



# Maximizing plant species inventory efficiency by means of remotely sensed spectral distances

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## ABSTRACT

**Aim** Inventorying plant species in an area based on randomly placed quadrats can be quite inefficient. The aim of this paper is to test whether plant species richness can be inventoried more efficiently by means of a spectrally-based ordering of sites to be sampled.

**Location** The study area was a complex wetland ecosystem, the Lake Montepulciano Nature Reserve, central Italy. This is one of the most important wetland areas of central Italy because of the diverse plant communities and the seasonal avifauna.

**Methods** Field sampling, based on a random stratified sampling design, was performed in June 2002. Plant species composition was recorded within sampling units of 100 m<sup>2</sup> (plots) and 1 ha (macroplots). A QuickBird multispectral image of the same date was acquired and corrected both geometrically and radiometrically. Species accumulation curves based on spectral information were obtained by ordering sites to be sampled according to a maximum spectral distance criterion (i.e. by ordering sampling units based on the maximum distances among them in a four-dimensional spectral space derived from the remotely sensed data). Different distance measures based on mean and maximum spectral distances among sampling units were tested. The performance of the species accumulation curve derived by the spectrally-based ordering of sampling units was tested against a rarefaction curve obtained from the mean of 10,000 accumulation curves based on randomly ordered sampling units.

**Results** The spectrally-derived curve based on the maximum spectral distance among sampling units showed the most rapid accumulation of species, well above the rarefaction curve, at both the plot and the macroplot scales. Other ordering criteria of sampling units captured less richness over most of the species accumulation curves at both the spatial scales. The accumulation curves based on other measurements of distance were much closer to the random curve and did not show differences with respect to the species rarefaction curve based on random ordering of sampling units.

**Main conclusions** The present investigation demonstrated that spectral-based ordering of sites to be sampled can lead to the maximization of the efficiency of plant species inventories, an activity usually driven by the 'botanist's internal algorithm' (intuition), without any formalized rule to drive field sampling. The proposed approach can reduce costs of plant species inventorying through a more efficient allotment of time and sampling.

## Keywords

QuickBird, remote sensing, sampling effort, sampling efficiency, satellite imagery, species accumulation curves, species richness.

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## INTRODUCTION

There are important links between biodiversity and ecosystem complexity and function (Kaennel, 1997; Yoccoz *et al.*, 2001). Species richness and complementarity are among the most

straightforward indicators of biodiversity (Colwell & Coddington, 1994). Therefore, many efforts have been made to develop tools for biodiversity assessment and monitoring based on the quantification of species diversity (Stoms & Estes, 1993; Noss, 2002; Rodrigues & Gaston, 2002).

In particular, species rarefaction curves demonstrated their usefulness in estimating the expected number of species as a function of sampling effort, quantified by the number of individuals or quadrats sampled (Gotelli & Colwell, 2001; Koellner *et al.*, 2004). These curves have also been used to obtain estimates of species richness based on a standardized sampling effort, which allows both valid comparisons between inventories and the estimation of the minimum sampling effort required to reach a satisfactory level of completeness (Moreno & Halffter, 2000).

On the other hand, plant inventories are typically not based on objective sampling methods, such as those required for calculating rarefaction curves. Usually, the botanist involved with species inventorying searches for rare habitats to maximize the list of plant species recorded with a given effort. Palmer *et al.* (2002) defined this approach as based on the internal botanist's algorithm, and observed that it is likely to outperform any objective sampling in terms of maximizing plant species inventories. They also proposed a series of methods for maximizing species inventories with the support of some ancillary data (Palmer *et al.*, 2002); one of these methods was based on the 'spectral variation hypothesis', which states that the sites with the highest spectral variation on a remotely sensed image are expected to have the highest number of species. This hypothesis was recently verified by Rocchini *et al.* (2004) using multispectral fine-scale satellite images. Several authors have related spectral heterogeneity to plant diversity, often measured as variance of spectral values (e.g. Gould, 2000; Foody & Cutler, 2003) or as the distance from the spectral centroid of the sampling units (e.g. Palmer *et al.*, 2002; Rocchini *et al.*, 2004), and reached interesting results in predicting the local species richness, namely the  $\alpha$ -diversity (Whittaker, 1972).

