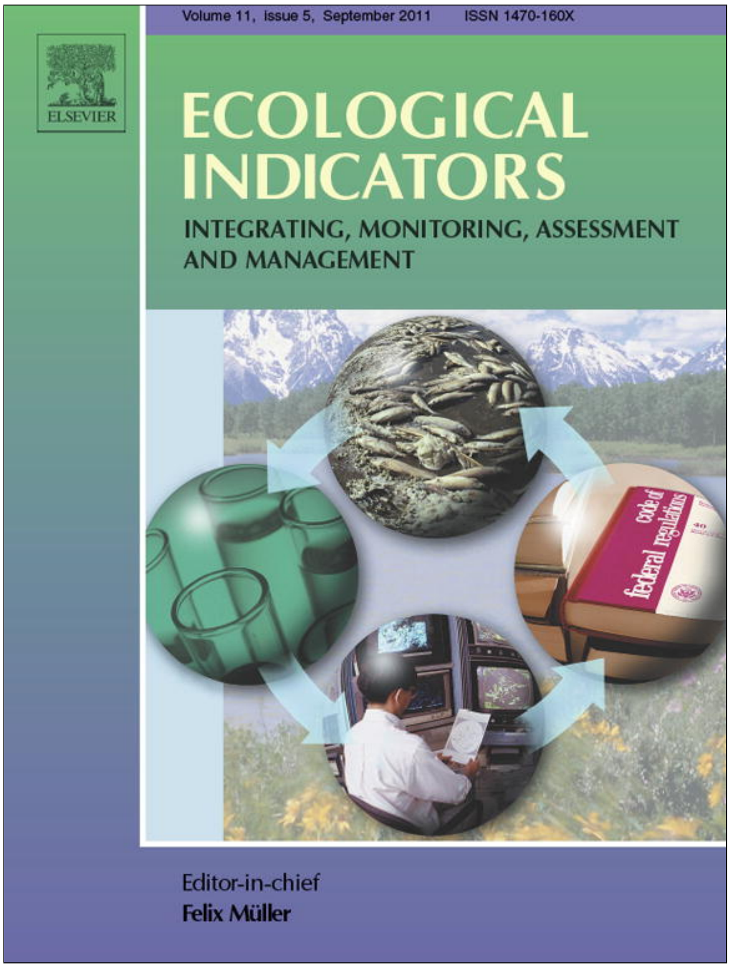
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Short communication

Remote sensing data predict indicators of soil functioning in semi-arid steppes, central Spain

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ABSTRACT

A substantial part of current research efforts on desertification are devoted to establish monitoring systems to evaluate the status of natural resources and the onset of desertification processes. Methodologies based on ground-collected soil and plant indicators are being increasingly used for this aim because they are affordable yet do not compromise accuracy. Despite their inherent value, these methods have limitations regarding the extent of the area that can be monitored using them. Such limitations can be overcome combining field-based approaches with remote sensing data, which allow the establishment of monitoring programs over large areas. In this article we tested the relationship between a field methodology based on indicators of ecosystem functioning, the landscape function analysis (LFA), and a vegetation index (NDVI) obtained from satellite images of the ASTER sensor using data gathered in *Stipa tenacissima* steppes from central Spain. LFA uses soil surface indicators to assess the condition of a given ecosystem by producing three numerical indices (stability, infiltration and nutrient cycling) reflecting the status of basic soil functions. We found a significant positive linear relationship between the NDVI, the three LFA indices and some key structural attributes of vegetation related to the cover of perennial plants. Our results indicate that NDVI can be used as a surrogate of ecosystem functioning in semi-arid Mediterranean steppes, and thus can be a helpful index to monitor the functional status of large areas in these ecosystems, and the possible onset of desertification processes.

1. Introduction

Arid and semiarid areas occupy almost two-fifths of the Earth surface, supporting the life of more than one billion people (Reynolds et al., 2007a). Certain demographic, socio-economic and technological changes in many of these areas have led to an excessive pressure on natural resources, which have led to an intense degradation of soils, vegetation and ecological processes resulting in a loss of biological and economic productivity called desertification (Reynolds et al., 2007b). Desertification is a major global environmental problem, and is estimated to affect 65–70% of all arid, semi-arid and dry-subhumid areas worldwide (Reynolds et al., 2007a).

