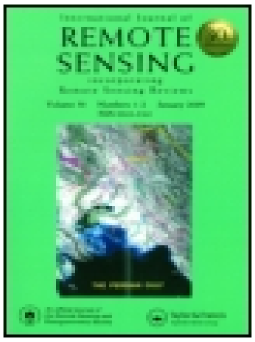

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Tree influence on soil and pasture: contribution of proximal sensing to pasture productivity and quality estimation in *montado* ecosystems

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ABSTRACT

Montado is a silvo-pastoral ecosystem of the Mediterranean region, a mixed system of trees and pasture, subject to animal grazing. Farmers need information on pasture production and quality in order to assess the direct effect of tree presence on the productivity of their pastoral system, and to devise management that balances farm production and profitability with sustainable soil management. The main objectives of this work were (1) to evaluate tree influence on soil and pasture parameters and (2) to evaluate the use of proximal sensing techniques that have potential for monitoring aspects related to spatial and temporal variability of pasture productivity and quality in *montado* ecosystems. Both objectives can support the decision-making process of the farmer. The study field is located in Mitra farm, in Southern Portugal. During October 2015, 24 geo-referenced composite soil samples (12 under tree canopy and 12 outside tree canopy) were collected from the 0.0–0.3 m soil layer. The soil samples were analysed for texture (sand, silt, and clay content), moisture content, pH, organic matter, total nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), and manganese (Mn). The evolution of the pasture was recorded in the 24 sampling points at five monitoring dates: at the end of autumn (December 2015), at the end of winter (March 2016), and then monthly during spring 2016 (April, May, and June). The following pasture parameters were measured: normalized difference vegetation index (NDVI), capacitance, temperature, green and dry matter, ash, crude protein (CP), and neutral detergent fibre. Soil under tree canopy had significantly higher levels of organic matter, N, P, K, and Mg, and better pasture quality while the pasture productivity was higher outside tree canopy. The correlation between pasture direct measurements and sensor parameters was more consistent between capacitance and pasture productivity and between NDVI and CP. The use of fast and efficient tools associated with geo-referenced systems can greatly simplify the pasture monitoring process, which is the basis for estimating feed availability in the field. The knowledge of

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biomass quality and quantity is fundamental to support decision-making regarding animal stocking rates and rotation among grazing parcels.

1. Introduction

1.1. *The* montado *ecosystem*

Agro-forestry systems under semi-arid Mediterranean conditions, called *montado* in Portugal and *dehesa* in Spain, are mixed systems of trees, pastures, and scattered shrubs, which have been proposed as a means of extending the benefits of forest to farmed land. The system also contributes to the comprehensive ecological equilibrium of the rural area and to its environmental quality and stability, both at regional and very local levels (Somarriba 1988). These silvo-pastoral systems cover substantial areas in the world and are the most extensive European agro-forestry system as they cover 3.5–4.0 Mha in Spain and Portugal and are a common landform in other Mediterranean countries such as Morocco, Algeria, Italy, and Greece (Seddaiu et al. 2013).

During the second half of the twentieth-century, millions of trees were eliminated in Mediterranean areas, mainly from the most productive lands (Marcos et al. 2007). As a consequence, the typical undulating topography associated with intensive forms of land use has led to erosion mechanisms and soil transport, resulting in degraded, shallow, and stony soils with low organic matter content and a propensity to acidification, all limiting factors of productivity (Serrano, Shahidian, and Marques Da Silva 2013). In the past two decades, a considerable effort has been devoted to the promotion of traditional and novel agro-forestry practices as a means of slowing down or reversing these trends (Marcos et al. 2007). The standard process for poor and degraded soils recovery in southern region of Portugal is the correction of acidity and other imbalances, improving soil fertility through fertilizer application and the installation of permanent pastures (Efe Serrano 2006). Other strategies such as balanced spatial distribution of trees may also have a relevant contribution.

In the *montado* of Southern Portugal (Alentejo province), the main tree species are *Quercus ilex* ssp. *rotundifolia* Lam. (holm oak) and *Quercus suber* L. (cork oak), managed mainly for the production of acorns (for livestock feed) and cork, respectively (David et al. 2013). They are mainly located in areas with a Mediterranean climate, with a strong seasonality and high variability, where vegetation has to withstand hot and dry summers as well as recurrent droughts (David et al. 2013). In these areas, evaporative demand is higher than annual rainfall and the dry season (summer) lasts for several months (Paço et al. 2009). Therefore, reaction/resilience to water stress becomes an essential feature of vegetation in these ecosystems, composed of two quite different plant life forms: the trees and the grassland (Paço et al. 2009).

1.2. *Contribution of tree and pasture to the water balance*

Deep-rooted evergreen trees and shallow rooted annual or perennial pastures are quite different in their water use strategy. Contribution of trees and pastures to the water balance of the *montado* ecosystems has been shown to be different, reflecting also distinct transpiration patterns (Paço et al. 2009). The pasture, mainly composed of annual species, is highly dependent on rainfall and topsoil moisture and very sensitive to summer drought. Pasture transpiration rate peaks in early spring (April), decreases thereafter till late spring, and stops by the beginning of July. During the summer (July–September), when the soil surface is dry, there is no transpiration from the pasture, and it only restarts after the onset of autumn rains (October). This dependency relation was also found by Joffre and Rambal (1993) and is of key importance to the understanding the ecology and the changes in land cover. On the other hand, trees are mostly dependent on deep soil and groundwater, showing a high resilience to drought: transpiration continues throughout the summer, even though the canopy conductance decreases (Paço et al. 2009). The positive effect of tree shade on the reducing evapotranspiration leads to higher soil moisture content (SMC) under the trees when compared to open pasture (Benavides, Douglas, and Osoro 2009).

1.3. *Soil–tree–pasture interaction*

Maximizing positive interactions (facilitation) and minimizing negative interactions (competition) among the vegetation strata is the motto. Nevertheless, no study has been carried out to determine the relative importance of the facilitative and competitive interactions between trees and pastures in *dehesas* and its consequence on the productivity of both components (Marcos et al. 2007). The two vegetation components differ in phenology as well as in radiation and rainfall interception, water and carbon dioxide (CO_2) fluxes. The potential for carbon (C) sequestration in systems that combine pastures with trees is higher because the secondary roots of the trees, which slowly accumulate great amounts of C in the soil, even in the underground, help to increase the soil organic carbon (Seddaiu et al. 2013). In the *dehesa* systems, the presence of trees, although scattered, has been recognized to positively affect soil physical and chemical properties (Joffre and Rambal 1993). The positive effect of trees on soil fertility has also been reported for other temperate silvo-pastoral systems (Benavides, Douglas, and Osoro 2009). Howlett et al. (2011) highlighted the relevant role of cork trees within the pastures in increasing SOM storage relative to areas under open native pasture. The potential soil C sequestration of agro-silvo-pastoral ecosystems has been widely confirmed due to the high amount of organic C stored in the aboveground biomass (Seddaiu et al. 2013).

Soil use and management in the *dehesa* agrosystem influence soil C sequestration by producing biomass and maintaining a positive nutrient balance. This has been shown in agro-forestry systems because they contribute to closing the C cycle due to the presence and integration of arboreal, herbaceous and animal components.

1.4. *Tree effect in pasture productivity and quality*

Farmers need information on pasture production and quality so they can assess the direct effect of planting trees on the productivity of their pastoral system and can devise management that balances farm production and profitability with sustainable use of the soil resource (Guevara-Escobar et al. 2007).

Monitoring of pasture quality through the evaluation of protein and fibre content across time is critical to define the nutritional value of pastures and design balanced diets for grazing animals (Demanet et al. 2015).

The effect of trees on pasture is a direct consequence of the extent to which they modify the microclimate and soil properties (Benavides, Douglas, and Osoro 2009). Competition for light, moisture and nutrients between trees and pasture species affects the pasture production in silvo-pastoral systems. The level of shade and its duration are among the most significant factors responsible for the variation in the pasture growth under trees (Benavides, Douglas, and Osoro 2009; Hussain et al. 2009). A reduction in the quantity and quality of light directly affects the physiological processes of plants, decreasing pasture carbohydrate manufacture and net dry matter production. Jackson and Ash (1998) showed a positive effect of the trees on pasture quality, but negative on their productivity, although variable in function of soil fertility. In temperate regions, competition for water is usually the other main factor limiting of pasture growth, particularly in regions subjected to summer droughts with high recorded temperatures and incident radiation. Soil water deficits result in lower forage dry matter yields primarily by limiting leaf area development and reduced photosynthesis due to stomatal closure (Benavides, Douglas, and Osoro 2009).

1.5. *Technologies for soil and pasture monitoring*

The application of sensing techniques to grazed production systems is difficult due to the complexity of these environments. Grassland systems are highly variable in composition, structure, and age and are continually changing in response to a range of drivers including grazing, pest and weed ingress, fertility, and moisture status (Pullanagari et al. 2013). The success of precision agriculture technologies in pasture is linked to the information integration provided by multiple sensors for monitoring plant, soil, and cattle grazing dynamics. These measurements along with more traditional indicators (e.g. soil fertility) allow the farmer to have much better understanding of the pasture system and formulate the most appropriate management strategy for grazing rotations, nutrient management, and yield prediction (Bernardi et al. 2016).

Traditional soil and pasture sampling and the necessary laboratory analysis are time-consuming and cost prohibitive, not viable from a practical perspective, leading to increased interest in automated monitoring methods (Handcock et al. 2016). The low economic value of grassland products limits the application of expensive hard technologies. However, grassland can benefit from technological developments that have been made for arable crops over the past decades (Schellberg et al. 2008). Remote sensing, particularly hyperspectral imaging, has been found to be a promising non-destructive tool for estimating nutrient concentrations of vegetation with a very short turnaround time. Along with spatial information, this offers a much more efficient and cost-effective way to map pasture nutrient concentration across large areas (Yule et al. 2015). Pullanagari et al. (2013) concluded that multispectral remote sensing has potential to rapidly estimate pasture quality in the field using non-destructive sampling. Satellite remote sensing constitutes an interesting prospect due to the scale of the response, speed of processing, and low cost. Satellite images with different geometric and spectral characteristics (i.e. 'Landsat 8' or 'Sentinel-2') are examples with applications in the *montado* ecosystems. 'Landsat 8' is equipped with two sensors: the Operational Land Imager and the Thermal Infrared Sensor. They provide data at a spatial resolution of 60 m for thermal, 30 m for visible, near-infrared (NIR), and shortwave infrared bands, and of 15 m for panchromatic bands, able to recognize features relevant to mapping cork oak population (Modica et al. 2016). Edirisinghe et al. (2011) have developed a method to quantitatively predict and map the biomass of annual pastures under grazing using the normalized difference vegetation index (NDVI) derived from high-resolution satellite imagery. However, in the *montado* ecosystems, satellite images have the disadvantage of not accessing the pasture under the trees.

The solution for monitoring pasture under these conditions may be through the use of proximal sensors and non-destructive techniques, useful for monitoring large areas (Handcock et al. 2016). Despite the fact that proximal sensors monitor only a small area or point and do not provide the extensive coverage of satellite imagery, when mounted on mobile platforms these sensors have the potential to deliver continual data on the feed base, to capture rapid changes in the proportions of photosynthetically active vegetation and to provide the basis for a more responsive management (Handcock et al. 2016). Active optical sensors (AOS), electronic capacitance probes, or infrared cameras are some examples of these technological developments, normally combined with the use of global navigation satellite systems (GNSS) and geographical information systems. Several vegetation indices, obtained by means of remote and proximal sensing, have been developed, tested, and improved in order to estimate and compare many leaf and canopy properties. NDVI is correlated with vegetative vigour (Gitelson 2004), so this can be seen as another rapid means of obtaining information for detailed pasture mapping. In the specific case of pastures, the relationship between pasture dry matter yield and corrected meter reading (CMR) of an electronic capacitance probe is known to vary with such factors as floristic composition, phenological stage or pasture moisture content (Serrano et al. 2011), and natural vegetation dynamics, which justify the interest in performing calibration tests.

