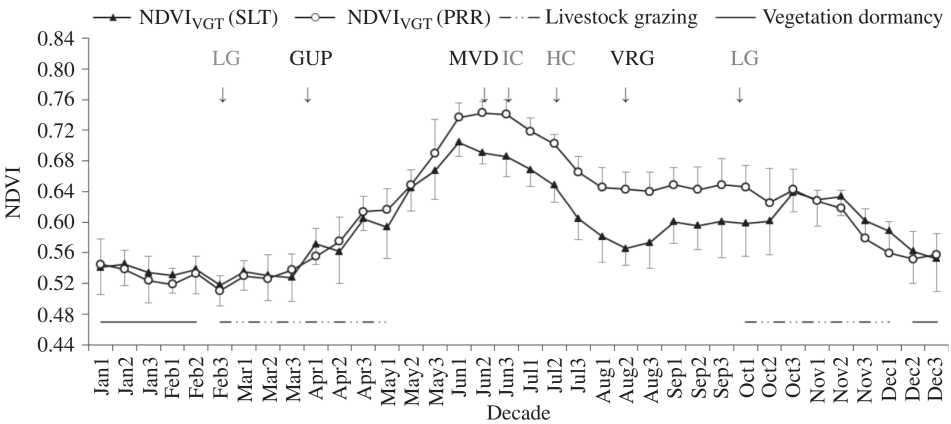

Figure 4. Average NDVI (1998–2008) throughout the year for the two test sites as related to the characteristic vegetation dynamics and management practices, including the periods of vegetation dormancy and grazing. Vertical bars represent half of the 95% confidence interval of the mean. Dates marked by arrows are determined from field observations between July 2007 and December 2008 and are averaged from both test sites: LG – start or re-start of livestock grazing; GUP – start of green-up; MVD – maximum vegetation development; IC – summer irrigation cut-off; HC – hay cutting; and VRG – vegetation re-growth.

vegetation GUP occurs (table 1). NDVI values continue to grow during the spring when vegetation is actively growing, including under livestock grazing. From May to the end of the summer, livestock grazing stops in *lameiros* and is transferred to common pastures. The highest NDVI values are reached by June, when vegetation development is at the maximum. By this time, $NDVI_{VGT}$ values are higher at PRR than at SLT (figure 4) because irrigation water availability is higher there and the grazing intensity is smaller than at SLT. Later, NDVI reflects the VRG and, by the end of summer and early autumn, the impact of livestock grazing on the vegetation (figure 4). Table 2 presents the NDVI metrics derived from VGT data between 1998 and 2008 for both test sites.

Table 2. Statistics of $NDVI_{VGT}$ metrics computed for each test site in the period between 1998 and 2008 and results of the paired *t*-test between test sites.

		NDVI metric‡					
		GUP		MVD		VRG	
Statistic*	Test site†	DOY	NDVI	DOY	NDVI	DOY	NDVI
Average	PRR	92.1	0.535	163.4	0.761	223.5	0.620
	SLT	85.5	0.510	162.3	0.720	234.9	0.590
CV	PRR	0.12	0.07	0.08	0.03	0.05	0.06
	SLT	0.14	0.13	0.08	0.03	0.05	0.08
t-test (significance)		0.032	0.114	0.343	0.000	0.001	0.003

Notes: *CV, coefficient of variation; *t*-test (significance), *t*-test statistical significance of the paired *t*-test analysis considering each year (1998–2008) as a repetition.
†PRR, Paredes do Rio; SLT, Salto.
‡GUP, green-up; MVD, maximum vegetation development; VRG, vegetation re-growth after hay cut; NDVI, normalized difference vegetation index; DOY, day of the year (Julian day).