However, different sites rich in species may be very similar in their species composition, thus showing a low species complementarity (the  $\beta$ -diversity of Whittaker, 1972), or they may be very different. Therefore, when aiming to maximize the number of pooled species recorded, one should follow a strategy revealing not only which sites are richer in species but also how to select the next site to be sampled once one site has already been sampled. In practical terms, because the sampling order of sites determines the slope of the accumulation curve (Ugland *et al.*, 2003), an optimal strategy for maximizing species inventory should result in the highest species accumulation curve among all the possible curves. The aim of this paper is to test whether plant species richness can be inventoried more efficiently by means of a spectrally-based ordering of sites to be sampled.

### Study area

The study area is a complex wetland ecosystem, the Lake Montepulciano Nature Reserve, central Italy (lat. 11°54'51", long. 43°05'47", datum WGS84). This area is 470 ha in size, and is centred on a 100-ha shallow lake surrounded on three sides by common reed, *Phragmites australis*, and *Carex* sp. pl. marsh of about 280 ha. This is one of the most important wetland areas of central Italy because of the seasonal avifauna and the plant communities, both rich in endangered species.

## METHODS

### Field data

During June 2002, a biodiversity monitoring program was initiated and it was based on a random stratified sampling design (Fig. 1). Plant species composition was sampled within squared sampling units of 100 m<sup>2</sup> (plots) and 1 ha (macroplots). The differently sized sampling units were organized such that four of the smaller units were nested within one of the larger ones. The sampling design resulted in a total of 88 plots and 22 macroplots. Data on species composition were collected in the plots and used to calculate the pooled species list for macroplots, and stored in a GIS-linked archive.

### Remotely sensed data

A QuickBird multispectral image (spatial resolution: c. 3 m; spectral resolution: 4 bands, from 0.45 to 0.90  $\mu$ m), was acquired for the same date of field sampling (June 2002) and corrected both geometrically and radiometrically. Geometric correction was achieved by means of 20 ground control points (GCPs) and a Digital Terrain Model (DTM, spatial resolution: 10 m) of the study area, reaching a root mean squared error (RMSE) of 3.1 m. The radiometric correction was achieved by dark object subtraction (Chavez, 1996).

For each sampling unit (plots and macroplots), pixel values were recorded as points, having as coordinates  $x$ ,  $y$ ,  $w$  and  $z$ , the pixel reflectance values within each spectral band, in a four-dimensional spectral space.