The establishment of programs for long-term monitoring of natural resources is an effective way of assessing their status (by detecting early changes in ecosystem structure and function) and the development of desertification processes, allowing the establishment of effective and economically sound management measures (Fernández et al., 2002; Reynolds et al., 2007b). In recent years, increasing efforts have been devoted to the development and calibration of ground-based monitoring methods based on indicators (Tongway and Hindley, 2004; Pyke et al., 2002; Herrick et al., 2005). These methods are based on measuring a selected suite of soil and vegetation attributes related to ecosystem processes defining their functionality and resilience.

Among the different indicator methods to monitor ecosystem processes developed, one of the most widely employed is the landscape function analysis (LFA) methodology developed in Australian rangelands by David Tongway and collaborators (Tongway and Hindley, 2004). LFA uses soil surface indicators to assess the status of a given ecosystem in terms of functionality, i.e. the degree to which resources tend to be retained, used and cycled within the system (Tongway and Ludwig, 2010). This methodology satisfies the requirements for meaningful indicator-based methods (Whitford,

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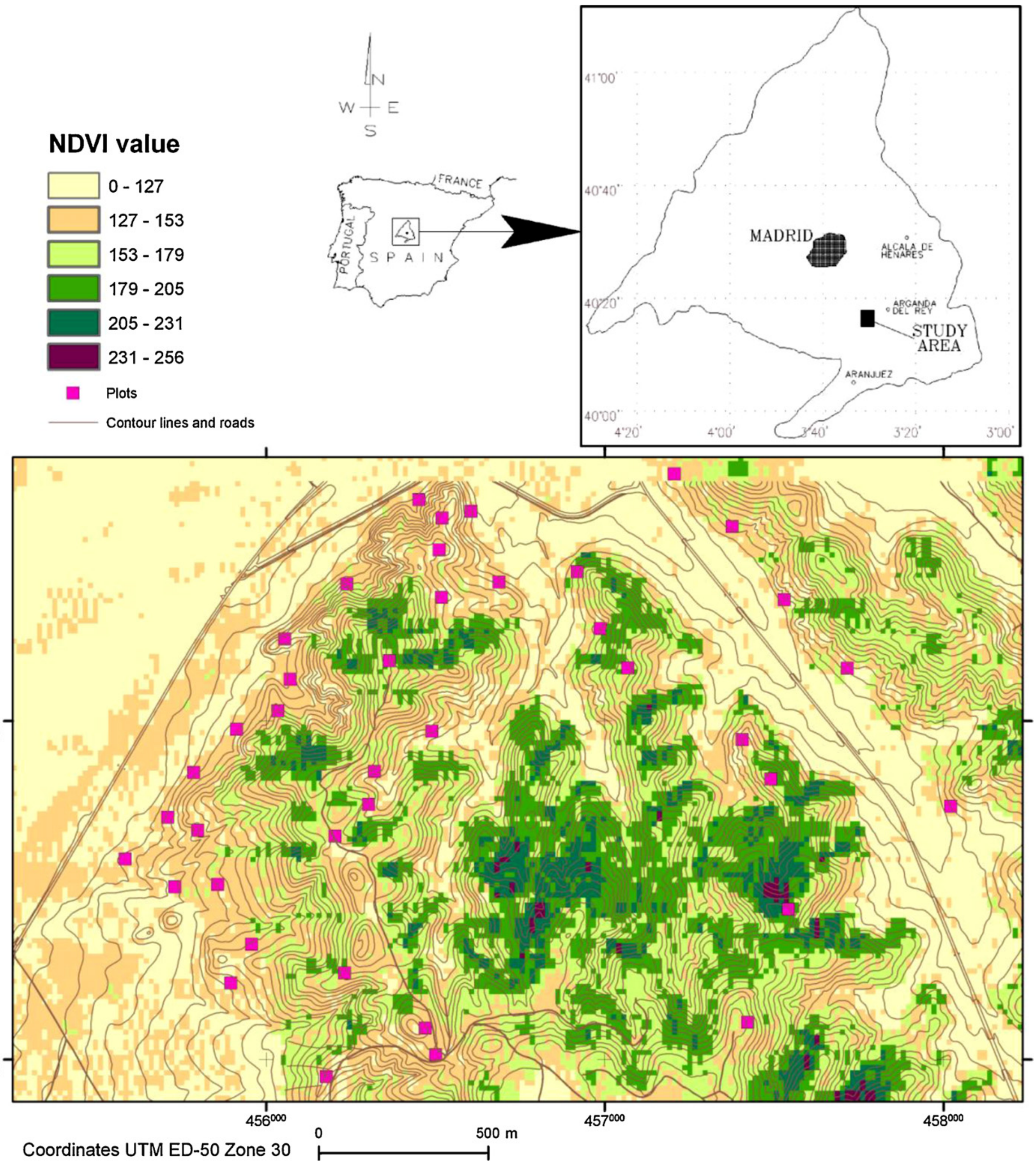

Fig. 1. Location of the study area within Spain (inset), and of the study plots within the study area. The values of the normalized difference vegetation index (NDVI) are shown in the background.

