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Original article

Testing the spectral variation hypothesis by using satellite multispectral images☆

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Abstract

In the present paper, a test of the spectral variation hypothesis (SVH) was performed using multispectral high resolution satellite data. The SVH was tested by comparing the relationship between the spectral heterogeneity and species richness in plots of different size (100–10000 m^2) in a complex wetland ecosystem, the "Montepulciano Lake", Central Italy. The nature reserve of the Montepulciano Lake is centered on a 100 ha shallow lake surrounded on three sides by a *Phragmites australis* and *Carex* sp. pl. marsh of about 280 ha. The monitoring program for the reserve vegetation started in 2002 and is based on the analysis of 1, 100 m^2 and 1 ha (10000 m^2) plots, organized in such a manner that four of the smaller size plots are nested, following a random design, within a larger one. Data on species composition and community structure were collected in the plots and stored in a GIS-linked archive. A multispectral Quickbird satellite image (3 m spatial resolution) acquired of the wetland and lake ecosystem during the same period was radiometrically and geometrically corrected. We performed an analysis to examine the use of spectral heterogeneity using the four visible and infrared wavebands of the satellite image to predict species richness at the different spatial scales. The spectral heterogeneity was found to explain about 20% of the variance of species richness at the 100 m^2 scale and about 50% at the 1 ha scale. It was concluded that multispectral high resolution satellite data can contribute to the biodiversity assessment of complex wetland ecosystems.

Keywords: GIS; Quickbird; Spectral variation hypothesis; Species richness; Wetland

1. Introduction

Biodiversity is a complex phenomenon that includes multiscalar and multitemporal structures and processes, with different levels of functional organization, from genetic to ecosystemic levels (Kaennel, 1997; Innes et al., 1998). Several authors suggested the use of a multiscalar approach for the study of biological diversity, based on the use of the components of one level to describe and characterize the components of the higher organization levels (Noss, 1990; Peck, 1998).

With regard to the assessment and monitoring of ecological diversity, plant communities are particularly important as they constitute the primary component of terrestrial ecosystems structure and functioning. Species diversity is a central component of biodiversity assessment (Wilson, 1988), making species richness and complementarity convenient 'proxies' for other components of biodiversity, such as genetic diversity and landscape diversity (Colwell and Coddington, 1994).

In recent times, the availability of new satellite sensors, with fine spatial resolution allows the remote investigation of highly heterogeneous ecosystems with a high level of accuracy.

Many authors investigated the use of remotely sensed information for mapping vegetation and land-use types (e.g. Fuller et al., 1998; Barrette et al., 2000), wetland plant stress (e.g. Anderson and Perry, 1996) and monitoring of vegetation restoration (e.g. Phinn et al., 1996; Shuman and Ambrose, 2003). However, few attempts have been directed to quantify plant species richness at local scales (e.g. Lauver and Whistler, 1993; Lauver, 1997; Gould, 2000; Foody and Cutler, 2003). Palmer et al. (2000) proposed the use of variations in the remotely sensed spectral responses as a tool to assess plant species diversity (Spectral Variation Hypoth-

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esis, SVH hereafter). Palmer et al. (2002) tested the SVH by using aerial panchromatic photos in the Tallgrass Praire reserve, Oklahoma, and, as far as we know this is the only test available of the SVH.

The aim of the present paper is to test the SVH, by using the variation of multispectral satellite images to estimate the species richness at different spatial scales. This hypothesis is based on the assumption that spectral heterogeneity of remotely sensed images is related to the spatial heterogeneity of the environment, in particular of the plant communities, which is in turn linked to species richness.

2. Materials and methods

2.1. Study area

The study area is the nature reserve of “Montepulciano Lake”, Tuscany, Italy. This reserve contains a 280 ha wetland, a 100 ha shallow lake and some cultivated and marginal areas. The wetland area contains different types of marshes, mostly dominated by *Phragmites australis* and *Carex* sp. pl. The nature reserve represents one of the most important wetland areas of central Italy, especially with respect to its rich seasonal avifauna population.