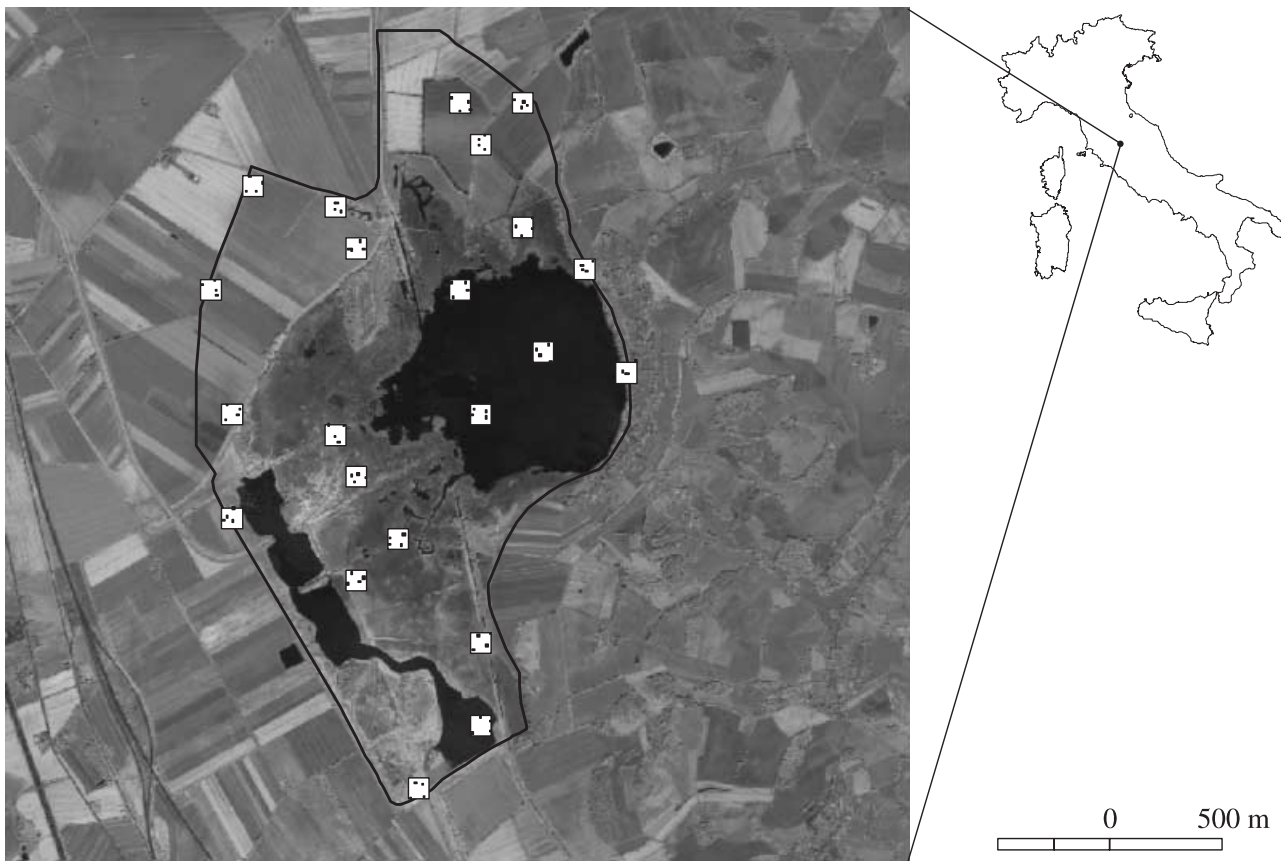
### Data analysis

The ID of the corresponding sampling unit was assigned to each pixel within a GIS environment by a spatial overlap. Sampling units (at the plot and the macroplot scales, separately) were then represented in the four-dimensional spectral space. In this space, each sample was a cloud of nine or 1089 points (pixels) at the plot and the macroplot scales, respectively. In fact, each pixel of the multispectral image could be viewed as a point in a four-dimensional spectral space having as coordinates  $x$ ,  $y$ ,  $w$  and  $z$ , its value in each band  $X$ ,  $Y$ ,  $W$  and  $Z$ .

Species accumulation curves based on spectral information were calculated by ordering the sampling units according to a criterion of maximum spectral distance (namely to a sequential ordering of sampling units based on their maximum distance in the previously described four-dimensional spectral space) and counting the pooled number of species resulting by such ordering. The number of pooled species inventoried by pooling the species presence data from these sampling units was then calculated.

Among the different feasible measures of spectral distance, the following were tested:

- (1) maximum distance among the centroids of the points of the sampling unit clouds ( $C_{ave}$ ), defined as those points having as coordinates the average of pixel coordinates within each sampling unit;



**Figure 1** QuickBird image (only band 4 is shown, near infrared, 0.76–0.90  $\mu\text{m}$ ). Black contour: Lake Montepulciano Nature Reserve; white squares: macroplots (1 ha) and black squares: plots (100  $\text{m}^2$ ).

- (2) maximum distance among the centroids of the points of the sampling unit clouds ( $C_{\text{med}}$ ), defined as those points having as coordinates the median of pixel coordinates within each sampling unit;
- (3) maximum of the mean distances among all the points of the sampling unit clouds ( $P_{\text{ave}}$ ); and
- (4) maximum distance among all the points of the sampling clouds ( $P_{\text{max}}$ ).

In order to avoid extreme outliers for the  $P_{\text{max}}$  distance (a single measure between the most distant extremes of the clouds of points), an average value of the highest  $n$  distances was calculated, as in equation 1:

$$P_{\text{max}} = \frac{\sum_{n=1}^{\sqrt[3]{N}} d}{n}, \quad (1)$$

where  $P_{\text{max}}$  = maximum distance among all sampling unit pixels;  $N$  = total number of measured distances;  $n$  = number of highest distances (notice that this was chosen as the nearest integer of the cubic root of  $N$ ) and  $d$  = measured distances.