The average date of GUP is earlier in SLT (Julian day 85) than in PRR (Julian day 92), while the average date for MVD in both test sites is quite close (Julian days 162 and 163, respectively). For the VRG, the average date is earlier in PRR (Julian day 223) than in SLT (Julian day 234), which relates to management. The high inter-annual variation of the GUP date (CV of 0.12–0.14) reflects the weather variability by late winter, when the CVs are high for the precipitation (0.88) and mean temperature (0.14). The average length of the development period, the period between GUP and MVD, is 71 days in PRR and 78 days in SLT, with coefficients of variation of 0.16 and 0.15, respectively. For the dry period, between MVD and VRG, the average length is 60 days in PRR and 72 days in SLT, with coefficients of variation between 0.22 and 0.23, respectively.

The difference in the NDVI at GUP ($NDVI_{GUP}$) between test sites is not statistically significant ($p < 0.114$), thus reflecting similar crop conditions in both test sites during the winter period (figure 4). In contrast, the significantly higher values of NDVI at MVD ($NDVI_{MVD}$) ($p < 0.000$) and at re-growth after cutting for hay ($NDVI_{VRG}$) ($p < 0.003$) at PRR are due to higher irrigation water availability and lower grazing intensity than at SLT, as mentioned earlier.

Figure 5 shows the NDVI derived from VGT ($NDVI_{VGT}$) and from spectroradiometer data ($NDVI_{Sp}$) observed during 2008. Results are generally consistent (coefficient of determination, $R^2 = 0.63$; $n = 11$; $p < 0.01$ for PRR and $R^2 = 0.68$; $n = 11$; $p < 0.01$ for SLT) but some differences occur because the spatial and temporal resolutions of both sensors are different. The handheld spectroradiometer allows identification of details on the vegetation condition in a small spatial scale (point scale), influenced by local management of the fields where observations were performed, while VGT provides broader information relative to a group of contiguous *lameiros* fields. The $NDVI_{Sp}$ values in Paredes do Rio for the campaigns of March and April 2008 show higher values than the $NDVI_{VGT}$ (figure 5). During this period, livestock grazing creates great variability in the vegetation conditions in contiguous *lameiros* fields and differences between the NDVI are probably related to the scale differences of the measurements obtained at field level

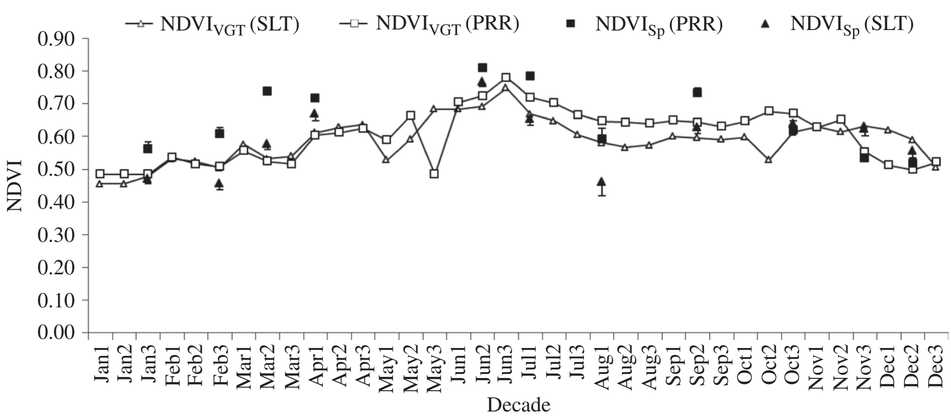

Figure 5. *Lameiros* NDVI profile observed in 2008 in both test sites computed from VGT data ($NDVI_{VGT}$) compared with values computed from spectroradiometer data ($NDVI_{Sp}$). Vertical bars represent half of the 95% confidence interval of the mean.

and by the satellite. The $NDVI_{Sp}$ values derived from the field campaign by early August 2008 are lower than $NDVI_{VGT}$, mainly in SLT test site, likely because hay was cut in one of the fields used for field measurements in SLT about 3 weeks later than in all other contiguous fields. Results in figure 5 show that differences between $NDVI_{Sp}$ and $NDVI_{VGT}$ are greater in periods when the management of fields used for spectroradiometer observations present more variations, thus indicating the need for careful interpretation of results taking into consideration the effects of spatial scale.