2.2. Field sampling of plant species richness data

Structure and species composition of plant communities were sampled at different spatial scales. Sampling units were quadrats of 1, 100, 10000 m^2. In particular, we proceeded as follows: a grid with a cell of 500 × 500 m (25 ha each), extracted from the kilometric UTM (ED50) grid, was superimposed over the area. In each cell, one macroplot of 1 ha was chosen by random selection. Each macroplot was divided into four quadrants of 2500 m^2 and a plot of 10 × 10 m was chosen in each quadrant by random selection. Four sub-plots of 1 × 1 m were selected within each plot with analogous procedure.

Sampling units were located in the field using a GPS receiver with static methodology, to decrease the deviation between the sampling design and the true position. GPS data were differentially corrected to obtain the most accurate positioning in a GIS environment.

Species composition of vascular plants was recorded for the sub-plot and plot scales. The species composition of the macroplot scale was obtained as the pooled list of species found in the four included plots. Only the sampling units of plots (100 m^2) and macroplots (1 ha) were used in this study. Plant species richness values were used to test the SVH.

2.3. Satellite image acquisition and calculation of the spectral heterogeneity

A Quickbird multispectral image (3 m spatial resolution) of the Montepulciano lake and wetland area, acquired in June 2002 was obtained and radiometrically corrected to convert measured irradiances to surface reflectances in the visible and infrared wavelengths. A dark object subtraction (Chavez, 1996) was used to reduce atmospheric effects. A high resolution DTM (Digital Terrain Model) was developed in a GIS environment by means of the TIN technique (Triangular Irregular Network). The image was orthorectified by means of the DTM and 22 GCP (Ground Control Points). The four bands obtained by the Quickbird sensor were used to calculate spectral heterogeneity at both the plot (100 m^2) and macroplot (1 ha) scales.

For the analysis of the reflectance of all bands at the plot scale (100 m^2), the spectral heterogeneity was calculated as the mean of the pairwise Euclidean distances, in a four-dimensional space (four wavebands as axes), using the 9 pixels covering the sampling plot. At the macroplot scale (1 ha), the previous approach resulted in an extremely high number of distances to be calculated for each sampling unit ($>10^6$) in relation to the number of pixels present in each sampling unit. A reduction of the system dimensions was obtained by principal components analysis (PCA); the first two axes of the PCA explained 99.56% of total variance of the four-dimension system. Distances among macroplot pixels were therefore calculated on the two-dimensional scatter defined by the first and second PCA axes rather than using the four-dimensional space. As an additional method to measure spectral heterogeneity, we used the mean of the distances from the centroid in the PCA scatter plot, namely the center mass of the points cloud, obtained for each plot, having as x the mean of all x values and as y the mean of all y values. This method determined a further decrease of number of distances to be calculated (1089 for the macroplot scale); this method was also applied at the plot scale (nine distances) to test possible discrepancies with respect to the results obtained with the previous method.

2.4. Test of the spectral variation hypothesis

The SVH predicts that, within a sampling unit of given size, it is possible to find a relation between spectral heterogeneity and plant species richness. Mean values of pairwise Euclidean distances (MED) and distances from the mass centroid (MCD) were thus used as indicators of spectral heterogeneity. The MED and MCD values were then compared to the number of species using linear regression analysis.

3. Results

The two measures of spectral heterogeneity (MED and MCD) led to comparable results at the plot scale. In fact, a perfect relation between these two variables was obtained by the regression analysis (Fig. 1). Given the strong congruence of the two methods, only the results of the centroid distances will be shown.