2002): it reflects the status of critical ecosystem processes, is unambiguous, and can be used over a wide range of ecosystems. In addition, its use in the field is rapid and inexpensive, and thus is particularly suitable for land managers and technicians.

The output of LFA is given by three indices (stability, infiltration, and nutrient cycling) that summarize different facets of the functionality of the ecosystem, and that are strongly related to quantitative measures of related ecosystem processes (Tongway and Hindley, 2003; Bartley et al., 2006; Maestre and Puche, 2009). The LFA methodology has been extensively used and tested in semi-arid ecosystems of Australia (Holm et al., 2002; Ludwig et al., 2004; Thompson et al., 2006; Bartley et al., 2006), Iran (Ata Rezaei et al., 2006), Tunisia (Derbel et al., 2009) and Spain (Maestre and Cortina, 2004; Maestre et al., 2006; Mayor, 2008; Maestre and Puche, 2009), and is currently being implemented in different Latin American countries such as Argentina (Oliva et al., 2009).

In addition to their relative simplicity, interpretability and minimum cost, indicator-based methodologies such as LFA allow the establishment of comparative spatio-temporal analysis of a given set of study areas (Tongway and Ludwig, 2010; Maestre and Cortina, 2004). This gives a large potential for this methodology to evaluate the success of environmental restoration efforts over time, and to create monitoring programs to combat desertification. However, ground-based methods such as LFA face limitations when applied over large geographical areas due to logistic problems such as access to particular sites and constraints such as lack of funding or personnel. These limitations can be overcome by complementing the information gathered by field methods with the use of remote sensing data, which have been successfully employed to monitor desertification processes in the United States (Asner and Heidebrecht, 2005), Latin America (Asner et al., 2003), Africa (Prince et al., 1998), Australia (Bastin et al., 2002), China (Wu and Ci, 2002) and Europe (Imeson and Prinsen, 2004), to name a few examples. The combination of ground- and remote sensing-based approaches offer great promise to advance in the establishment of sound and cost-effective desertification monitoring programs in drylands (Ludwig et al., 2007; Reynolds et al., 2007b).

In this study we explored the relationship between both the LFA indices and key structural attributes of vegetation and the normalized difference vegetation index (NDVI; Sellers, 1985; Tucker et al., 1985) obtained from the sensor ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), onboard the TERRA satellite (http://www.jpl.nasa.gov). We did so using a database obtained from 40 *Stipa tenacissima* L. steppes located in central Spain. These steppes are one of the most important ecosystems in the driest areas of Europe and North of Africa, and are widely distributed from Lybia to Morocco (see Maestre et al., 2009 for a recent account of their natural history). The three LFA indices have been satisfactorily calibrated with different surrogates of ecosystem functioning in these steppes (Mayor, 2008; Maestre and Puche, 2009). Recent work has also used remote sensing data to calibrate the LFA indices in restored mines in Australia (Ong et al., 2009). However, such calibration has not been carried out in *S. tenacissima* steppes, a crucial step in order to evaluate the potential of remote sensing data to implement its use as a monitoring tool in this ecosystem. We aimed to do so by evaluating the relationships between the LFA indices, key features of perennial vegetation and the NDVI.

2. Materials and methods

2.1. Study area

The study area is located approximately 15 miles southeast of the city of Madrid, and belongs to the Southeast Regional Park, within the limits of the municipalities of Arganda del Rey and San Martín de la Vega (Fig. 1). This area has remained mostly undisturbed during the last 40 years because it is part of a larger private game reserve. All the study sites were located in soils derived from limestone (*Lithic Calciorthid*; Soil Survey Staff, 1994) or in gypsum-rich soils (*Typic Gypsiorthid*; Soil Survey Staff, 1994), two of the main substrates over which *S. tenacissima* steppes develop in Spain (Maestre et al., 2007). Climate of study area is Mediterranean semi-arid, with an average annual temperature and precipitation of 14.5 °C and 400 mm, respectively. Vegetation was either a Mediterranean shrubland dominated by *Quercus coccifera* L. in the north-facing slopes and in the most elevated areas or an open grassland dominated by *S. tenacissima* in the south-facing slopes and less elevated areas.