The effect of trees on pasture development is highly conditioned by soil, moisture availability, sun exposure, and temperature. The infrared thermography images allow the calculation of the temperature at pasture surface, a parameter that can help to explain the tree effect on pasture development. According to Benavides, Douglas, and Osoro (2009), temperature is an important factor affecting pasture production because it affects the physiological processes of plants such as photosynthesis, respiration, and germination.

1.6. *Objectives of this study*

The existing knowledge on the distribution and characteristics of the soil nutrient pools and pasture productivity and quality in the *montado* is still insufficient to develop conservation strategies (Seddaiu et al. 2013). This difficulty results from the characteristic variability of this ecosystem, accentuated by the presence of trees (David et al. 2013) and by the dynamics of animal grazing (Schellberg et al. 2008). In order to implement conservation and recovery of natural resources through silvo-pastoral systems, it is necessary to know and correct potential limiting factors, especially the soil factor, and this requires agronomic knowledge as well as the implementation of the available new technologies. The main objectives of this work were (1) to evaluate tree influence on soil and pasture parameters and (2) to evaluate the use of proximal sensing techniques that have potential for monitoring aspects related to spatial and temporal variability of pasture productivity and quality in *montado* ecosystems and, therefore, support the decision-making process of the farmer.

2. Materials and methods

2.1. *Study area*

The studied field, with an area of 2.3 ha, is located at the Mitra farm (coordinates 38° 32.2′ N; 8° 01.1′ W), at Évora University, Southern Portugal. This field of oak trees (*Q. ilex* ssp. *rotundifolia* Lam.), with a relatively reduced tree density (approximately 10 trees ha^{-1}), has had an understory of natural pasture for the past 30 years and is grazed by sheep in a rotational system. A permanent biodiverse pasture (legumes and grasses) was planted in October 2013 at the same time that 150 kg ha^{-1} of phosphate fertilizer (super phosphate 18%) was applied. Since March 2014 the pasture has been grazed permanently by 15 adult *Black Merino* sheep. The predominant soil of this field is classified as a Cambisol derived from granite (FAO 2006). Cambisols are characterized by slight or moderate weathering of parent material and by absence of appreciable quantities of illuviated clay, organic matter, aluminium, and/or iron compounds. Acid Cambisols are not very fertile and are mainly used for mixed arable farming and as grazing and forest land. Cambisols in undulating or hilly terrain are planted to a variety of annual and perennial crops or are used as grazing land.

2.2. *Characterization of the climate*

The Mediterranean climate can be considered as a transition between temperate and dry subtropical climates. It is characterized by summer drought, variable rainfall, and mild or moderately cold winters. The monthly average temperature is between 8°C and 26°C; minimum temperatures are close to 0°C between December and February. The annual rainfall in the region is between 400 and 600 mm; rainfall occurs mainly between October and March and is practically non-existent during the summer. According to Murray et al. (2007), the concentration of rainfall between March and June is one of the major factors governing annual pasture production, mainly due to its influence on maintaining the growth of the pasture and extending its vegetative cycle.

Figure 1 illustrates the average thermo-pluviometric diagrams of the Évora meteorological station between 1981 and 2010 and the monthly rainfall between September 2015 and August 2016. Figure 1 shows very significant difference between the agricultural year 2015/2016 and the average historical values in terms of average monthly precipitation, which transformed 2016 into an atypical year, with direct influence on the vegetative cycle of the dryland pastures in Alentejo. In terms of accumulated rainfall between March and June, the average historical value is 186.4 mm, while in 2016 the rainfall was 238.3 mm. This difference is aggravated when we observe the distribution of the monthly rainfall. Thus, while the average historic values of accumulated rainfall are 83.2, 44.9, 33.5, and 24.8 mm, respectively, in March, April, May, and June, for the same period of 2016 the following values were observed: 31.6, 96.5, 109.8, and 0.4 mm. The concentration of rainfall in the

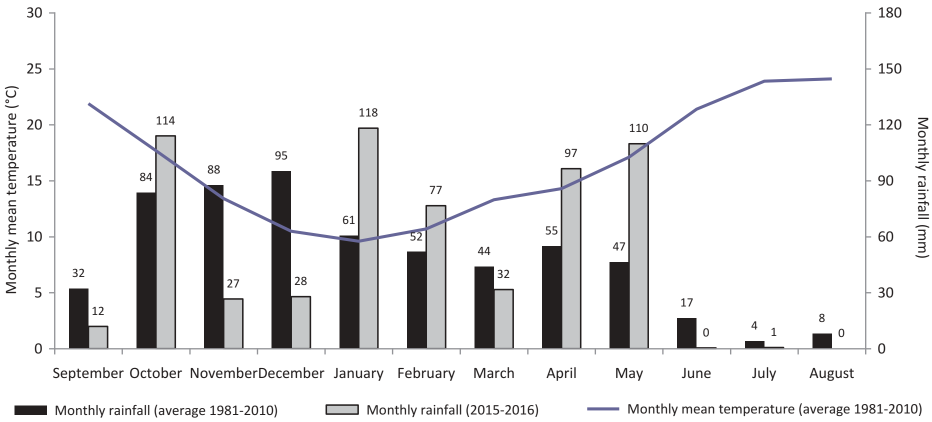

Figure 1. Thermo-pluviometric diagrams of the Évora meteorological station between 1981 and 2010 and the monthly rainfall between September 2015 and August 2016.

months of April and May is an important factor for maintaining the growth of the pasture and lengthening its vegetative cycle. In June, the combined influence of smaller rainfall and higher temperatures naturally impacts the productivity and quality of the pasture.

2.3. *Experimental methodology*

Figure 2 shows the outer border of the studied field, delimitated by a fence. In October 2015 six trees were selected (a1, a2, a3, b1, b2, and b3; Figure 2).

For each of these trees, four wooden grazing exclusion cages measuring 0.5 m × 0.5 m × 0.5 m were installed along an *N–S* axis (Figure 3). For each tree the radius of the canopy was measured from the trunk (r_c), in the north and south directions. In each one of these two directions, an exclusion cage was placed (to protect the pasture from grazing in the sampling areas) under tree canopy (UTC), at the intermediate point ($r_c/2$), and outside three canopy, at a distance equal to two times the radius of the canopy ($2r_c$; Figure 3). Thus 24 sampling points were defined, and the exact location marked with a stick, thus allowing the placement of the exclusion cage at the very same spot after each measurement.

2.4. *Soil sample collection and analysis*

In October 2015, one composite soil sample was taken in each of the 24 geo-referenced sampling points using a gouge auger and a hammer from the 0.0–0.3 m soil layer. Each composite sample comprised of four subsamples, taken from within 1 m of the centre of exclusion cage. The soil samples were inserted in plastic bags, air-dried, and analysed for particle-size distribution (texture: sand, silt, and clay content) using a sedimentographer (Sedigraph 5100, manufactured by Micromeritics, Norcross, GA, USA). The fine soil (fraction with diameter < 2 mm) was characterized in terms of pH, organic matter, total nitrogen (N_t), phosphorus (P_2O_5), potassium (K_2O), magnesium (Mg), and manganese (Mn).

These fine components were analysed using the following methods (Egner, Riehm, and Domingo 1960): (1) pH in 1:2.5 (soil: water) suspension, using the potentiometric method; (2) organic matter by combustion and CO_2 measurement, using an infrared

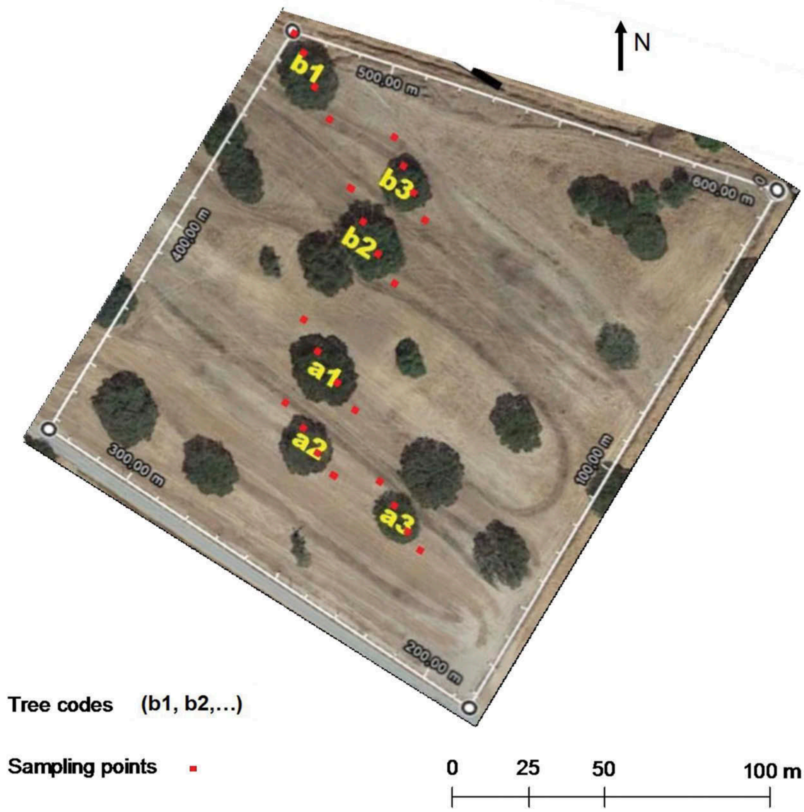

Figure 2. Studied field located at the Mitra farm (the outer border indicated in white), tree codes (yellow), and sampling points (red).

detection cell; (3) N_t with the Kjeldahl method; (4) P_2O_5 and K_2O were extracted by the Egner–Riehm method, and P_2O_5 was measured using colorimetric method, while K_2O content was measured with a flame photometer; and (5) Mg and Mn were measured using atomic absorption spectrometry.

Sampling of the soil in terms of gravimetric moisture was carried out at the end of autumn (December 2015), at the end of winter (March 2016), and then monthly during spring (April, May, and June 2016). The measurement of gravimetric soil moisture at two depths (0.0–0.2 m and 0.2–0.4 m) was carried out using a gouge auger and a hammer. For determining soil moisture, the soil samples were transported to the lab in metallic boxes, weighed, and then dried at 105°C for 48 h; once cooled, they were weighed again, to establish SMC. The volumetric SMC was then obtained through multiplying the values by the bulk density.

2.5. *Pasture monitoring*

The evolution of the pasture was recorded in the 24 sampling points at each monitoring date: at the end of autumn (December 2015), at the end of winter (March 2016), and then monthly during spring (April, May, and June 2016). Multispectral, capacitance and infrared measurements were carried out previously to pasture cut.