Table 3 compares the basic NDVI metrics derived from VGT and spectroradiometer for both test sites in the year 2008. The occurrence date (day of year, DOY) of the NDVI metrics registered for each sensor varies from 10 (GUP) to 21 (VRG) days in PRR and 10 (GUP and VRG) to 11 (MVD) days in SLT. However, these differences are influenced by the fact that temporal resolutions of VGT and spectroradiometer data are different, respectively 10 and about 30 days. The highest differences in the NDVI values derived from the spectroradiometer and from the VGT were observed for GUP and VRG in Paredes do Rio (table 3). Differences for the GUP mainly relate to the vegetation conditions in the *lameiros* sampled at field level and in the group of contiguous *lameiros* sampled at satellite level, considering that dates when livestock grazing starts vary among fields. The NDVI differences for VRG in PRR mainly relate to the larger interval between the acquisition of data for the two sensors (VGT and spectroradiometer).

The regression between $NDVI_{VGT}$ and the $NDVI_{Sp}$ values for the period from July 2007 to December 2008 is shown in figure 6, grouping data from both test sites. The regression coefficient is close to 1 (0.98), but the determination coefficient is relatively small (0.49) due to differences in space and timescales between NDVI data obtained from both sensors. When the relationship between the $NDVI_{VGT}$ and $NDVI_{Sp}$ is analysed separately for the two test sites, the coefficients of determination are statistically significant (data not shown): SLT ($R^2 = 0.72$; $n = 17$; $p < 0.01$) and PRR (R^2 0.41; $n = 15$; $p < 0.05$). The lower R^2 for PRR is likely due to a large heterogeneity in the hay cut dates in this site as observed from field surveys (figure 6). The large number of fields and the higher slopes in PRR make hay cut less efficient, thus resulting in larger differences in reflectance as observed at point scale with the spectroradiometer relative to values observed with VGT, which correspond to a coarser spatial resolution. This interpretation is also supported by the CV of $NDVI_{Sp}$ in the period of hay cut in 2007 and 2008, which averaged 0.22 in SLT and

Table 3. Comparison of basic NDVI metrics (NDVI values and day of occurrence DOY) derived from VGT and spectroradiometer (Sp) sensors for each test sites in 2008.

		NDVI metric*					
		GUP 2008		MVD 2008		VRG 2008	
Test site	Sensor	DOY	NDVI	DOY	NDVI	DOY	NDVI
PRR	VGT	85	0.516	177	0.780	238	0.640
SLT	Sp	95	0.716	166	0.810	259	0.732
	VGT	85	0.540	177	0.748	249	0.600
	Sp	95	0.668	166	0.765	259	0.627

Note: *GUP, green-up; MVD, maximum vegetation development; VRG, vegetation re-growth after hay cut; NDVI, normalized difference vegetation index; DOY, day of the year.

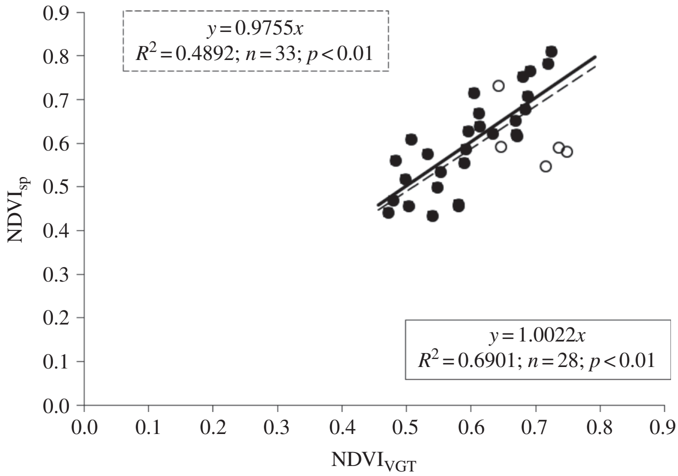

Figure 6. Relationship between the NDVI derived from spectroradiometer data ($NDVI_{Sp}$) and VGT satellite data ($NDVI_{VGT}$), for both test sites and the period July 2007–December 2008: dashed line, considering all the points of the period studied, and continuous line, excluding the points concerning to the hay cut period in PRR (white points).