2.2. Field sampling

This study was conducted in 40 15 m × 15 m plots located in the study area (Fig. 1). Plots were placed according to a stratified random sampling aiming to capture most of the variability in the NDVI observed in the study area (Fig. 1). All the plots were oriented in the direction of the maximum slope (i.e. the upper part of the plot was located in the upper part of the slope), which corresponds with the predominant water flow. The four corners of each plot were located using a GPS (Trimble GeoXH; http://www.trimble.com/geoxh.shtml), corrected in differential real-time SBAS (EGNOS) to locate with metric precision the study plot in the satellite image. All the field sampling was carried out in July 2009.

2.2.1. Vegetation survey

In the upper left corner of each plot, we located one 15 m long transect downslope for vegetation and soil surveys. Two parallel transects of the same length, each located 7.5 m apart across the slope, were added. In each transect we collected a continuous record of patch and inter-patch zones. A patch is defined as a long-lived feature that is able to collect water, sediments, and nutrients coming from runoff such as perennial plants and shrub branches contacting soil (Tongway and Hindley, 2004) and that is separated by bare soil surface from the next patch. From these transects, we obtained data on the following vegetation distribution attributes: the total cover of plant patches (TPA, total patch area), their number per unit length of transect (Number of patches/10 m, number of patch zones every 10 m), their area (PAI, patch area index) and the average distance between consecutive patches (AIL, average interpatch length) and the landscape organisation index (LOI), derived by dividing the sum of the patch zones by the length of the transect line.

2.2.2. Soil surface assessment

The assessment of LFA indices was performed in bare ground areas devoid of vascular vegetation and under the canopy of dominant perennial species (*S. tenacissima* and perennial shrubs), respectively. Within each site, we randomly located five 50 cm × 50 cm sampling points in open areas and under the canopy of *S. tenacissima* tussocks for the assessment of the LFA indices. Some of the sites had well-developed individuals of sprouting shrubs (mostly *Q. coccifera* and *Retama sphaerocarpa* Boiss.). In these sites, five shrub individuals were also randomly selected for the assessment of the LFA indices under their canopies. A total of 595 sampling points were surveyed. In each sampling point, we measured eleven soil surface features (total soil cover, basal cover of perennial grasses and shrub canopy cover, litter cover and degree of decomposition, cover of biological soil crusts, crust brokenness, erosion type and severity, deposited materials, soil surface roughness, surface resistance to disturbance, slake test and soil texture), which were combined to obtain the three LFA indices: stability, infiltration and nutrient cycling. Details on how these surface indicators are combined to obtain the LFA indices are given elsewhere (Tongway and Hindley, 2004; Tongway and Ludwig, 2010). The stability index provides information about the ability of the soil to withstand erosive forces, and to recover after disturbance. The infiltration index shows how the soil partitions rainfall into plant-available water, and runoff water that is lost from the system. The nutrient cycling index provides information about how efficiently organic matter is cycled back into the soil.

The LFA indices obtained in the different microsites were scaled up to obtain average estimates for each site. This was done by multiplying the proportion of the area covered by each microsite by the average LFA indices obtained at that microsite and then adding them together (Holm et al., 2002; Maestre and Cortina, 2004; Mayor, 2008; Maestre and Puche, 2009).