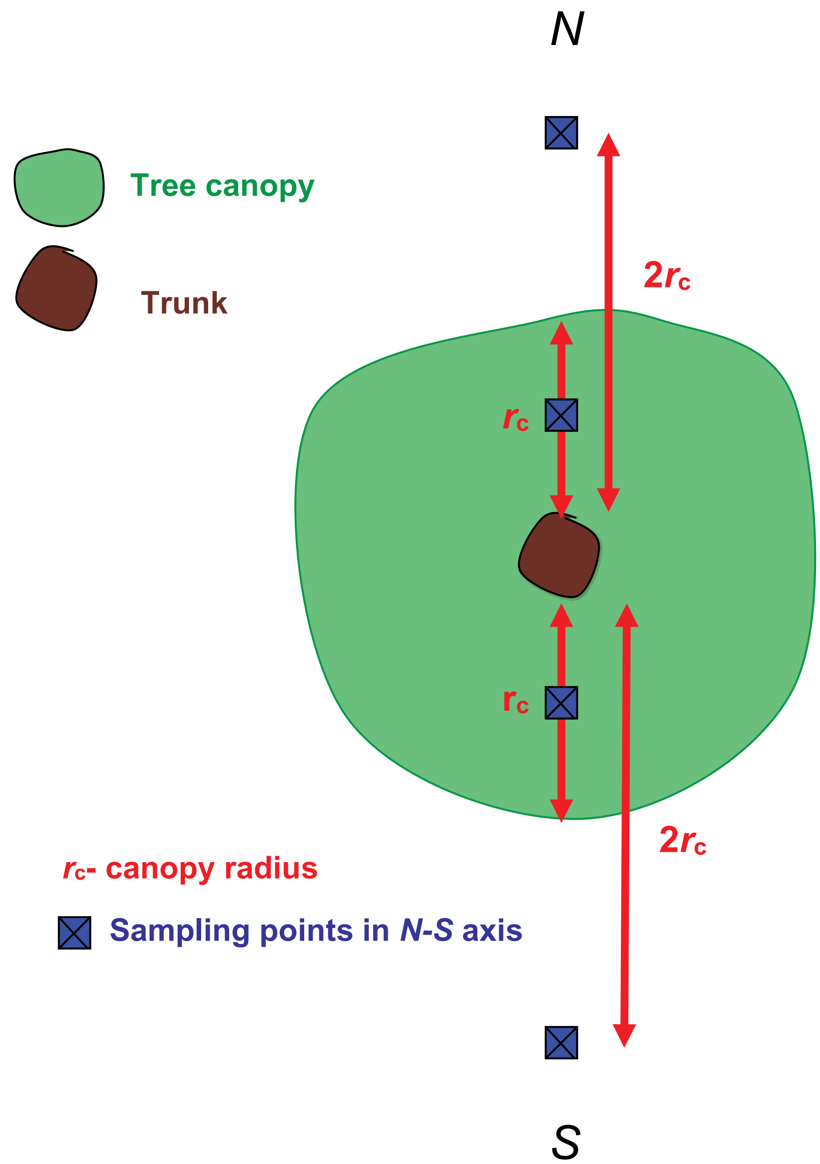

Figure 3. Schematic diagram of four sampling positions around each tree.

2.5.1. *Vegetation multispectral measurements*

The multispectral bands were measured with a commercial OptRx® AOS (Figure 4(*a*)), constructed by Ag Leader (2202 South River Side Drive Ames, Iowa 50010, USA), associated with a Trimble GNSS GeoExplorer 6000 series model 88951 with sub-meter precision (Trimble: GmbH, Am Prime Parc 11, 65479 Raunheim, Germany) and its power source (small portable battery).

The sensor, placed on a platform standing 0.7 m above the ground surface (about 0.5 m above the pasture, considering an average pasture height of 0.2 m), measures simultaneously three visible and infrared bands: (1) RED (670 nm with a bandwidth of

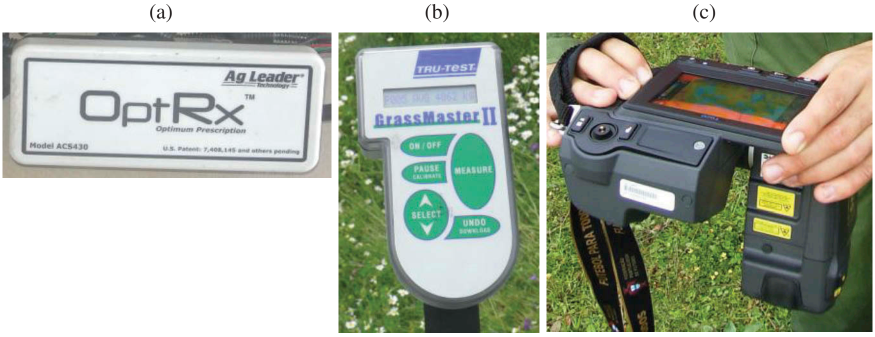

Figure 4. Active optical sensor (OptRx®) (*a*), capacitance probe (*b*), and infrared camera (*c*) used in field trials.

20 nm); (2) RED EDGE (728 nm with a bandwidth of 16 nm); and (3) NIR (775 nm with basically everything under 750 nm being filtered). With two of the previous spectral bands, NDVI vegetation index was calculated considering the following expression (Equation (1)):

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{RED}}{\mathrm{NIR} + \mathrm{RED}} \tag{1}$$

The operator stood still at the area of each geo-referenced point and performed measurements for a 2 min period. The values of NDVI were organized in a spreadsheet and associated with the coordinates of the respective sampling points to calculate the mean and standard deviation (SD) of NDVI from about 120 measurements taken at each point.

2.5.2. *Capacitance measurements*

Each measurement of capacitance with the Grassmaster probe (Figure 4(*b*)) was preceded by an air humidity-level correction. The capacitance readings (CMR) were registered after the instrument had been positioned vertically over the vegetation, some 0.2–0.3 m away from the operator's body. In each measuring area, 10 readings were carried out with the probe and averaged. Greater detail on the operation of the probe can be found in Serrano et al. (2011) and Serrano, Shahidian, and Marques Da Silva (2016b).

2.5.3. *Temperature measurements*

Infrared thermography images were obtained from each sampling point at each monitoring date (December 2015 and March, April, May, and June 2016) using an infrared camera (ThermaCAM™, FLIR systems, USA; Figure 4(*c*)). Thermal images were analysed using the 'ResearchIR® 3.0' software, and data was exported to a spreadsheet where the information was processed in order to determine the mean and SD of temperature of each infrared image.

2.5.4. *Pasture sample collection and analysis*

After sensor data acquisition, the operator placed a metallic rim with a 0.1 m^2 area on pasture. Inside each sampling point, pasture was harvested with a portable electric grass shears at 1–2 cm above ground level and stored in marked plastic bags. The collected pasture samples were then taken to the Pasture and Forage Technology Laboratory of the University of Évora, where they were weighed, dehydrated (for 72 h at 65°C), and then weighed again to establish pasture productivity in terms of green matter (kg GM ha^{-1}) and dry matter (kg DM ha^{-1}), respectively, according to standard procedures (Serrano et al. 2011).

The dehydrated samples from March, April, May, and June 2016 were analysed in order to determine the key components of pasture quality (content of ash, crude protein (CP), and neutral detergent fibre (NDF), all in % of DM) using conventional methods of wet chemistry according to the Association of Official Analytical Chemists (AOAC 2005).

In the pasture flowering period (between April and May 2016), the floristic inventory of species and families present in each of the sampling points was carried out by an expert in conservation biology. This information was then converted into percentage of sampling area coverage.

2.6. *Statistical analysis of the data*

Descriptive statistics analysis, including mean, SD, coefficient of variation (CV), and range, were determined for each data set of soil and pasture parameters.

Statistical procedures were performed using 'MSTAT-C' software with a significance level of 95% ($p < 0.05$). The statistical treatment of the results consisted of analysis of variance and simple linear regression. Least-square differences test (*Fisher's least significant difference*) was used to determine significant differences among means. Linear regression analysis was used to study the relationships between soil and pasture variables. The Pearson correlation coefficients '*r*' for the statistically significant ($p < 0.05$) regression relations were then presented.

3. Results and discussion

3.1. *Spatial variability of soil characteristics*

Table 1 summarizes the results of descriptive statistics (mean, SD, CV, and interval of variation) of soil properties in the top 0.0–0.3 m, in the set of 24 sampling points of the studied field, in October of 2015.

The average characteristics of the soil are sandy loam texture (mean clay content = 9.7% ± 2.7%); acid (mean pH = 5.4 ± 0.3); rich in potassium (mean = 269.9 ± 135.9 mg kg^{-1}); average level of organic matter (mean = 2.4% ± 0.8%), magnesium (mean = 95.6 ± 43.7 mg kg^{-1}) and phosphorus (mean = 92.6 ± 62.4 mg kg^{-1}); poor in nitrogen (mean = 0.1% ± 0.0%). According to Guevara-Escobar et al. (2007), the soils of grazed pastures tend to acidify as a consequence of leaching NO_3^-, nutrient extraction, and SOM accumulation.

The spatial CVs for some soil properties are large, especially with regard to P, Mn, K, Mg, N, and SOM (spatial CV > 30%). Others, such as clay and silt, are less variable (spatial CV between 15% and 30%). Coarse and fine sand and pH are even less variable (spatial CV of 5–6%). SMC shows variable CV, between 15% and 47%, depending on the data

Table 1. Descriptive statistics of soil properties in the set of 24 sampling points of the studied field.

Parameter	Mean ± SD	Coefficient of variation (%)	Range
Depth 0.0–0.3 m			
October 2015			
Coarse sand (%)	48.4 ± 2.6	5.3	44.0–54.8
Fine sand (%)	32.2 ± 2.0	6.3	29.4–36.7
Silt (%)	9.7 ± 2.5	26.2	0.7–13.0
Clay (%)	9.7 ± 2.7	27.4	6.7–20.5
SOM (%)	2.4 ± 0.8	33.7	1.1–4.0
pH	5.4 ± 0.3	6.0	4.9–6.2
N_t (%)	0.1 ± 0.0	35.1	0.1–0.2
P_2O_5 (mg kg^{-1})	92.9 ± 62.4	67.1	26.0–343.0
K_2O (mg kg^{-1})	269.9 ± 135.9	50.3	94.0–540.0
Mg (mg kg^{-1})	95.6.0 ± 43.7	45.7	20.0–180.0
Mn (mg kg^{-1})	14.0 ± 6.3	45.3	6.2–29.5
Depth 0.0–0.2 m			
SMC (%)			
December 2015	7.3 ± 3.4	47.0	4.3–18.7
March 2016	9.1 ± 2.8	30.7	5.4–17.7
April 2016	12.6 ± 2.4	19.1	7.2–16.9
May 2016	9.4 ± 2.3	24.9	5.4–14.9
June 2016	5.2 ± 1.5	28.8	2.2–8.1
Depth 0.2–0.4 m			
SMC (%)			
December 2015	6.8 ± 2.6	38.0	3.2–11.9
March 2016	12.9 ± 5.5	42.5	6.0–24.0
April 2016	9.8 ± 1.7	16.9	7.0–12.4
May 2016	10.0 ± 1.6	15.9	6.7–13.0
June 2016	4.2 ± 1.5	36.6	2.2–7.6

SOM: soil organic matter; SMC: soil moisture content.

and depth. Other authors have documented this soil variability in studies involving the soil–pasture–tree–animal ecosystem. Mallarino and Wittry (2004), in field tests with grazed pastures in similar soils, also found largest CV for P and lowest for pH, whereas those for K and SOM were intermediate. The results of Serrano, Shahidian, and Marques Da Silva (2013), in another *montado* ecosystem in southern region of Alentejo, show that N has the greatest CV (>80%), while SMC and P also present high values of this indicator (CV between 30% and 50%), SOM and K have intermediate values (CV < 20%), while soil clay content and pH present greater stability (CV < 10%). Bernardi et al. (2016) found higher CV in P, K, and N (>30%), intermediate (CV between 10% and 20%) in SOM, and low CV (<10%) in pH and soil clay content. The degree of variability is important because highly variable soil properties are potentially better candidates for site-specific management (Bernardi et al. 2016).

The regression analysis between the different soil parameters shows a significant correlation between the SOM and: N_t ($r = 0.959$; $p < 0.01$), K ($r = 0.772$; $p < 0.01$), Mg ($r = 0.677$; $p < 0.01$), P ($r = 0.529$; $p < 0.01$), pH ($r = 0.316$; $p < 0.05$), and Mn ($r = 0.302$; $p < 0.05$). According to Weerasekara et al. (2016), SOM an N_t are good indices of soil quality and this relation between the SOM and the different parameters may reflect the effect of the accumulation of organic residues generated by the animals in their rest zones, preferably under the trees (Serrano, Shahidian, and Marques Da Silva 2016a). According to McCormick, Jordan, and Bailey (2009), grazing animals are a remarkable source of variability of nutrients in the soil as a result of the heterogeneous deposition of excreta.

3.2. *Soil properties UTC versus OTC*

Table 2 shows the mean and SD of soil properties and probability of significant differences (p < 0.05%) between two situations: UTC and outside tree canopy (OTC). Soil under the tree canopy had significantly higher levels of organic matter (SOM), N, P, K, and Mg. No significant differences were found in texture, pH, and Mn.