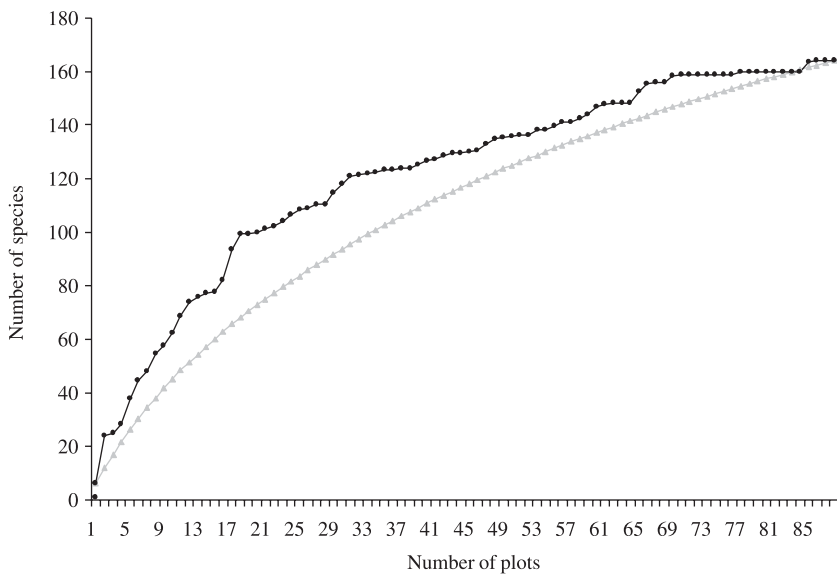
The ordering procedure was repeated by using each of 88 plots and 22 macroplots as starting points. The species accumulation curves were then obtained by the ordering of the sampling units

resulting from the criteria previously described. The mean and empirical variance of the resulting 88 and 22 species accumulation curves, for the plot and macroplot scales, respectively, were calculated.

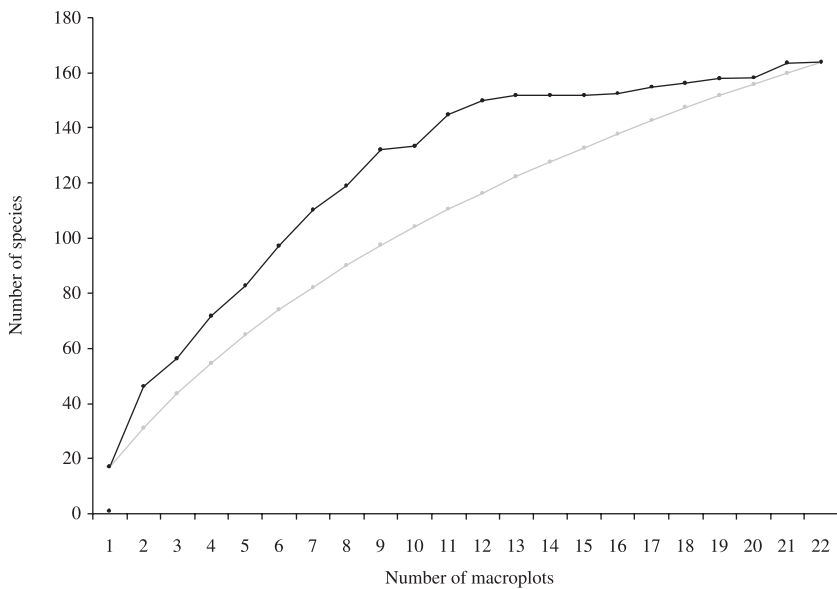
The performance of the spectrally-based accumulation curve was tested against a rarefaction curve obtained from the mean of 10,000 accumulation curves resulting from random ordering of sampling units. The latter was used as a neutral reference model. The probability of obtaining lower values of accumulated species with other ordering criteria (than spectrally derived ordering) was calculated by using the following equation:

$$P_i = \frac{\sum \binom{n_{lv}}{n_r}}{n_s}, \quad (2)$$

where  $P_i$  = probability of obtaining lower values with other ordering criteria than spectrally-derived ordering with the  $i^{\text{th}}$  number of sampled units;  $n_{lv}$  = number of lower values derived from random accumulation curves with respect to spectrally-derived values, given the same number of sampling units;  $n_r$  = number of all calculated random accumulation curves values (in this case  $n_r = 10,000$ ) and  $n_s$  = number of spectrally-derived values (88 at the plot scale and 22 at the macroplot scale).



**Figure 2** Accumulation curves at the plot scale (100 m<sup>2</sup>). Black: mean of 88 curves derived from a sequential ordering of sampling units based on their maximum spectral distance  $P_{\max}$ ; grey: rarefaction curve obtained as the mean of 10,000 accumulation curves based on random ordering of sampling units.



**Figure 3** Accumulation curves at the macroplot scale (1 ha). Black: mean of 22 curves derived from a sequential ordering of sampling units based on their maximum spectral distance  $P_{\max}$ ; grey: rarefaction curve obtained as the mean of 10,000 accumulation curves based on random ordering of sampling units.

## RESULTS

### General

One hundred and sixty-four subgeneric taxa — species and subspecies (thereafter referred to as species) — of vascular plants were recorded in the 88 plots of 100 m<sup>2</sup>, nested within the 22 macroplots of 1 ha. Species richness per sampling unit ranged from 0 to 29 at the plot scale and from 0 to 56 at the macroplot scale.