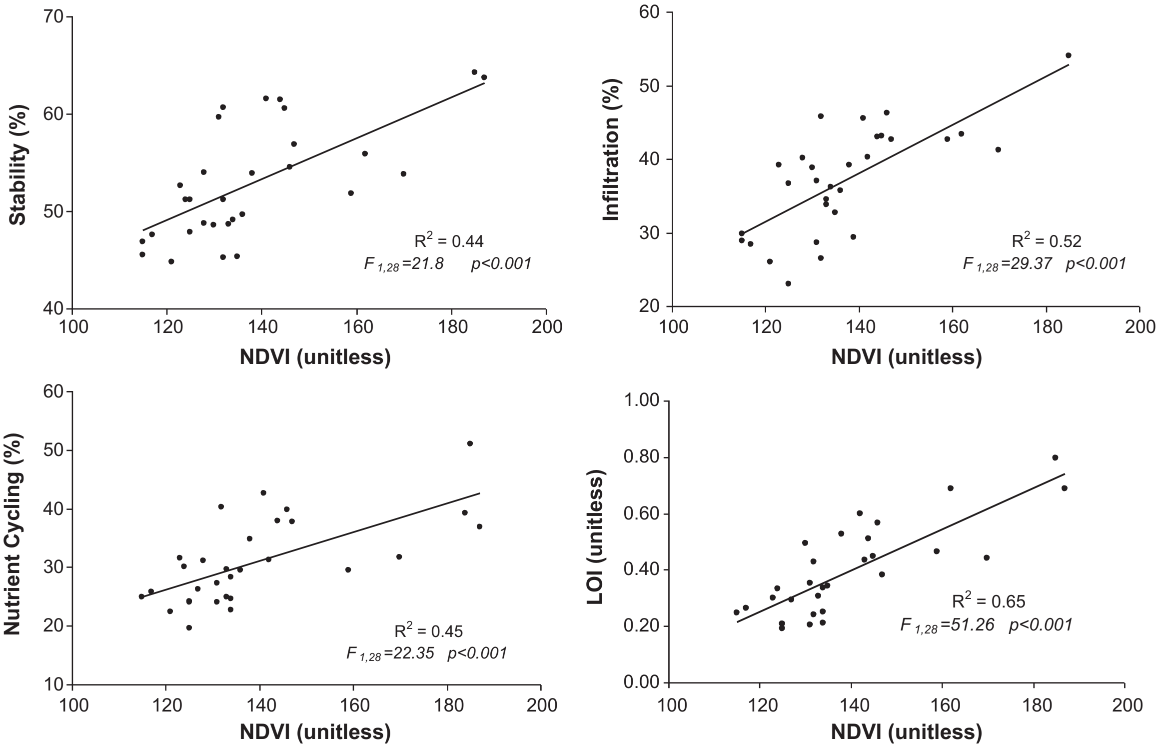

Fig. 2. Examples of the models fitted to the relationships between the the normalized difference vegetation index (NDVI) and the stability, infiltration and nutrient cycling indices, and between NDVI and the landscape organization index (LOI). See Table 1 for a summary of all the models obtained. Results of a linear regression are shown in all cases.

2.3. Remote sensing data and image processing

For this study we used multispectral images of the ASTER sensor onboard the TERRA satellite taken on 27/08/2008 (L1A_dbID = SC: AST_L1A.003: 2066051010), with no cloud cover and with an imaging center located at 40°30′38″N, 3°42′39″W. ASTER covers a wide spectral region with 14 bands, from the visible to thermal infrared, and has high spatial, spectral and radiometric resolution. The spatial resolution in the visible and near infrared (VNIR, required for the NDVI calculation) is 15 m, like plots surveyed in the field. We corrected images geometrically with support of field points to reduce error below 2 m, and corrected it for radiometric atmospheric attenuation by subtracting the minimum level of each band using the software ERDAS Imagine 9.1 Professional (Leica Geosystems Geospatial Imaging, Atlanta, GA, USA). As the error of the differential real-time SBAS GPS (EGNOS; http://www.esa.int/esaNA/GGG63950NDC_egnos_0.html) used are typically 1.5 m, we matched the size of each plot sampled in the field to that a pixel in such image to facilitate the comparison between field and remote sensing data.

2.4. Data analysis

LOI was highly correlated with TPA ($r = 0.722$, $P < 0.001$, $n = 40$), PAI ($r = 0.726$, $P = 0.001$, $n = 40$) and AIL ($r = -0.477$, $P = 0.002$, $n = 40$), and TPA was highly correlated with the number of patches per unit length of transect ($r = -0.457$, $P = 0.003$, $n = 40$). Therefore, we only used LOI – which is a surrogate of total perennial plant cover – as the structural attribute of vegetation in further analyses.

We investigated the relationships between NDVI data, the three LFA indices and the vegetation structural attributes obtained from the field transects using simple regression analysis. All the variables were normally distributed (Kolmogorov–Smirnov test, $P > 0.05$), and thus were not transformed. Predictive linear models of the three LFA indices and LOI were generated using a two-step approach. First, we randomly selected 75% of the plots ($n = 30$) to generate each predictive model (random sampling without replacement); the remaining 25% of the dataset ($n = 10$) were set aside for validation purposes. We repeated this process 200 times to estimate the average and variation ranges of the model parameters and their validations. All statistical analyses were performed with SPSS for Windows, version 17.0 (SPSS Inc., Chicago, IL, USA).