0.32 in PRR. When the regression between the $NDVI_{VGT}$ and $NDVI_{Sp}$ excludes HC data in PRR (three measurements in July and early August from 2007 and two from 2008), the determination coefficient increases to 0.69, with a regression coefficient of 1.0022 (figure 6), which confirms that assumption. Therefore, topographic conditions and management practices have a large impact on local variability of NDVI, which is greater in PRR when compared with SLT. This field-to-satellite scaling problem is reported by Fisher *et al.* (2006) as a critical issue for the understanding of fine-scale spatial variability. Further studies may be implemented in the study area considering the fine-temporal scale of spectroradiometer measurements and intermediate to high spatial resolution sensors (e.g. MODIS and DEIMOS-1 (Spanish satellite operated by DEIMOS Imaging), which integrate the Disaster Monitoring Constellation systems) to assess the influence of temporal and spatial scaling in the monitoring of *lameiros*.

The relationship between vegetation height and NDVI values derived from VGT and from the spectroradiometer fits a logarithmic function for values of both test sites and the period from July 2007 to December 2008, as shown in figure 7. Statistical results show that variation in vegetation height explains 46% and 52% of the variation in $NDVI_{Sp}$ and $NDVI_{VGT}$ (figures 7(*a*) and (*b*)), respectively.

When the relationship between $NDVI_{Sp}$ and vegetation height was performed for each test site, a similar logarithmic regression was found, with significant coefficients of determination: 0.45 ($n = 16$; $p < 0.01$) for PRR and 0.57 ($n = 16$; $p < 0.01$) for SLT (data not show). Payero *et al.* (2004) also found a nonlinear relationship between vegetation height and NDVI derived from a field radiometer for alfalfa and grass crops.

The nonlinear regressions obtained may be related to a saturation of the $NDVI_{VGT}$ for vegetation height above 60 cm (figure 7(*b*)). Several authors refer to saturation problems of NDVI for high biomass conditions or vegetation height (Huete *et al.* 2002, Payero *et al.* 2004, Phillips *et al.* 2008, Zhang *et al.* 2009). Nevertheless, the

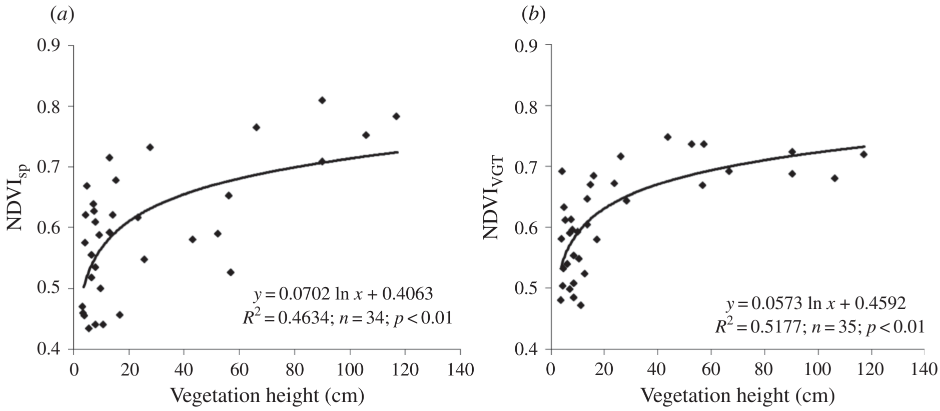

Figure 7. Relationship between ground-based vegetation height and NDVI derived from (*a*) the spectroradiometer and (*b*) the VGT sensor, using data from both study areas.

statistically significant correlation between NDVI and vegetation height reveals the potential for using the VGT sensor to study vegetation dynamics. These results are in agreement with those obtained by Cayrol *et al.* (2000), in which remotely sensed time series of NDVI from coarse resolution satellite sensors (AVHRR and VGT) successfully revealed the variability observed in biomass and LAI ground measurements in grasslands, which are parameters highly related to vegetation height.