In *montado* ecosystems, several authors have reported positive effects of trees on soil nutrient contents, soil water storage capacity, and pasture production in terms of yield, quality, diversity, and seasonality, essential factors for the sustainability of this ecosystem (Marcos et al. 2007). The balance of the interaction between trees and pasture is positive in terms of soil fertility and microclimate, negative in terms of competition for light, water and nutrients, and uncertain in terms of pests and diseases (Marcos et al. 2007).

Limited studies have described the physical properties of soils in silvo-pastoral systems, and none have shown evidence of changes in soil physical properties. As in this study, Benavides, Douglas, and Osoro (2009) found similar soil texture and physical properties for open pasture and under trees.

The positive effect of trees in SOM, N, P, and K was also verified by Marcos et al. (2007). Benavides, Douglas, and Osoro (2009) found relatively high concentrations of K and Mg beneath trees and justified these as result of nutrient absorption by the tree roots from deeper layers of soil and their incorporation into the nutrient cycling, returning them to the soil surface via falling leaves. These improve soil quality by enhancing SOM and N contents, contributing to atmospheric carbon (C) sequestration in the ecosystem due to their long-term storage of high amounts of C in biomass, especially in the deep root systems (Benavides, Douglas, and Osoro 2009; Gómez-Rey, Garcês, and Madeira 2012). However, the improvement of soil N status may cause soil acidification by excessive N mineralization and nitrate leaching during rainy season (Gómez-Rey, Garcês, and Madeira 2012).

The positive effect of trees on soil fertility has also been reported for other silvo-pastoral systems (Jackson and Ash 1998; Marcos et al. 2007; Benavides, Douglas, and Osoro 2009; Howlett et al. 2011). According to Gómez-Rey, Garcês, and Madeira (2012), scattered trees lead to a great spatial variation of soil conditions, creating islands of enhanced quality and improving soil physical properties and biological activity, and can affect productivity in understory vegetation compared with surrounding open areas. The increase of organic (litter and dead roots) and mineral components in soils located UTC is due partly to leaf shedding and other litter fall but also to animal excretion because grazing animals are always attracted to trees in grassland in response to the environmental conditions (Somarriba 1988).

Table 2 also shows significant differences in SMC in the two depths measured (0.0–0.2 m and 0.2–0.4 m) and throughout practically the entire vegetative cycle of the plants. Figure 5 shows the behaviour of SMC between December 2015 and June 2016 in the two depths tested.

The relationship between rainfall, SMC, water uptake by plants, and evapotranspiration is complex and varies seasonally (Benavides, Douglas, and Osoro 2009). At both depths, SMC tends to be higher in OTC zone in winter and early spring, but when temperature increases greatly and precipitation decreases (late spring), the situation reverses (larger SMC in UTC zone), a process that occurs earlier within the topsoil (0.0–

Table 2. Mean and standard deviation of soil parameters and probability of significant differences between under tree canopy (UTC) and outside tree canopy (OTC).

Parameter	UTC	OTC	Probability
Depth 0.0–0.3 m			
Coarse sand (%)	49.0 ± 2.4	47.8 ± 2.6	ns
Fine sand (%)	31.8 ± 1.5	32.6 ± 2.4	ns
Silt (%)	9.8 ± 1.5	9.5 ± 3.3	ns
Clay (%)	9.4 ± 1.0	10.1 ± 3.7	ns
SOM (%)	3.1 ± 0.5	1.7 ± 0.4	0.0000
pH	5.4 ± 0.4	5.3 ± 0.2	ns
N_t (%)	0.2 ± 0.0	0.1 ± 0.0	0.0001
P_2O_5 (mg kg^{-1})	117.7 ± 77.0	68.2 ± 29.5	0.0471
K_2O (mg kg^{-1})	359.3 ± 112.8	180.5 ± 91.9	0.0012
Mg (mg kg^{-1})	115.0 ± 38.8	76.3 ± 40.9	0.0493
Mn (mg kg^{-1})	16.2 ± 7.0	11.8 ± 4.9	ns
Depth 0.0–0.2 m			
SMC (%)			
December 2015	5.3 ± 0.9	8.8 ± 3.9	0.0000
March 2016	8.9 ± 2.7	9.4 ± 3.0	ns
April 2016	13.5 ± 2.3	11.6 ± 2.1	0.0000
May 2016	10.8 ± 2.2	8.0 ± 1.5	0.0001
June 2016	5.8 ± 1.1	4.6 ± 1.6	0.0000
Depth 0.2–0.4 m			
SMC (%)			
December 2015	5.3 ± 1.9	8.2 ± 2.4	0.0000
March 2016	12.1 ± 6.3	13.6 ± 4.7	0.0008
April 2016	9.0 ± 1.5	10.6 ± 1.4	0.0000
May 2016	10.5 ± 1.0	9.6 ± 2.0	0.0005
June 2016	5.3 ± 1.4	3.2 ± 0.9	0.0000

SOM: soil organic matter; SMC: soil moisture content; Probability: probability of significant differences ($p < 0.05\%$); ns: correlation not significant.

0.2 m depth). This behaviour reflects the effect of the canopy: when it rains, it acts as a barrier to the penetration of rain in UTC zone; when the temperature begins to increase (during spring growing period), the canopy acts as a protection and shade for the pasture, thus decreasing the evapotranspiration of the plants and helping to maintain higher moisture contents in UTC zone (Guevara-Escobar et al. 2007; Benavides, Douglas, and Osoro 2009).

In summary, the negative effects of trees (competition for resources) in terms of transpiration and water interception can be compensated by positive effects in terms of a microclimate that improves soil fertility, soil water-holding capacity, and infiltration rate (facilitation) (Marcos et al. 2007). This apparent limited competition between trees and pasture for soil, water, and nutrients could be explained by the spatial separation of the root system of crops and trees in the *montado*, with a much deeper root system of oak with respect to herbaceous vegetation (Guevara-Escobar et al. 2007; Marcos et al. 2007). The advantage of mixed species crops would be in their ability to have complementary rooting systems that can fully occupy the soil and utilize all soil moisture. For the system to operate at maximum efficiency over time, the roots must explore to a depth and breadth that will remove as much water as can be recharged during the winter period, thus minimizing drainage losses from the profile and maximizing the plant available water content (Pollock, Mead, and McKenzie 2009).

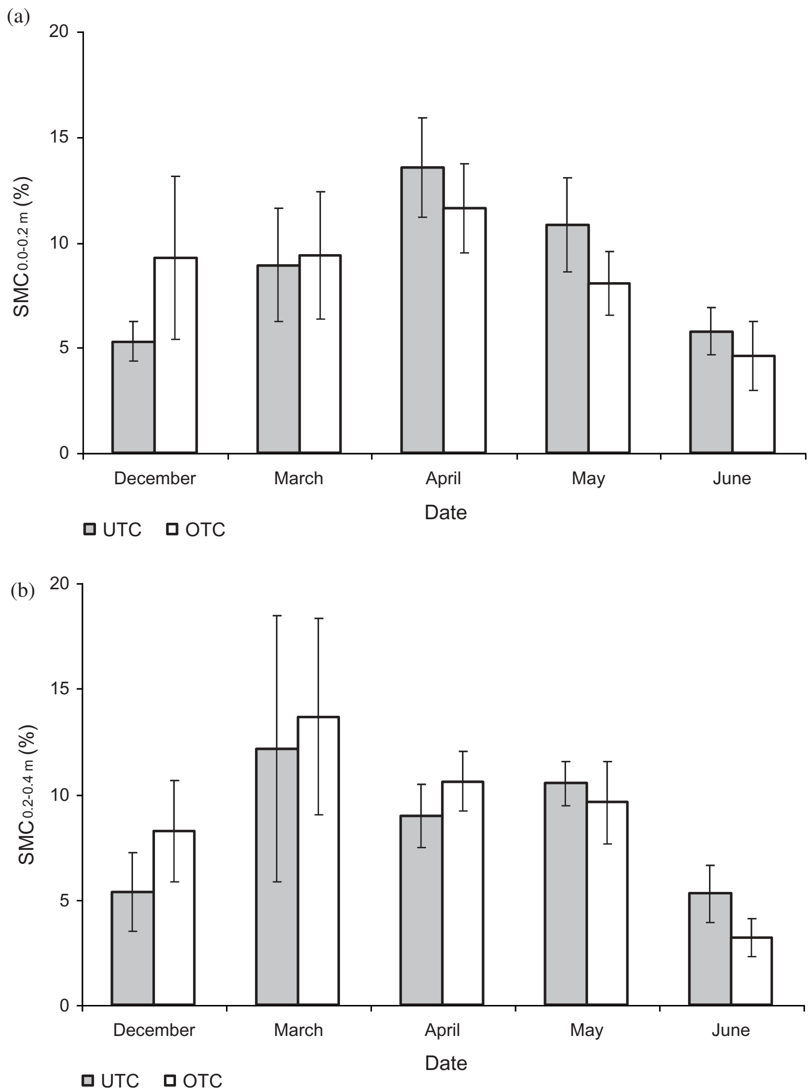

Figure 5. Soil moisture content (SMC) in both study situations (under tree canopy, UTC, and outside tree canopy, OTC): (*a*) soil depth 0.0–0.2_m; (*b*) soil depth 0.2–0.4_m.

3.3. *Spatial variability of pasture characteristics*

Information on pasture production and quality is therefore a useful tool in predicting and preparing balanced diets, which are the basis for making timely and effective decisions, and that achieve optimum use of forage resources in a pastoral system (Demanet et al. 2015).

Table 3 shows the results of descriptive statistics (mean, SD, CV, and interval of variation) of pasture parameters, in the set of 24 sampling points of the studied field, for each sampling date.

These results show the typical evolution of productivity and quality parameters of dryland Mediterranean pastures throughout their vegetative cycle: yield increase (GM

Table 3. Descriptive statistics of pasture parameters in the set of 24 sampling points of the studied field for each sampling date.

Parameter	Mean ± SD	Coefficient of variation (%)	Range
GM (kg ha^{-1})			
December 2015	2840 ± 3075	108.3	0–9280
March 2016	11,426 ± 6328	55.4	1920–29,700
April 2016	16,903 ± 8264	48.9	6170–37,530
May 2016	24,148 ± 13,584	56.3	7010–52,290
June 2016	11,003 ± 6483	58.9	1440–25,920
DM (kg ha^{-1})			
December 2015	431 ± 448	103.9	0–1190
March 2016	1550 ± 679	43.8	350–2720
April 2016	2395 ± 1091	45.5	1030–4520
May 2016	3166 ± 1009	31.9	1400–5840
June 2016	4277 ± 2419	56.6	610–9820
Ash (%)			
March 2016	12.0 ± 3.5	29.4	9.1–26.0
April 2016	9.8 ± 1.4	14.2	7.6–12.9
May 2016	8.4 ± 1.4	17.1	6.2–12.1
June 2016	8.6 ± 3.2	37.2	5.8–20.7
CP (%)			
March 2016	13.8 ± 2.8	20.6	8.7–19.8
April 2016	11.9 ± 3.5	29.2	6.5–22.2
May 2016	10.3 ± 3.0	29.5	5.1–17.5
June 2016	7.6 ± 2.5	32.6	4.1–14.5
NDF (%)			
March 2016	38.1 ± 5.3	13.8	29.5–50.2
April 2016	52.9 ± 5.9	11.1	43.1–64.3
May 2016	64.0 ± 4.4	6.8	53.8–74.1
June 2016	66.8 ± 6.1	9.1	55.3–78.3

GM: green matter; DM: dry matter; CP: crude protein; NDF: neutral detergent fibre.

and DM) from winter to late spring, and an inverse pattern of pasture quality (reduction of nutritional value, total ashes and CP, and a continuous increase of NDF with the approach of summer). The variability measured by CV is high, especially in productivity parameters (30–60%), being lower in the case of total ashes (15–37%), CP (20–33%), and NDF (7–14%).

3.4. *Pasture parameters UTC* versus *OTC*

The quantity and quality of pastures beneath trees are useful indicators of the sustainability of farms because they significantly influence both economic farm output and resource status (Benavides, Douglas, and Osoro 2009). Tree shade improves the microclimate of the crop, with daily and seasonal air and soil temperature variation decreasing with the proximity of the trees. This should have a direct consequence on the pasture phenology and productivity (Marcos et al. 2007).