3. Results and discussion

Structural attributes of vegetation in our study area were highly variable, as LOI and NDVI varied between 0.14 and 0.79 (unitless), and 115–187 (unitless), respectively. High variability was also found for the three LFA indices, as the stability, infiltration and nutrient cycling indices varied between 45% and 62%, 23% and 54%, and 20% and 51%, respectively. The regressions fitted showed a linear and positive relationship between the NDVI and both the three LFA indices and the LOI ($R^2 > 0.36$, $P < 0.001$ in all cases, Table 1 and Fig. 2). The models fitted were successfully validated, as the relationships between predicted and observed values were significant in all cases (Table 1 and Fig. 3).

It is well known that the NDVI is directly related to the photosynthetic capacity, and therefore to the ability of absorbing energy, of vascular plants (e.g., Sellers, 1985; Tucker et al., 1985). NDVI was linearly related to total plant cover (measured with LOI) in our study area, a pattern also found in other regions (Tucker and Sellers, 1986; Paruelo et al., 2004). Plant cover and other structural attributes of vegetation, such as average inter-patch length, have been found to be primary determinants of variations in the LFA indices in semi-arid *S. tenacissima* steppes from Spain (Maestre and Cortina, 2004; Maestre and Puche, 2009). Furthermore, NDVI has also been found to correlate well with soil properties linked to vegetation, such as soil carbon (Sumfleth and Duttmann, 2008)

Table 1
Summary of the 200 models conducted to predict and validate the relationships between the normalized difference vegetation index (NDVI) and the stability, infiltration and nutrient cycling indices, and between NDVI and the landscape organization index.

Model	Variables	Mean R^2	Range R^2	% of significant ($P < 0.05$) models
Prediction[a]	NDVI–stability index	0.461	0.39–0.59	100
	NDVI–infiltration index	0.521	0.41–0.58	100
	NDVI–nutrient cycling index	0.453	0.36–0.49	100
	NDVI–landscape organization index	0.648	0.53–0.73	100
Validation[b]	Stability index	0.660	0.58–0.82	100
	Infiltration index	0.745	0.65–0.78	100
	Nutrient cycling index	0.533	0.42–0.74	100
	Landscape organization index	0.755	0.64–0.92	100

[a] In all cases, $n = 30$.
[b] In all cases, $n = 10$.

and phosphorus (Rivero et al., 2009), which can also be predicted by the LFA indices (Maestre and Puche, 2009). The relationships found between NDVI and the LFA indices agree with theoretical and empirical work showing the importance of vegetation cover for the proper functioning of semiarid ecosystems in general (e.g., Ludwig and Tongway, 1995; Bastida et al., 2007; Li et al., 2007), and of *S. tenacissima* steppes in particular (Maestre and Escudero, 2009; Maestre et al., 2009).

Most of the studies carried out to date using NDVI have employed this index to monitor changes in vegetation structure, overall health status and phenology (e.g., Holme et al., 1987; Small, 2001; Zhao et al., 2009). In recent years, NDVI is being used to assess soil properties such as nutrients (Sumfleth and Duttmann, 2008; Rivero et al., 2009), and moisture (Han et al., 2010). Our results complement these studies, as they indicate that NDVI can also predict functional indicators related to soil stability, infiltration and nutrient cycling in semi-arid steppes. The use of "slow" soil variables, such as organic carbon, total nitrogen and phosphorus, has been recommended to monitor desertification processes because they have lengthy turnover times, and are thus useful for gaining insights into long-term ecosystem changes and resource collapses (Reynolds et al., 2007a).

Our results indicate that NDVI data obtained from an ASTER satellite image are suitable for monitoring and assessing changes in the functionality of ecosystems over large areas. While the relationships between NDVI and the LFA indices evaluated were significant, average R^2 values were below 70% in all cases (Table 1), suggesting that improvements on the predictive capability of remote sensing information to predict such indices are possible. To achieve such improvements, future research could evaluate the potential use of remotely sensed vegetation indices other than NDVI, such as the Soil Adjusted Vegetation Index, which has some advantages over NDVI on some soil types (Jafari et al., 2007). The combined use of more advanced remote sensing tools, such as LiDAR and QuickBird imagery (Johansen et al., 2010), could also improve the accurate of predicting the LFA indices. However, such increase in precision must be balanced against the increased costs of other remote sensing data compared to ASTER images, which are inexpensive and have a good spatio-temporal replication. This is particularly important to facilitate the monitoring of large areas in areas lacking the resources and expertise to acquire and use advance remote sensing information.