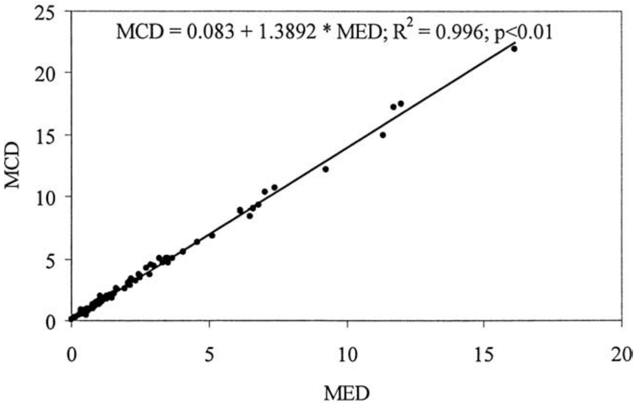

Fig. 1. Relationship between the values of spectral variation obtained by the two methods (mean of all Euclidean distances in a four-dimensions space, MED, and mean distance of the points from the centroid in the scatter obtained by the PCA first two axes, MCD).

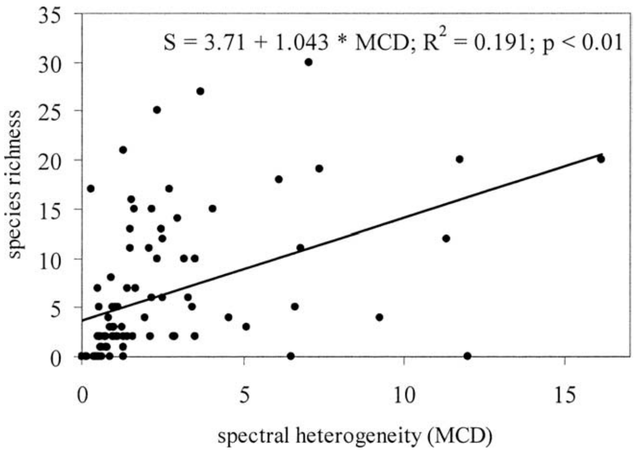

Fig. 2. Relationship, at the plot scale (100 m^2), between spectral heterogeneity measured by distance from centroid in two-dimensions (MCD) and species richness.

At the plot scale, the measure of spectral heterogeneity was able to predict about 20% of the variance of species richness (Fig. 2). Although the determination coefficient was relatively low, the slope of the regression line was significant ($P = 0.000021$).

At the macroplot scale, the predictive ability of the spectral heterogeneity with respect to the species richness was greatly increased, with a determination coefficient (R^2) equal to 0.481 (Fig. 3) and significant slope ($P = 0.000342$).

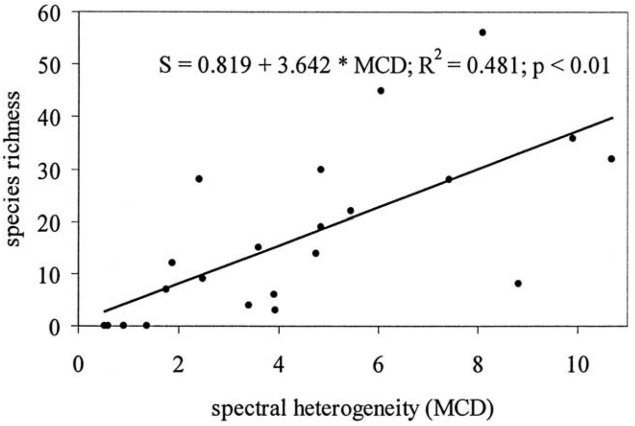

Fig. 3. Relationship, at the macroplot scale (1 ha), between spectral heterogeneity measured by distance from centroid in two-dimensions (MCD) and species richness.