Table 4 shows the mean and SD of pasture parameters and probability of significant differences ($p < 0.05\%$) between UTC and OTC, respectively. Significant differences were found between March and June favouring the pasture productivity (GM and DM) outside the tree canopy. During winter, which coincides with the period of least pasture growth, no significant differences in pasture accumulation were found between under trees and open pasture, which is in line with the study of Benavides, Douglas, and Osoro (2009).

Table 4. Mean and standard deviation of pasture parameters and probability of significant differences between under tree canopy (UTC) and outside tree canopy (OTC).

Parameter	UTC	OTC	Probability
GM (kg ha^{-1})			
December 2015	2005 ± 2352	3675 ± 3565	ns
March 2016	8747 ± 4210	14,106 ± 7095	0.0307
April 2016	12,403 ± 3910	21,403 ± 9128	0.0002
May 2016	15,148 ± 5856	33,149 ± 13,221	0.0000
June 2016	6017 ± 3122	15,990 ± 4888	0.0000
DM (kg ha^{-1})			
December 2015	437 ± 483	425 ± 425	ns
March 2016	1232 ± 554	1868 ± 661	0.0162
April 2016	1804 ± 546	2987 ± 1195	0.0001
May 2016	2751 ± 910	3582 ± 961	0.0499
June 2016	2363 ± 1017	6191 ± 1791	0.0000
Ash (%)			
March 2016	13.9 ± 4.3	10.2 ± 0.7	0.0049
April 2016	10.5 ± 1.4	9.1 ± 1.0	0.0048
May 2016	8.8 ± 1.5	8.0 ± 1.3	ns
June 2016	9.7 ± 4.2	7.4 ± 1.1	ns
CP (%)			
March 2016	14.8 ± 3.5	12.8 ± 1.6	0.0300
April 2016	13.4 ± 4.2	10.5 ± 1.8	0.0375
May 2016	12.0 ± 2.9	8.6 ± 2.2	0.0009
June 2016	8.5 ± 3.1	6.7 ± 1.3	ns
NDF (%)			
March 2016	40.0 ± 5.8	36.2 ± 4.1	0.0487
April 2016	55.4 ± 5.3	50. 5 ± 5.5	0.0084
May 2016	63.6 ± 5.6	64.5 ± 2.9	ns
June 2016	68.5 ± 6.8	65.1 ± 5.0	ns

GM: green matter; DM: dry matter; CP: crude protein; NDF: neutral detergent fibre; Probability: probability of significant differences ($p < 0.05\%$); ns: correlation not significant.

In addition to changes in the productivity, pastures in Mediterranean areas also exhibit changes in the quality of the produced forage, changes which are related to the growth stage, nutrition, frequency, and intensity of pasture use throughout the year and season (Demanet et al. 2015). In this study, significant differences were found in pasture quality between March and April (ash and NDF) or between March and May (CP), with the tree canopy favourably influencing the pasture quality.

Figures 6 and 7 show the evolution of the pasture productivity parameters (GM and DM) and pasture quality parameters (ash, CP, and NDF), respectively, UTC and OTC, respectively, throughout the vegetative cycle.

The effects of trees on the pasture understory are a direct consequence of the extent to which they modify the microclimate and soil properties (Guevara-Escobar et al. 2007; Benavides, Douglas, and Osoro 2009). Pasture production UTC in silvo-pastoral systems normally depends on the degree of competition between trees and pasture for resources (light, moisture, and nutrients) (Hussain et al. 2009) and does not generally reflect the soil fertility gradient (Jackson and Ash 1998). Of all the competitive constraints, the level of shade and its duration (and, consequently, the interception of light) are among the most significant factors reported as responsible for the greatest negative effect on pasture production under trees (Somarriba 1988; Guevara-Escobar et al. 2007; Benavides, Douglas, and Osoro 2009; Hussain et al. 2009), given that holm oak is an evergreen tree with a dense canopy (Marcos et al. 2007). Hussain et al. (2009) showed that shade influenced pasture growth more than soil moisture in spring. This negative

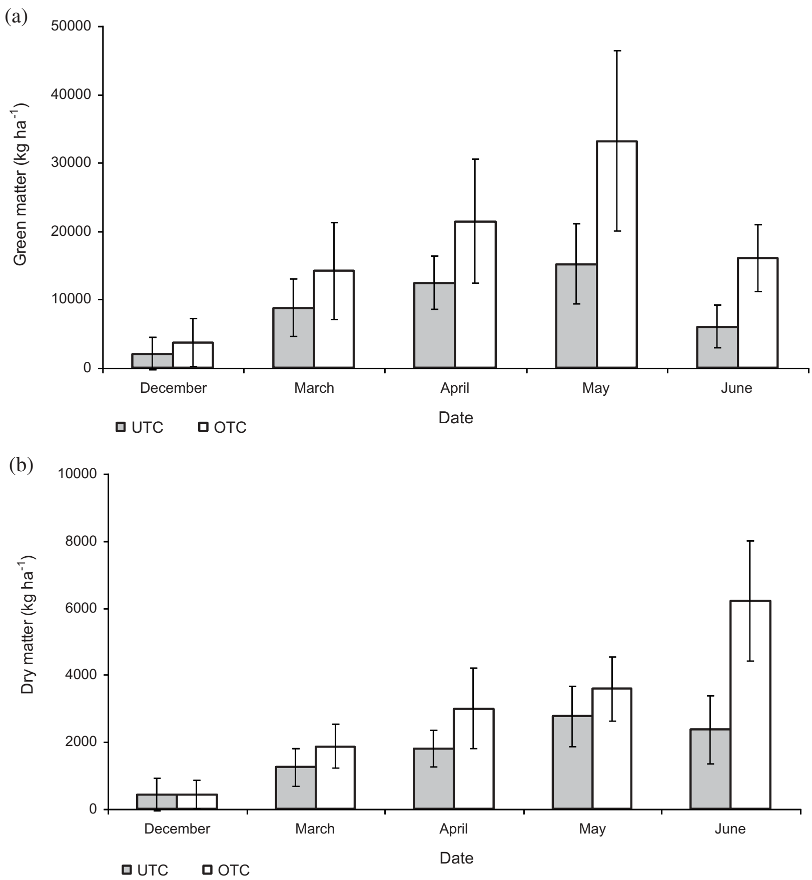

Figure 6. Evolution of the pasture productivity parameters: (*a*) green matter (GM) and (*b*) dry matter (DM), under tree canopy and outside tree canopy (UTC and OTC, respectively), throughout the vegetative cycle.

relationship between pasture productivity and light transmission to the understory is a consequence of the reduction of solar radiation and thus photosynthesis (Bird 1998) and has been recorded in different studies (Guevara-Escobar et al. 2007; Benavides, Douglas, and Osoro 2009). However, according to Marcos et al. (2007) the positive effect of trees on soil fertility does not mean that trees do not compete with pasture for nutrients and belowground competition could sometimes be more important than light interception. Hussain et al. (2009) considered that other factors, such as frequency of sheep grazing and difference in composition of pasture species, are also responsible for the lower pasture production under trees relatively to open pastures. Tree litter, mainly leaves, overlaying the pasture smothers it in places, and the subsequent incorporation and decomposition of the litter into the topsoil can immobilize nitrogen and also contribute to reduce pasture growth during winter and spring (Guevara-Escobar et al. 2007). Also deleterious effects of substances (allelopathic agents) exuded from leaves or roots may retard plant growth in the vicinity of the trees (Bird 1998). Gómez-Rey, Garcês, and Madeira (2012) reported that the soil UTC presents higher density and lower porosity as a result of the greater compaction caused by the animals. This situation may be

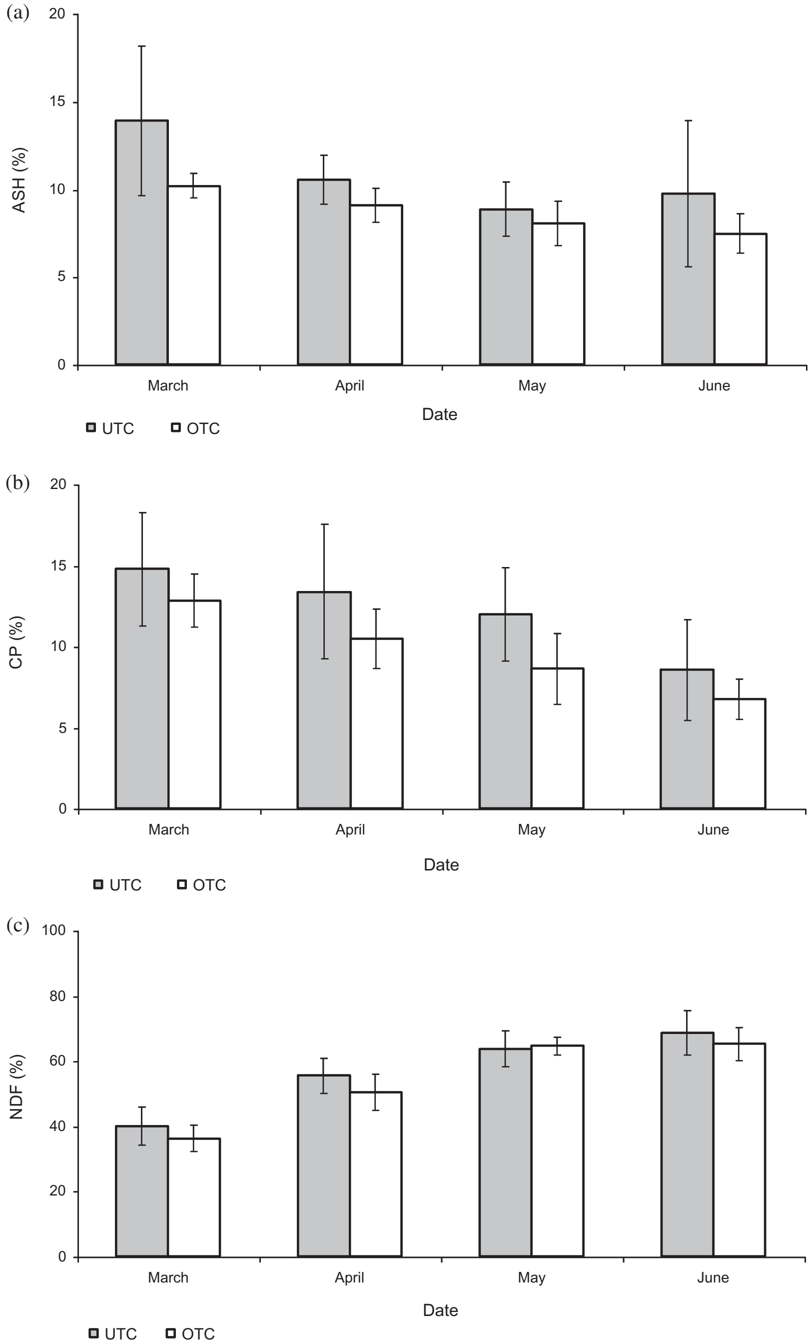

Figure 7. Evolution of the pasture quality parameters: (*a*) ash, (*b*) crude protein (CP), and (*c*) neutral detergent fibre (NDF), under tree canopy and outside tree canopy (UTC and OTC, respectively), throughout the vegetative cycle.

responsible for a greater difficulty in root development, which, together with the lower incidence of light, may justify the lesser development of the plants. On the other hand, Marcos et al. (2007) verified detrimental effect of the tree on pasture production when belowground resources are less limiting, in fertilized plots (e.g. beneath the canopy, tree shade can limit response to fertilization).