Recent studies conducted in *S. tenacissima* steppes have shown that the LFA indices are good predictors of soil variables related

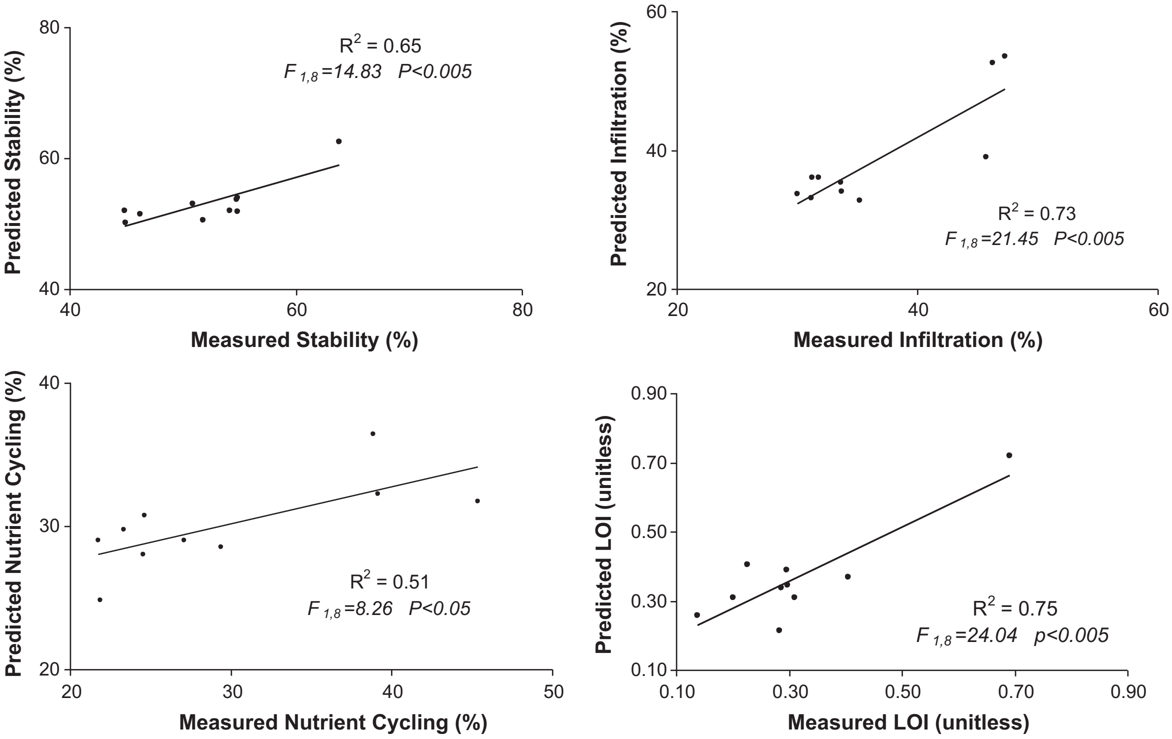

Fig. 3. Examples of regressions between field-measured values and predicted model values for stability, infiltration and nutrient cycling indices, and for the landscape organization index (LOI). See Table 1 for a summary of the validation models conducted. Results of a linear regression are shown in all cases.

with microbial activity, nutrient cycling, and infiltration, such as soil compaction, pH, total soil N and P, soil respiration and the activities of soil enzymes (urease, phosphatase and β-glucosidase; Mayor, 2008; Maestre and Puche, 2009). Our results show that the NDVI can successfully predict the three LFA indices in *S. tenacissima* steppes, and thus indicate that NDVI can be used as an indicator of ecosystem functioning, defined as its ability to retain and utilize resources. They complement previous field-based studies and indicate that NDVI can be used to monitor changes in ecosystem functioning over large spatial scales, something very difficult and costly to achieve using only field-based monitoring. Thus, NDVI can be used as a reliable and relatively easy to use tool for managing and monitoring degradation/desertification processes in *S. tenacissima* steppes.

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