The statistically significant correlations between $NDVI_{VGT}$ and ground-based data ($NDVI_{Sp}$ and vegetation height) open perspectives for the use of this sensor to compare the *lameiros* dynamics in different years since 1998. However, further field surveys with fine-temporal scale might help to increase the accuracy of the assessment of vegetation dynamics. Nevertheless, the results obtained allow us to conclude that using data from the VGT might be appropriate for monitoring *lameiros* in other mountain areas of northeast Portugal and for monitoring similar vegetation in other European areas.

3.2 *Relationship between NDVI metrics and weather data*

The inter-annual changes in vegetation dynamics can give information on the vegetation response to climate variability (Martínez and Gilabert 2009, Verbesselt *et al*. 2010). Often, more important than the actual date of each phenological event is the interval between events, which gives an indication of the overall climate during those periods. In this perspective, NDVI metrics (values and DOY) corresponding to vegetation dynamics and management practices in *lameiros* (table 1) were tested against selected climatic variables for the period 1998–2008 (table 4).

The average NDVI during the periods studied have similar values in both test sites and the major difference was found for the dry period (table 4), which is related to the hay cut date (§3.1). During the development and dry periods, mean temperature and reference evapotranspiration in PRR are equal to or higher than in SLT (table 4). The precipitation sum (R) in SLT is higher than in PRR (table 4), which is related to longer development and dry periods (table 2).

In both test sites, significant negative correlations are observed between the MVD date and both mean temperature (correlation coefficient, $r = -0.73$; $n = 11$;

Table 4. Mean values and coefficients of variation (in brackets) of $NDVI_{VGT}$ values, and climatic variables during the winter, spring, development period and dry period, for the years 1998–2008 in both study areas (PRR and SLT).

	Winter		Development period†		Spring		Dry period†	
Variable*	PRR	SLT	PRR	SLT	PRR	SLT	PRR	SLT
T_{mean} (°C)	5.8		11.5	11.2	11.6		16.3	16.1
	(0.14)		(0.11)	(0.10)	(0.07)		(0.10)	(0.12)
R (mm)	436.4		245.6	273.8	317.6		121.6	160.3
	(0.95)		(0.49)	(0.42)	(0.36)		(0.54)	(0.42)
ET_o (mm day^{-1})	1.4		3.4	3.3	3.4		4.3	4.3
	(0.14)		(0.09)	(0.10)	(0.06)		(0.12)	(0.12)
$NDVI_{VGT}$	0.53	0.54	0.64	0.62	0.64	0.62	0.69	0.62
	(0.05)	(0.07)	(0.04)	(0.04)	(0.03)	(0.02)	(0.04)	(0.05)

Notes: *T_{mean}: mean daily temperature; R: precipitation sum; ET_o: mean daily reference evapotranspiration; $NDVI_{VGT}$: NDVI derived from VGT.

†Development period, between the GUP and maximum vegetation development; dry period, between the maximum vegetation development and vegetation re-growth after hay cut.

Weather data source: INMG.

$p < 0.05$) and reference evapotranspiration ($r = -0.63$; $n = 11$; $p < 0.05$) during the spring season (table 5). Results show that higher temperatures and larger mean reference evapotranspiration (ET_o) are associated with an earlier date for MVD (table 5). In PRR, these meteorological variables relative to the dry period are also significantly correlated ($p < 0.05$) with the length of the dry period. The lower correlation results between the length of the dry period and both mean temperature and ET_o in SLT ($r = -0.40$ and $r = -0.47$, respectively) may be due to the occurrence date of VRG in this test site. The NDVI metrics for 1998–2008 shows that the date of occurrence of VRG was usually 10 days later in SLT when compared to PRR.