On the other hand, the nutrient cycling and the improved soil fertility have been interpreted as the cause of the increased pasture quality in the vicinity of the trees (Bird 1998; Jackson and Ash 1998; Marcos et al. 2007). Modifications to botanical composition in the presence of trees are caused by changes in the microclimate, soil properties, and livestock grazing (Benavides, Douglas, and Osoro 2009; Hussain et al. 2009). According to Hussain et al. (2009), livestock grazing of pasture can have an important influence on sward composition, sward quality, and herbage production. Benavides, Douglas, and Osoro (2009) considered that lack of light, cool temperatures, and low SMC reduce the growth rate of pasture species, and consequently delay their life cycle. Changes in botanical composition and species phenology affect the nutritional value of pasture under trees (Guevara-Escobar et al. 2007). Higher CP content (% DM) has been found in swards under trees (Pullanagari et al. 2013), which can be attributed to a reduction in light intercepted by pasture (Kallenbach, Kerley, and Bishop-Hurley 2006). This, in turn, causes a decrease in photosynthates, with a consequent rise in N concentration, or an increase in SOM mineralization that provides more N for grass uptake (Sousa et al. 2010; Gómez-Rey, Garcês, and Madeira 2012; Pullanagari et al. 2013). The protein content of the pasture is dependent on genetic and environmental conditions while the efficiency of soil nitrogen uptake depends on the plant species, SOM, SMC, and temperature (Demanet et al. 2015). Sousa et al. (2010) attributed the higher quality of pasture under trees in terms of CP levels to the delay in the ontogenic development of shady plants (less advanced state of vegetative development), keeping them younger physiologically and allowing the maintenance of higher metabolic levels for a longer period of time. Furthermore, the fibre content (NDF, % DM), another indicator of forage quality that is inversely related to digestibility and defines the consumption capacity of grazing animals (Demanet et al. 2015), usually reaches similar levels in open pasture as those in pasture beneath trees (Kallenbach, Kerley, and Bishop-Hurley 2006; Benavides, Douglas, and Osoro 2009; Sousa et al. 2010; Pullanagari et al. 2013), which is in agreement with the results obtained in this study. According to Demanet et al. (2015), the fibre content is dependent on the growth stage and of the proportion of plant components, species, and cultivars (Demanet et al. 2015).

Figure 8 shows the predominant pasture species UTC and OTC in spring 2015.

The 10 most frequent botanical species present in the set of 24 sampling points were *Erodium moschatum* family Geraniaceae – others (UTC = 40.2%; OTC = 15.6%); *Chamaemelum mixtum* family Asteraceae – composites (UTC = 6.9%; OTC = 17.0%); *Leontodon taraxacoides* family Asteraceae – composites (UTC = 6.2%; OTC = 12.3%); *Gramínea* sp. family Poaceae – grasses (UTC = 12.9%; OTC = 1.6%); *Vulpia* sp. family Poaceae – grasses (UTC = 11.1%; OTC = 3.3%); *Plantago coronopus* family Plantaginaceae – others (UTC = 1.8%; OTC = 8.5%); *Trifolium resupinatum* family Fabaceae – legumes (UTC = 0.5%; OTC = 9.6%); *Diplotaxis catholica* family Brassicaceae – others (UTC = 0.6%; OTC = 6.3%); *Rumex bucephalophorus* family Polygonaceae – others (UTC = 0.2%; OTC = 5.9%); and *Trifolium repens* family Fabaceae – legumes (UTC = 1.4%; OTC = 4.2%). Taken together, these 10 species represent 81.8% of the total cover UTC and 84.3% OTC. This distribution of botanical species presented significant differences ($p < 0.05\%$) between UTC and OTC. According to Benavides, Douglas, and Osoro (2009), the botanical

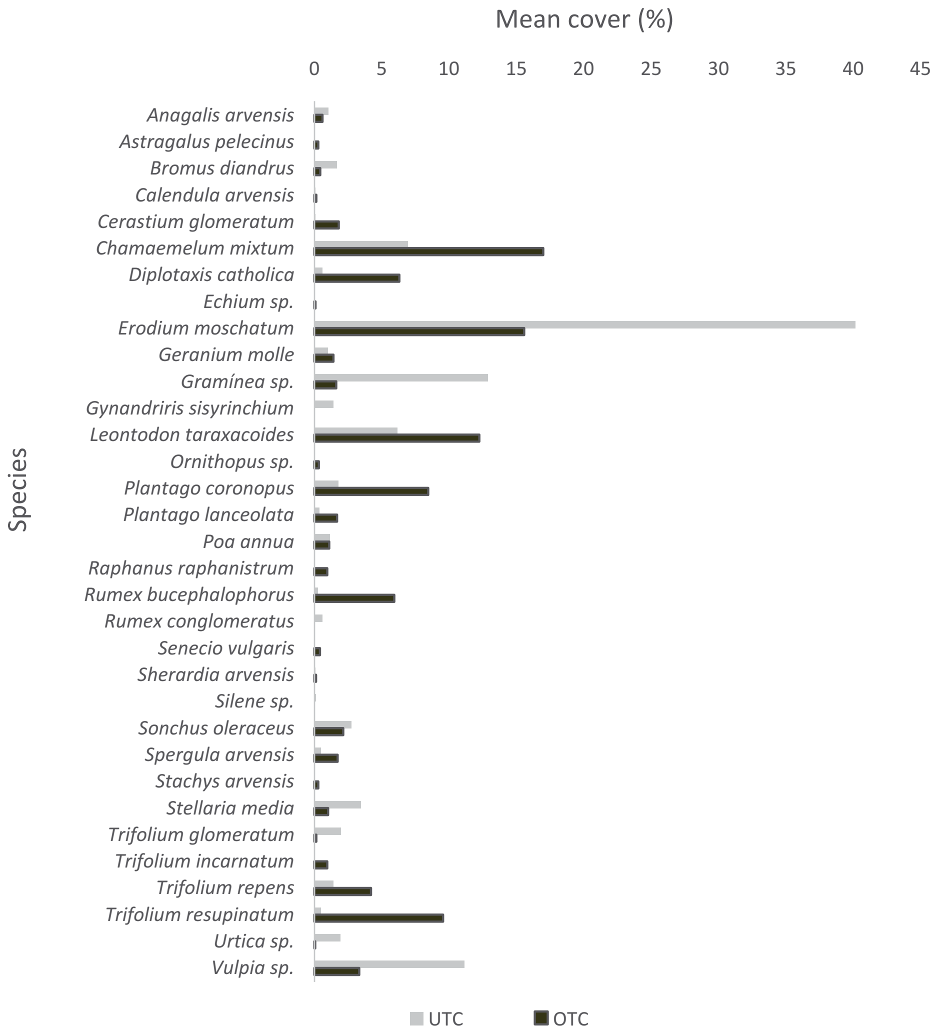

Figure 8. Predominant pasture species under tree canopy and outside tree canopy (UTC and OTC, respectively) in spring 2016.

composition of pasture beneath trees generally deteriorates over time because there is a decline in legume contents and an increase in the contents of litter and dead matter. The overall content of grasses increases under trees, likely related to their shade tolerance, tillering ability, phenological development, and growth in winter and spring.

3.5. *Spatial variability of parameters measured by sensors*

Table 5 presents the results of descriptive statistics (mean, SD, CV, and interval of variation) of sensor parameters in the set of 24 sampling points of the studied field in sampling dates.

Figure 9 shows the pattern of NDVI, CMR, and temperature of pasture between December of 2015 and June of 2016 UTC and OTC.

On average, the tendency of NDVI is to decrease throughout the vegetative cycle of the pasture, from December to June, which reflects the corresponding decrease in the

Table 5. Descriptive statistics of sensor parameters in the set of 24 sampling points of the studied field in sampling dates.

Parameter	Mean ± SD	Coefficient of variation (%)	Range
NDVI			
December 2015	0.721 ± 0.131	18.1	0.356–0.864
March 2016	0.780 ± 0.063	8.1	0.625–0.849
April 2016	0.732 ± 0.065	8.9	0.621–0.843
May 2016	0.644 ± 0.063	9.8	0.524–0.757
June 2016	0.346 ± 0.074	21.3	0.204–0.506
CMR			
December 2015	2717 ± 2103	77.4	0–6321
March 2016	6692 ± 1879	26.9	3453–10,731
April 2016	8564 ± 2101	24.5	4760–12,153
May 2016	11,296 ± 3872	34.3	4583–17,889
June 2016	5735 ± 1953	34.1	3400–10,861
T (°C)			
December 2015	10.0 ± 1.2	11.6	8.3–12.8
March 2016	10.9 ± 1.0	9.3	9.2–13.3
April 2016	14.0 ± 1.7	12.2	11.5–17.7
May 2016	15.3 ± 1.5	9.5	13.1–19.8
June 2016	16.1 ± 1.8	11.0	11.4–19.4

NDVI: normalized difference vegetation index; CMR: corrected meter reading of capacitance; *T*: temperature (infrared).

vegetative vigour of the pasture (Gitelson 2004; Serrano, Shahidian, and Marques Da Silva 2016a). In this study, the pattern was similar UTC and OTC.

On the other hand, CMR increases from December to May, decreasing in June, with significantly higher values OTC relatively to UTC, a pattern similar to the evolution of pasture productivity, expressed in terms of GM (see Figure 6).

Pasture temperature increases from December to June, which in the first analysis corresponds to the normal evolution of the air temperature. The effect of tree canopy shade resulted in lower pasture temperature, a factor that may be decisive for lower pasture productivity (Benavides, Douglas, and Osoro 2009).

3.6. *Parameters measured by sensors UTC versus OTC*

Table 6 shows the mean and SD of sensor parameters and probability of significant differences (p < 0.05%) between UTC and OTC, respectively. Significant differences were found in the NDVI only in the end of autumn (December) and in the end of winter (March), with higher values outside the tree canopy. During the spring (March, April, and June), no significant differences were found in NDVI between UTC and OTC.

Regarding the capacitance, also higher values were measured outside the tree canopy, with significant differences in the end of winter (March) and during the spring (March, April, May, and June).

As expected due to increased sun exposure, temperatures were significantly higher OTC between March and May; however, there were no significant differences in June. A possible explanation for these results might reside in the existence of clouds in the early hours of the day when the measurements were mad (7:30 to 9:00 a.m.) or the dew effect, which reduces the temperature of the grass during the early morning hours.

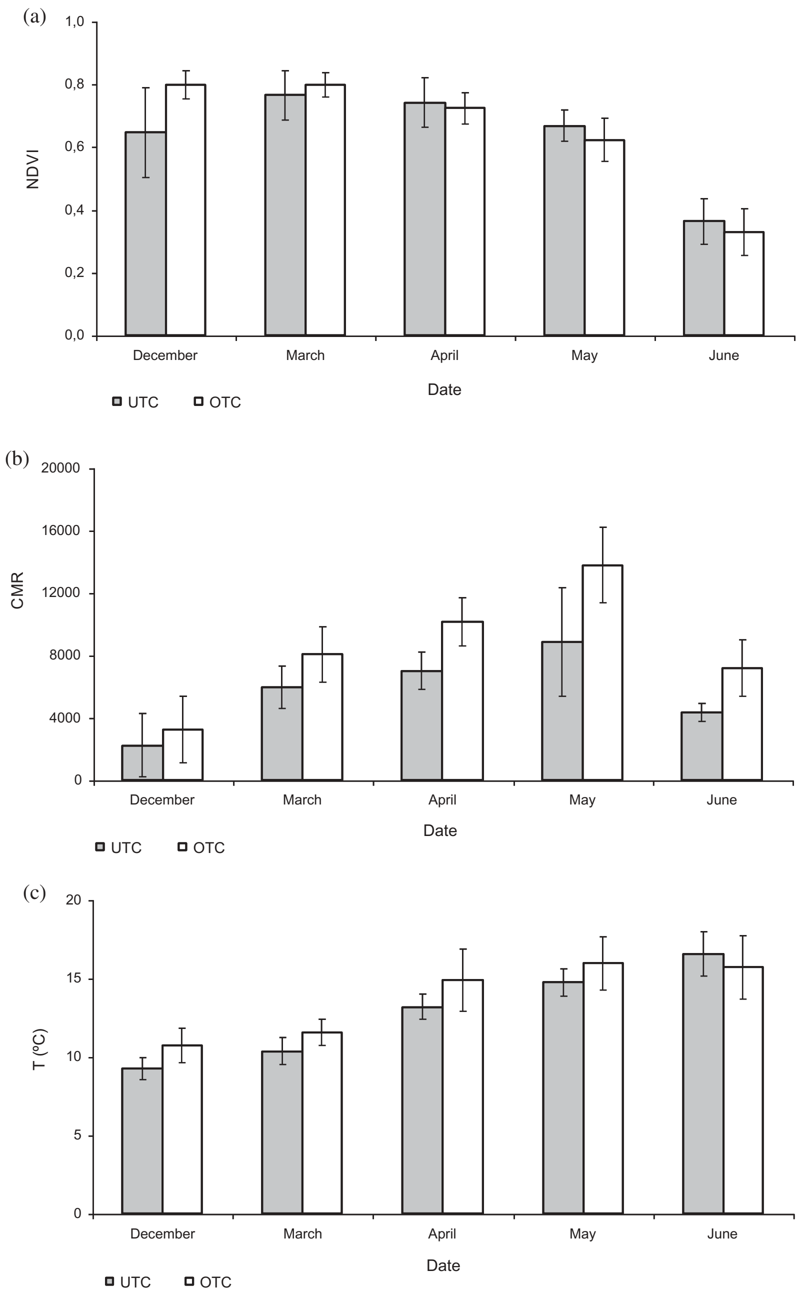

Figure 9. Evolution of the sensor parameters: (*a*) NDVI, (*b*) CMR, and (*c*) temperature (*T*), under tree canopy and outside tree canopy (UTC and OTC, respectively), throughout the vegetative cycle.