### Performance of spectrally-based accumulation curves

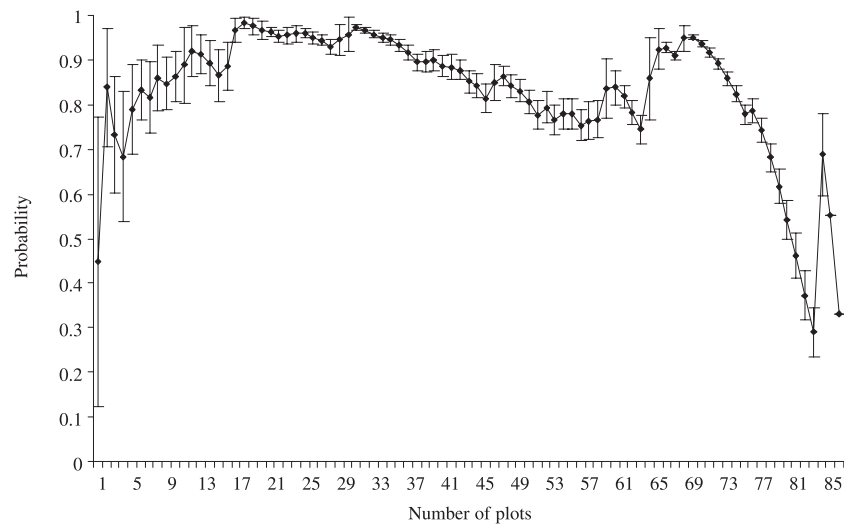
Among all spectrally-derived accumulation curves, the  $P_{\max}$  ordering criterion resulted in the most ‘rapid’ species accumulation curve, well above the rarefaction curve obtained with a random ordering of sampling sites, at both the plot and the macroplot (Figs 2 & 3, respectively) scales. The other measures

of spectral distance performed less well and were much closer to the rarefaction curve obtained with a random ordering of sampling sites.

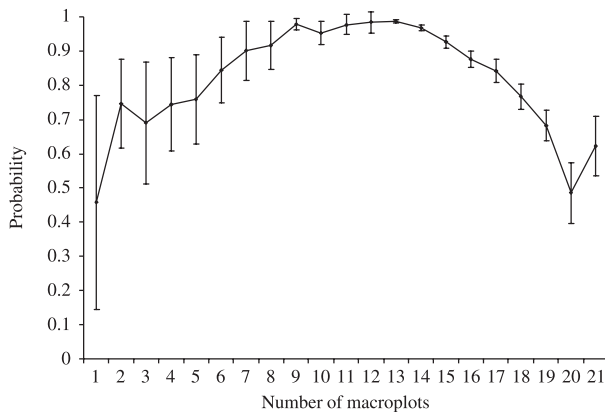
The scatterplot of the probability of obtaining a lower number of pooled species values with other ordering than that obtained with the  $P_{\max}$  criterion showed a value higher than 90% for most part of the curve at both the plot and the macroplot scales (Figs 4 & 5).

## DISCUSSION

As few species occur in all habitats (e.g. Kerr *et al.*, 2001), the addition of new habitats in a sample leads to an increase in the recorded pooled species richness (Fairbanks & McGwire, 2004). Our results support this theory and demonstrated how the addition of a spectrally, and thus environmentally, different site to a sample results in an improvement of the pooled list of recorded species. The maximum average spectral distance criterion did



**Figure 4** Scatterplot of the probability of obtaining lower values of pooled species richness by using other ordering criteria than the  $P_{\max}$  ordination of plots (100 m<sup>2</sup>). Bars represent standard deviation.



**Figure 5** Scatterplot of the probability of obtaining lower values of pooled species richness by using other ordering criteria than the  $P_{\max}$  ordination of macroplots (1 ha). Bars represent standard deviation.

not lead to any positive outcomes in accumulating species, compared to the maximum spectral distance criterion, indicating that the latter better differentiates between (two) sites, at both the considered spatial scales. As an ecological-mechanistic basis, we hypothesize that the extremes of the environmental gradient, and not its average condition, are important in controlling differences in species composition among the sites. In fact, the ordering of sampling sites based on the maximization of distances in a four-dimensional spectral space resulted in a more rapid accumulation of species on the species accumulation curve.