4. Discussion

An interesting relation between spectral heterogeneity of multispectral remotely sensed images and the number of species, at both the 100 m^2 and 1 ha spatial scales, was reported for the first time in the present study. The explanation power of the spectral variation obtained by remotely sensed images, with respect to plant species richness, was found to improve with increasing the spatial scale of analysis. A larger window led to a higher spectral and ecological heterogeneity and, thus, to both higher spectral heterogeneity and species richness. Palmer et al. (2000; 2002), who first introduced the SVH, pointed out that the relation between spectral heterogeneity and species richness is scale dependent, with the overall fit improving with the increasing window of analysis. These authors used data (1 m) with a higher spatial resolution with respect to the present study (3 m), and consequently a higher number of pixels to calculate spectral heterogeneity. However, the single waveband panchromatic images (aerial gray-scale photos) used were not found to produce a significant correlation with plant species richness at the smaller spatial scales (4 and 100 m^2), but only at the larger one (900 m^2). The present test resulted in a statistically significant relation for both the investigated spatial scales (100 m^2 and 1 ha). However, we were able to use, for our test, images with higher spectral resolution (four wavebands rather than one) and this increased spectral resolution led to a higher predictive capability with respect to species richness at the 100 m^2 scale, despite the lower spatial resolution. The spectral heterogeneity varies in relation to the spatial scale of the sample area because the distribution characteristics of a variable depend on the area within which these are measured or estimated (Dungan et al., 2002). Spatial scale also exerts a basic role in controlling species richness (Arrhenius, 1921; Gleason, 1922; Connor and McCoy, 1979). Thus, one would expect to observe some scale dependence in the relationship between these two variables.

The availability of data with improved spatial and spectral resolutions represents an opportunity for the study of the relationship between spectral and ecological heterogeneity (Innes and Koch, 1998). The resultant instruments should allow an improved estimation of species diversity in plant communities. The spatial scales at which SVH was verified during this study (100 m^2–1 ha) correspond to those mostly used for field vegetation sampling (Kent and Coker, 1992). The development of remotely sensed tools for estimating species richness data at these spatial scales may prove to be useful for floristic exploration, monitoring activities and management practices.

Conservation decisions are often taken with incomplete information (Polasky et al., 2000). Methods utilizing remotely sensed optical characteristics can provide important information on the dynamics of the compositional features of plant communities in a given area. As Kerr and Ostrovsky (2003) point out, the scale gap perceived with coarse resolution satellites is narrowing with the increasing availability of very high-resolution data that can be linked to field measurements. A number of studies have been successful in developing biodiversity indicators by means of satellite information, mostly using vegetation indices such as NDVI (Gould, 2000; Oindo and Skidmore, 2002) and vegetation maps. Gould (2000) utilized NDVI variability alone to explain a greater portion of the variation in species richness than a vegetation map, finding values of 65% vs. 34%, and using both NDVI and a vegetation map to obtain values of 79%. Foody and Cutler (2003) pointed out that more accurate predictions could be obtained using more complex approaches, e.g. by using standard deviation of nearest pixels and neural networks. They obtained a correlation coefficients (r) up to 0.52 between remotely sensed estimates and field observed species richness. However, most of these studies deal with local scales but coarser resolution of satellite data (e.g. LANDSAT TM, 30 m).

In the present research, regression analysis between NDVI standard deviation and species richness accounted for no more than 6% for the variance at the 0.01 ha scale and 30% for that at the 1 ha scale, compared to 19% and 48%, respectively obtained with the spectral heterogeneity approach. Thus, spectral heterogeneity appears to be a promising approach to predict species richness at local sc ales and not only at the 1–1000 as argued by Palmer et al. (2002). Furthermore, such an analysis was performed without requiring models of vegetation spectral response. In addition, in our data set, it was not possible to observe any relation between the classified vegetation types and the position of the site in the scatter plot of species richness vs. spectral heterogeneity.

As mentioned by Palmer (2002), processing and classifying images can result in an important loss of information, due to the degradation of continuous quantitative information into discrete classes. Our approach, using continuous (unclassified) reflectance values resulted in a positive outcome and provides a new possibility for researchers to develop relationships between species richness and remotely sensed data.

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