3.7. *Correlation between pasture and sensor parameters*

The conventional methods to determine key components of pasture productivity and quality are time consuming and expensive (Pullanagari et al. 2013), hence the interest in evaluating faster and cost-effective tools. Nonetheless, there are no published works

Table 6. Mean and standard deviation of sensor parameters and probability of significant differences between under tree canopy (UTC) and outside tree canopy (OTC).

Parameter	UTC	OTC	Probability
NDVI			
December 2015	0.645 ± 0.144	0.798 ± 0.046	0.0011
March 2016	0.764 ± 0.079	0.796 ± 0.039	0.0490
April 2016	0.741 ± 0.078	0.723 ± 0.050	ns
May 2016	0.667 ± 0.051	0.622 ± 0.069	ns
June 2016	0.362 ± 0.072	0.329 ± 0.075	ns
CMR			
December 2015	2222 ± 2027	3213 ± 2146	ns
March 2016	5944 ± 1367	8039 ± 1765	0.0026
April 2016	6994 ± 1199	10,134 ± 1553	0.0000
May 2016	5818 ± 3507	9176 ± 2420	0.0001
June 2016	4322 ± 568	7148 ± 1817	0.0000
T (°C)			
December 2015	9.2 ± 0.7	10.7 ± 1.1	0.0000
March 2016	10.3 ± 0.9	11.5 ± 0.8	0.0011
April 2016	13.2 ± 0.8	14.9 ± 2.0	0.0108
May 2016	14.7 ± 0.9	15.9 ± 1.7	0.0165
June 2016	16.6 ± 1.4	15.7 ± 2.0	ns

NDVI: normalized difference vegetation index; CMR: corrected meter reading of capacitance; *T*: temperature (infrared); Probability: probability of significant differences ($p < 0.05\%$); ns: correlation not significant.

that provide a direct comparison of the capacitance probe and optical sensor in the monitoring of pasture productivity, which makes it difficult to provide background literature for this discussion, but increases the relevance of this study.

Table 7 presents the correlation coefficients between parameters obtained by multiple sensors and pasture parameters using the set of 24 sampling points (UTC and OTC).

The best and more consistent correlations were obtained between CMR and pasture productivity (GM and DM), which were significant throughout the entire vegetative cycle, at all moments of evaluation (between December 2015 and June 2016, with correlation coefficients between 0.606 and 0.818, $p < 0.01$). These results confirm the practical interest of the Grassmaster II probe as a fast method of estimating the productivity of the Mediterranean pastures in Southern Portugal and are in line with the studies of Serrano et al. (2011) and Serrano, Shahidian, and Marques Da Silva (2016a, 2016b).

Regarding NDVI, the work of Serrano, Shahidian, and Marques Da Silva (2016a) in natural pastures in the same region of Portugal showed that the OptRx® sensor measures higher values of NDVI in areas with higher concentration of GM and DM, what is directly related to higher density of photosynthetically active vegetation (Dusseux et al. 2015). However, in this study, correlations of NDVI with pasture productivity (GM and DM) were only relevant in December 2015 (0.609 and 0.522, respectively; $p < 0.01$). The great heterogeneity of productivity in the two situations under study (UTC and OTC; Table 4) can help to justify these results. On the other hand, after which the maturation of the pasture leads to a decrease in the chlorophyll content, and thus a decrease in NDVI, but not of total biomass, which continues to increase with the development of the plants until the end of the season, in June. Another important aspect is that the correlations were weaker or even not significant when productivity increased greatly from the beginning of spring. According to Schaefer and Lamb (2016), there may be a problem of saturation at top-end biomass levels. Trotter et al. (2010) referenced the

Table 7. Correlation coefficients (*r*) between parameters obtained by multiple sensors and pasture parameters.

Parameter	GM (kg ha^{-1})	DM (kg ha^{-1})	PMC (%)	ASH (%)	CP (%)	NDF (%)
NDVI						
December 2015	0.609**	0.522**	0.525**			
March 2016	0.399*	0.217*	0.588**	0.208*	0.507**	ns
April 2016	ns	−0.230*	0.474*	0.548**	0.527**	ns
May 2016	ns	−0.416*	−0.227*	0.294*	0.587**	ns
June 2016	ns	ns	0.179*	0.187*	ns	ns
CMR						
December 2015	0.786**	0.737**	0.249*			
March 2016	0.729**	0.738**	0.419*	ns	0.285*	ns
April 2016	0.818**	0.794**	0.395*	−0.282*	−0.291*	ns
May 2016	0.606**	0.689**	0.486*	−0.307*	−0.472*	ns
June 2016	0.658**	0.626**	0.260*	−0.346*	−0.321*	ns
T (°C)						
December 2015	ns	ns	0.572**			
March 2016	0.259*	0.396*	ns	−0.472*	−0.445*	−0.247*
April 2016	0.258*	0.385*	−0.246*	-0.522**	−0.496*	ns
May 2016	ns	ns	ns	ns	−0.212*	ns
June 2016	−0.245*	−0.222*	ns	ns	ns	ns

GM: green matter; DM: dry matter; PMC: pasture moisture content; CP: crude protein; NDF: neutral detergent fibre; NDVI: normalized difference vegetation index; CMR: corrected meter readings of capacitance; *T*: temperature (infrared); ns: correlation not significant.
*Correlation is significant at the 0.05 level.
**Correlation is significant at the 0.01 level.

saturation of surface reflectance index at around 4000–5000 kg GM ha^{-1} for their tall fescue (*Festuca arundinacea* var. Fletcher) pasture. Schaefer and Lamb (2016) also refer the spectral reflectance indices used to infer biomass that seek to address the non-linearity in the optical response of sensors, especially the impending saturation at high leaf area index. The biomass value at which saturation occurs is critically dependent on the species, morphology, and chlorophyll concentration in the leaves. Pastures have greater diversity as spatial and temporal heterogeneity result from a number of confounding factors, including diverse species, morphology and interactions between the grazing animals, the natural environmental conditions, and management practice (Pullanagari et al. 2013). Ultimately, and irrespective of species or environmental conditions, the use of optical reflectance measurements alone to infer pasture biomass is challenging in pastures with high leaf area index (Schaefer and Lamb 2016).

Correlations with pasture quality (ash, CP, and NDF) were weak for all sensors practically throughout the entire vegetative cycle of the pasture. However, in March, April, and May the NDVI showed relatively strong and significant correlations (*r* between 0.507 and 0.587) with CP, which may be justified by the operational principle of the sensor. The OptRx® sensor detects vegetation with higher levels of chlorophyll (photosynthetically active vegetation), and this will be correlated with CP levels. Pullanagari et al. (2013) also found satisfactory relationships between spectral measurements and pasture quality parameters such as CP content that can be attributed to absorbance of visible radiance by chlorophyll, which is abundant in green vegetation. According to Albayrak (2008), canopy reflectance can be used for non-destructive prediction of forage quality variables in pastures. The results of this work can be an important starting point for studies that allow the evaluation and calibration of the optical sensor for this concrete application of pasture quality assessment in different types of biodiverse pastures. This is a key factor for the management of animal grazing intensity and calculation of food supplementation needs throughout the vegetative cycle of the pasture. According to Rascher and Pieruschka (2008), optical remote-sensing techniques have the potential to detect physiological and biochemical changes in plant ecosystems, and non-invasive detection of changes in photosynthetic energy conversion, which may be of great potential for managing agricultural production in a future bio-based economy.

Correlations of pasture parameters (yield and quality) were also established with the temperature measured by the infrared camera, but no strong correlations were found. The spatial variation of the pasture surface temperature is influenced by the sun exposure, which in the *montado* is greatly influenced by the proximity of the trees and by the effect of microclimate under the canopy (Marcos et al. 2007). Rapid measurement of temperature with the infrared camera may therefore be an indicator of the differential conditions of pasture development under or outside the canopy (Guevara-Escobar et al. 2007), but a cause-and-effect relationship cannot be expected to reveal significant correlations since other factors, such as global radiation, fertility, or SMC (especially in dryland pasture systems, as is the case), will be decisive (Pullanagari et al. 2013).

4. Conclusions

The optimization of agro-forestry systems by choosing the right density and spatial arrangement of trees or species of trees and pasture is a complex and long-term process requiring practical studies. This work demonstrated the influence of holm oak trees (*Q. ilex* ssp. *rotundifolia* Lam.) on the soil and pasture in the Mediterranean *montado* ecosystems. Soil under the tree canopy had significantly higher levels of organic matter, N, P, K, and Mg. The increase of organic (litter and dead roots) and mineral components in soils located under the tree canopies is due partly to leaf shedding and other litter fall but also to animal excretion since these are always attracted by trees in grassland in response to the environmental conditions.

In this study, significant differences were found in pasture productivity (green and dry matter), between March and June, showing greater pasture productivity OTC. These results show that pasture production UTC in silvo-pastoral systems depends on the degree of competition between trees and pasture for resources (light, moisture, and nutrients) and does not generally reflect the soil fertility gradient.

On the other hand, significant differences were found in pasture quality between March and April (ash and NDF) or between March and May (CP), with the tree canopy favourably influencing the pasture quality. The higher quality of pasture under trees is a consequence to the delay in the ontogenic development of shaded plants (less advanced state of vegetative development), keeping them physiologically younger and allowing the maintenance of higher metabolic levels for a longer period of time. Associated with these, significant differences were found in botanical composition caused by changes in the microclimate, soil properties, and livestock grazing.

The application of sensing techniques to grazed production systems is complex due to the highly spatial and temporal variability of these environments. Proximal sensing tools with higher spatial and spectral resolution could overcome some of these challenges. In this work, the correlation between pasture and sensor parameters was more consistent between capacitance and pasture productivity and between NDVI and CP. In the future, it will be important to evaluate the possibility of developing an ideal pasture monitoring system that combines data from multiple sources: proximal sensing data for repeated and continuous monitoring of the pastures, and remote-sensing images collected a limited number of times, when a spatial assessment of pastures is required. These measurements allow to the farmer to simplify the pasture monitoring process and provide a much better understanding of the livestock system, as well as the basis for formulating the most appropriate management strategies, such as grazing rotations, nutrient management, or yield prediction, which are fundamental for ensuring the sustainability of extensive animal production.

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References

Albayrak, S. 2008. “Use of Reflectance Measurements for the Detection of N, P, K, ADF and NDF Contents in Sainfoin Pasture.” *Sensors* 8: 7275–7286. doi:10.3390/s8117275.

AOAC Official Method. 2005. *Official Methods of Analysis of AOAC International*. 18th ed. Arlington, VA: AOAC International.