The inter-annual (1998–2008) variation in the $NDVI_{VGT}$ relative to the development period also shows a close relationship with the mean temperature during the development period (figure 8). For both study areas, more than 57% of the inter-annual variability of the average $NDVI_{VGT}$ during the development period can be explained by the mean air temperature for that period (see figure 8). The highest temperature values were observed in 2000, 2004 and 2007 (2006), which correspond to the highest $NDVI_{VGT}$ values, while the lowest $NDVI_{VGT}$ values were observed for the years 2001 and 2005 when air temperature was lowest. During the development period, the temperatures are usually low (see table 4), arguing that thermal conditions are a limiting factor for *lameiros* vegetation growth. Similar results were also observed by Piao *et al.* (2006) for temperate grasslands in China.

Because the temperature is correlated with NDVI (figure 8) and with phenology timings (table 5), the results derived from this study can help to understand the impact of the inter-annual climatic variations on the vegetation dynamics. In the foreseen scenario of future temperature increase (e.g. Yu *et al.* 2003, Lavalle *et al.* 2009), the observed results could indicate a trend for earlier occurrence of the MVD, with impacts on the opportunity of management practices. Some possible impacts could be: (i) bringing forward of the date of the irrigation cut-off to allow vegetation drying before the hay cut; and (ii) bringing forward of the date of the hay cut itself. This bringing forward of the date of irrigation cut-off could allow some water saving, but climatic demand for water is likely to increase. Another impact could be a longer grazing period in the spring, delaying the vegetation growth for the hay cut, thus decreasing the need for alternative fodder resources.

For SLT, a positive correlation was also found between the NDVI values at the VRG date after hay cut and precipitation during the dry period ($r = 0.64$; $n = 11$; $p < 0.05$), which however was not observed in PRR (table 5). The lower correlation in PRR may result from higher water availability in this site during the considered period, thus smoothing the precipitation impact. This is in contrast to SLT, where irrigation water availability is lower.

No other significant correlations with precipitation were found for the development or dry periods (table 5), thus suggesting that precipitation may not be a limiting factor, since irrigation is practised. In their study on temperate grasslands, Piao *et al.* (2006) observed a weak NDVI–precipitation relation for precipitation values above 200 mm. This value corresponds to the precipitation amount in Montalegre region during the development period (table 4). Because irrigation of *lameiros* is regularly practised all year round, crop water requirements are generally satisfied and the crop does not depend directly on precipitation; therefore, it is difficult to establish a correlation between *lameiros* vegetation development or NDVI and climatic variables related with water, mainly precipitation. Further studies can be implemented to monitor the response of vegetation dynamics to water availability.

Table 5. Pearson correlation matrix between NDVI metrics (value and time) and weather variables for both test sites.

Climatic variables*	Test site	NDVI mertics†														
		GUP			MVD			VRG			Development period			Dry period		
			NDVI	DOY		NDVI	DOY		NDVI	DOY		NDVI	Days		NDVI	Days
T_{mean}	PRR	Winter period‡	0.51	0.20	Spring period‡	0.54	**−0.73**	Dry period‡	−0.30	−0.60	Development period‡	**0.74**	0.29	Dry period‡	0.09	**−0.70**
	SLT		0.25	0.20		0.16	**−0.73**		−0.11	−0.50		**0.83**	0.32		0.05	−0.40
R	PRR		−0.25	−0.42		0.30	0.09		0.15	0.42		−0.03	0.57		0.06	0.51
	SLT		−0.34	−0.09		0.27	0.09		**0.64**	0.56		0.15	0.36		0.51	0.54
ET_o	PRR		−0.53	0.21		0.05	**−0.63**		−0.27	−0.58		**0.61**	0.20		0.05	**−0.62**
	SLT		−0.01	0.08		0.20	**−0.63**		−0.06	−0.58		0.48	0.21		0.10	−0.47

Notes: *T_{mean}, mean temperature of the period; R, rainfall in the period; ET_o, mean reference evapotranspiration of the period.
†GUP, green-up; MVD, maximum vegetation development; VRG, vegetation re-growth after hay cut; development period, between the GUP and maximum vegetation development; dry period, between the maximum vegetation development and first vegetation re-growth after hay cut; NDVI, normalized difference vegetation index; DOY, day of the year; day, number of days in the period.
‡These periods are related to climatic variables.
Significance level of Pearson coefficient for 11 observations: $r > 0.602$ ($p < 0.05$); $r > 0.735$ ($p < 0.01$). Values statistically significant for $p < 0.05$ and $p < 0.01$ are highlighted in bold type.