Benavides, R., G. B. Douglas, and K. Osoro. 2009. “Silvopastoralism in New Zealand: Review of Effects of Evergreen and Deciduous Trees on Pasture Dynamics.” *Agroforestry Systems* 76: 327–350. doi:10.1007/s10457-008-9186-6.

Bernardi, A. C. C., G. M. Bettiol, R. P. Ferreira, K. E. L. Santos, L. M. Rabello, and R. Y. Inamasu. 2016. “Spatial Variability of Soil Properties and Yield of a Grazed Alfalfa Pasture in Brazil.” *Precision Agriculture* 17 (6): 737–752. doi:10.1007/s11119-016-9446-9.

Bird, P. R. 1998. “Tree Windbreaks and Shelter Benefits to Pasture in Temperate Grazing Systems.” *Agroforestry Systems* 41: 35–54. doi:10.1023/A:1006092104201.

David, T. S., C. A. Pinto, N. Nadezhdina, C. Kurz-Besson, M. O. Henriques, T. Quilhó, J. Cermak, M. M. Chaves, J. S. Pereira, and J. S. David. 2013. “Root Functioning, Tree Water Use and Hydraulic Redistribution in *Quercus Suber* Trees: A Modeling Approach Based on Root Sap Flow.” *Forest Ecology and Management* 307: 136–146. doi:10.1016/j.foreco.2013.07.012.

Demanet, R., M. L. Mora, M. A. Herrera, H. Miranda, and J. M. Barea. 2015. “Seasonal Variation of the Productivity and Quality of Permanent Pastures in Adisols of Temperate Regions.” *Journal of Soil Science and Plant Nutrition* 15 (1): 111–128. doi:10.4067/S0718-95162015005000010.

Dusseux, P., L. Hubert-Moy, T. Corpetti, and F. Vertès. 2015. “Evaluation of Spot Imagery for the Estimation of Grassland Biomass.” *International Journal of Applied Earth Observation and Geoinformation* 38: 72–77. doi: 10.1016/j.jag.2014.12.003.

Edirisinghe, A., M. J. Hill, G. E. Donald, and M. Hyder. 2011. "Quantitative Mapping of Pasture Biomass Using Satellite Imagery." *International Journal of Remote Sensing* 32 (10): 2699–2724. doi:10.1080/01431161003743181.

Efe Serrano, J. 2006. *Pastures in Alentejo: Technical Basis for Characterization, Grazing and Improvement*, 165–178. Évora, Portugal: Universidade de Évora, ICAM.

Egner, H., H. Riehm, and W. R. Domingo. 1960. "Utersuchungeniiber Die Chemische Bodenanalyse Als Grudlagefiir Die Beurteilung Des Nahrstoff-Zunstandes Der Boden. II." *K Lantbrhogsk Annlr* 20: 199–216. (in German). doi:10.1007/s11119-015-9419-4.

FAO. 2006. *World Reference Base for Soil Resources*. *Food and Agriculture Organization of the United Nations, World Soil Resources Reports N º 103*. Rome, Italy: IUSS Working Group WRB.

Gitelson, A. A. 2004. "Wide Dynamic Range Vegetation Index for Remote Quantification of Biophysical Characteristics of Vegetation." *Journal of Plant Physiology* 161 (2): 165–173. doi:10.1078/0176-1617-01176.

Gómez-Rey, M. X., A. Garcês, and M. Madeira. 2012. "Soil organic-C Accumulation and N Availability under Improved Pastures Established in Mediterranean Oak Woodlands." *Soil Use and Management* 28: 497–507. doi:10.1111/j.1475-2743.2012.00428.x.

Guevara-Escobar, A., P. D. Kemp, A. D. Mackay, and J. Hodgson. 2007. "Pasture Production and Composition under Poplar in a Hill Environment in New Zealand." *Agroforestry Systems* 69 (3): 199–213. doi:10.1007/s10457-007-9038-9.

Handcock, R. N., D. L. Gobbett, L. A. González, G. J. Bishop-Hurley, and S. L. McGavin. 2016. "A Pilot Project Combining Multispectral Proximal Sensors and Digital Cameras for Monitoring Tropical Pastures." *Biogeosciences* 13: 4673–4695. doi:10.5194/bg-13-4673-2016.

Howlett, D. S., G. Moreno, M. R. Losada, P. K. R. Nair, and V. D. Nair. 2011. "Soil Carbon Storage as Influenced by Tree Cover in the Dehesa Cork Oak Silvopasture of Central-Western Spain." *Journal of Environmental Monitoring* 13: 1897–1904. doi:10.1039/C1EM10059A.

Hussain, Z., P. D. Kemp, D. J. Horne, and I. K. D. Jaya. 2009. "Pasture Production under Densely Planted Young Willow and Poplar in a Silvopastoral System." *Agroforestry Systems* 76: 351–362. doi:10.1007/s10457-008-9195-5.

Jackson, J., and A. J. Ash. 1998. "Tree-Grass Relationships in Open Eucalypt Woodlands of Northeastern Australia: Influence of Trees on Pasture Productivity, Forage Quality and Species Distribution." *Agroforestry Systems* 40 (2): 159–176. doi:10.1023/A:1006067110870.

Joffre, R., and S. Rambal. 1993. "How Tree Cover Influences the Water Balance of Mediterranean Rangelands." *Ecology* 74: 570–582. doi:10.2307/1939317.

Kallenbach, R., M. Kerley, and G. Bishop-Hurley. 2006. "Cumulative Forage Production, Forage Quality and Livestock Performance from an Annual Ryegrass and Cereal Rye Mixture in a Pine–Walnut Silvopasture." *Agroforestry Systems* 66: 43–53. doi:10.1007/s10457-005-6640-6.

Mallarino, A. P., and D. J. Wittry. 2004. "Efficacy of Grid and Zone Soil Sampling Approaches for Site-Specific Assessment of Phosphorus, Potassium, pH, and Organic Matter." *Precision Agriculture* 5: 131–144. doi:10.1023/B:PRAG.0000022358.24102.1b.

Marcos, G. M., J. J. Obrador, E. Garcia, E. Cubera, M. J. Montero, F. Pulido, and C. Dupraz. 2007. "Driving Competitive and Facilitative Interactions in Oak Dehesas through Management Practices." *Agroforestry Systems* 70: 25–40. doi:10.1007/s10457-007-9036-y.

McCormick, S., C. Jordan, and J. Bailey. 2009. "Within and between Field Spatial Variation in Soil Phosphorus in Permanent Grassland." *Precision Agriculture* 10: 262–276. doi:10.1007/s11119-008-9099-4.

Modica, G., F. Solano, A. Merlino, S. Di Fazio, F. Barreca, L. Laudari, and C. R. Fichera. 2016. "Using Landsat 8 Imagery in Detecting Cork Oak (*Quercus Suber* L.) Woodlands: A Case Study in Calabria (Italy)." *Journal of Agricultural Engineering* 47 (4): 205–215. doi:10.4081/jae.2016.571.

Murray, R. I., I. J. Yule, and A. G. Gillingham. 2007. "Developing Variable Rate Application Technology: Modelling Annual Pasture Production on Hill Country." *New Zealand Journal of Agricultural Research* 50: 41–52. doi: 10.1080/00288230709510281.

Paço, T. A., T. S. David, M. O. Henriques, J. S. Pereira, F. Valente, J. Banza, F. L. Pereira, C. Pinto, and J. S. David. 2009. "Evapotranspiration from a Mediterranean Evergreen Oak Savannah: The Role of Trees and Pasture." *Journal of Hydrology* 369: 98–106. doi:10.1016/j.jhydrol.2009.02.011.

Pollock, K. M., D. J. Mead, and B. A. McKenzie. 2009. "Soil Moisture and Water Use by Pastures and Silvopastures in a Sub-Humid Temperate Climate in New Zealand." *Agroforestry Systems* 75 (3): 223–238. doi:10.1007/s10457-008-9172-z.

Pullanagari, R. R., I. J. Yule, M. P. Tuohy, M. J. Hedley, R. A. Dynes, and W. M. King. 2013. "Proximal Sensing of the Seasonal Variability of Pasture Nutritive Value Using Multispectral Radiometry." *Grass Forage Science* 68: 110–119. doi:10.1111/j.1365-2494.2012.00877.x.

Rascher, U., and R. Pieruschka. 2008. "Spatio-Temporal Variations of Photosynthesis: The Potential of Optical Remote Sensing to Better Understand and Scale Light Use Efficiency and Stresses of Plant Ecosystems." *Precision Agriculture* 9 (6): 355–366. doi:10.1007/s11119-008-9074-0.

Schaefer, M. T., and D. W. Lamb. 2016. "A Combination of Plant NDVI and LiDAR Measurements Improve the Estimation of Pasture Biomass in Tall Fescue (*Festuca Arundinacea* Var. Fletcher)." *Remote Sensing* 8 (2): 1–10. doi:10.3390/rs8020109.

Schellberg, J., M. J. Hill, G. Roland, M. Rothmund, and M. Braun. 2008. "Precision Agriculture on Grassland: Applications, Perspectives and Constraints." *European Journal of Agronomy* 29 (2–3): 59–71. doi:10.1016/j.eja.2008.05.005.

Seddaiu, G., G. Porcua, L. Luigi, P. P. Roggero, A. Agnelli, and G. Cortic. 2013. "Soil Organic Matter Content and Composition as Influenced by Soil Management in a Semi-Arid Mediterranean Agro-Silvo-Pastoral System." *Agriculture, Ecosystems and Environment* 167: 1–11. doi:10.1016/j.agee.2013.01.002.

Serrano, J., J. Peça, J. Marques Da Silva, and S. Shahidian. 2011. "Calibration of a Capacitance Probe for Measurement and Mapping of Dry Matter Yield in Mediterranean Pastures." *Precision Agriculture* 12: 860–875. doi:10.1007/s11119-011-9227-4.

Serrano, J., S. Shahidian, and J. Marques Da Silva. 2013. "Small Scale Soil Variation and Its Effect on Pasture Yield in Southern Portugal." *Geoderma* 195–196: 173–183. doi:10.1016/j.geoderma.2012.12.001.

Serrano, J., S. Shahidian, and J. Marques Da Silva. 2016a. "Monitoring Pasture Variability: Optical OptRx® Crop Sensor versus Grassmaster II Capacitance Probe." *Environmental Monitoring and Assessment* 188 (2): 1–17. doi:10.1007/s10661-016-5126-5.

Serrano, J., S. Shahidian, and J. Marques Da Silva. 2016b. "Calibration of GrassMaster II to Estimate Green and Dry Matter Yield in Mediterranean Pastures: Effect of Pasture Moisture Content." *Crop and Pasture Science* 67 (7): 780–791. doi:10.1071/CP15319.

Somarriba, E. 1988. "Pasture Growth and Floristic Composition under the Shade of Guava (Psidium Guajava L.) Trees in Costa Rica." *Agroforestry Systems* 6: 153–162. doi:10.1007/BF02344752.

Sousa, L. F., R. M. Maurıcio, G. R. Moreira, L. C. Gonçalves, I. Borges, and L. G. R. Pereira. 2010. "Nutritional Evaluation of "Braquiaro" Grass in Association with "Aroeira" Trees in a Silvopastoral System." *Agroforestry Systems* 79: 189–199. doi:10.1007/s10457-010-9297-8.

Trotter, M. G., D. W. Lamb, G. E. Donald, and D. A. Schneider. 2010. "Evaluating an Active Optical Sensor for Quantifying and Mapping Green Herbage Mass and Growth in a Perennial Grass Pasture." *Crop and Pasture Science* 61: 389–398. doi:10.1071/CP10019.

Weerasekara, C., R. P. Udawatta, S. Jose, and S. R. Kremer. 2016. "Soil Quality Differences in a Row-Crop Watershed with Agroforestry and Grass Buffers." *Agroforestry Systems* 90 (5): 829–838. doi:10.1007/s10457-016-9903-5.

Yule, I., R. Pullanagari, M. Irwin, P. McVeagh, G. Kereszturi, M. White, and M. Manning. 2015. "Mapping Nutrient Concentration in Pasture Using Hyperspectral Imaging." *Journal of New Zealand Grasslands* 77: 47–50.