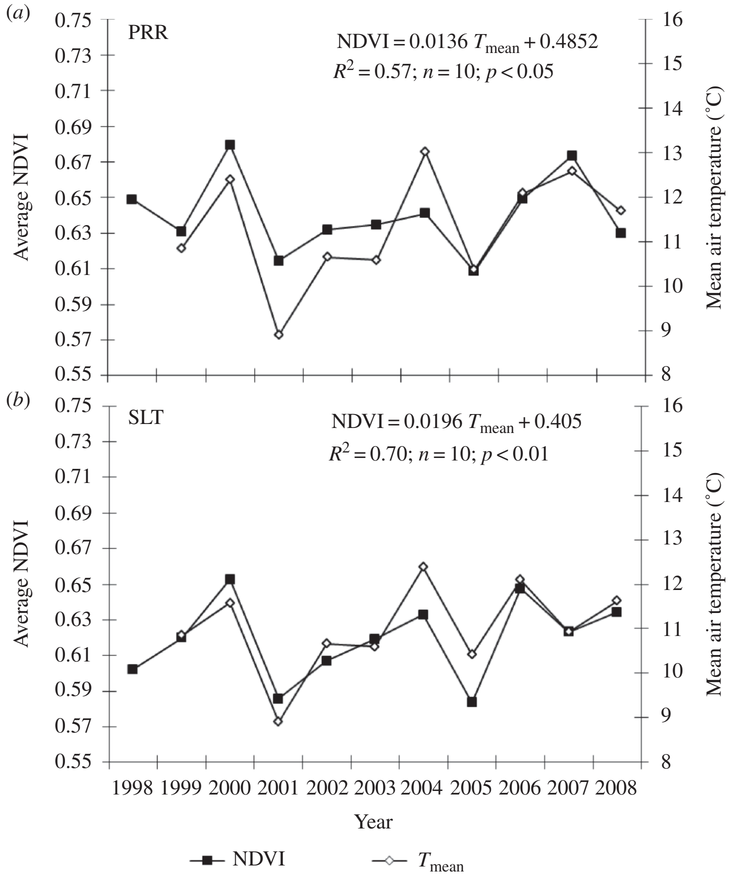

Figure 8. Relation between average $NDVI_{VGT}$ and mean air temperature during the development period, for 1998–2008 and both study areas (Paredes do Rio – PRR; Salto – SLT).

4. Conclusion

Ten-day VGT images from 1998 to 2008 were used to examine temporal and spatial patterns of NDVI and their relationship with ground-based observations of vegetation growth and agronomic practices in *lameiros*. The remotely sensed time series of NDVI from both test sites suggest that VGT satellite data are appropriate to detect the main phenological events that are important to support management practices. Thus, the SPOT-VEGETATION sensor has proven to be very useful for *lameiros* monitoring despite the low spatial resolution of the images.

The access to VGT data since 1998–2008 and the low time-consuming processing of the images makes the use of these data particularly interesting to infer both intra-annual and inter-annual dynamics of *lameiros* vegetation. The analysis of the inter-annual variation of $NDVI_{VGT}$ for an 11-year period has shown that temperature is the main driver of vegetation growth, and of average NDVI, for the development period and for the date of MVD. At the farm level, this information could support grass/hay production estimations and help in the scheduling of the hay cut in *lameiros*, thus increasing the management efficiency of the farm activities. It could also help in the decision about the irrigation cut-off timing, thus increasing the efficiency of water use. At a broader scale, this information could also be used to analyse the *lameiros* response under different scenarios of climate change. Time series NDVI inferred from VGT have shown good potential to derive information to support *lameiros* management decisions for the next decades and help in decisions relative to conservation strategies.

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