According to Diamond (1988) and Palmer *et al.* (2002), a higher heterogeneity in habitat characteristics results in higher species richness. Spectral heterogeneity has been previously demonstrated to have a high predictive power with respect to species richness within a given site, at different spatial scales (Gould, 2000; Kerr *et al.*, 2001; Oindo & Skidmore, 2002; Rocchini *et al.*, 2004). Therefore, the relationship between spectral heterogeneity and species richness (spectral variation hypothesis) can be used to locate the sites with the highest species richness ( $\alpha$ -diversity). Further, extending on Palmer *et al.* (2002)

and Rocchini *et al.* (2004), the present investigation demonstrated that species complementarity among sites ( $\beta$ -diversity) can also be maximized by a spectrally-based ordering. This approach allows the detection of important spatial gradients of species diversity, and thus maximizes the inventorying of plant species in an area for a constrained sampling effort. In fact, even if the use of the slope of species accumulation curves as an index of  $\beta$ -diversity is still controversial (Scheiner, 2003; Gray *et al.*, 2004), it is evident that the higher the slope of the accumulation curve, the higher the species dissimilarity among sampled sites (Ricotta *et al.*, 2002).

Plant species inventorying in relatively large areas has always been an important task for plant ecologists, despite the lack of common standards in measuring the completeness of the resulting species lists and in quantifying the sampling effort (see, e.g. Palmer *et al.*, 1995, 2002). This type of data has been utilized for describing and testing phytogeographical and ecological patterns (e.g. Qian, 1998; Nekola & White, 1999; Pysek *et al.*, 2002), but also for nature reserve evaluation and planning (e.g. Heikkinen, 2002; Zurlini *et al.*, 2002). However, as stated by Palmer *et al.* (2002), accurately inventorying species over a large region is complicated by the fact that the botanists cannot inspect every individual plant in the region and that species composition changes through time (Robinson *et al.*, 1994; Kirby & Thomas, 2000; McCollin *et al.*, 2000). On the other hand, floristic lists for relatively large areas cannot yet be obtained with objective sampling combined with statistical estimators of species richness (Chiarucci *et al.*, 2001; D'Alessandro & Fattorini, 2002; Chiarucci *et al.*, 2003). Thus, the development of methods for perfecting species lists is potentially useful for developing lists of species composition over large areas (Palmer *et al.*, 2002). Different methods have been proposed to locate those environmental gradients offering the maximum change in species richness (e.g. Gillison & Brewer, 1985), and the availability of satellite data could render the proposed method straightforward to apply, especially in regions where basic environmental data are scarce or inaccurate.

The wetland environment surveyed in this paper represents a relatively suitable ecosystem for testing the proposed method, as most of the vegetation was structurally simple and the remotely

sensed images recorded almost all the vegetation response on the ground. In forest ecosystems, on the other hand, the spatial heterogeneity perceived by the remote sensor could be lower because of a potentially similar canopy cover (Nagendra, 2001). However, the structure of the canopy layers could reveal the heterogeneity related to forest structure and diversity, providing thus useful results, especially in ecosystems with a very high degree of fragmentation. The use of high resolution multispectral data can significantly improve the capability of the proposed methodology to discern between apparently similar vegetation structures. Data sources such as QuickBird or Ikonos — *c.* 3 m and 4 m of spatial resolution, respectively — permit the identification of transition zones and heterogeneous habitats, avoiding the problem of a lack of detectability of subpixel heterogeneity (e.g. mixed pixels, see Small, 2004; Schiwe, 2005). This type of data is very likely to discern small-scale heterogeneity in forest canopy cover and to detect spatial gradient in apparently similar habitat. To date, few researchers have tried to assess species diversity at a detailed scale by using these high resolution multispectral data (Read *et al.*, 2003; Mehner *et al.*, 2004; Rocchini *et al.*, 2004).

Satellites with a coarser spatial resolution (e.g. Landsat, 30 m), which are widely used (e.g. Gould, 2000; Oindo & Skidmore, 2002; Foody & Cutler, 2003; Fairbanks & McGwire, 2004) for their lower cost and easier availability, can hide fine grained patterns, such as margins between vegetation types, hedges and small forest gaps, and thus result in the loss of many species within the obtained lists. Even if Landsat imagery has a higher spectral resolution than QuickBird or Ikonos sensors, the addition of redundant data can increase noise without adding valuable information, by including spectral information not related to habitat heterogeneity as noise in statistical models (Bajcsy & Groves, 2004). Future analyses will better clarify the relative importance of spatial and spectral resolutions in controlling the maximization of plant species inventory efficiency.

The proposed approach may be applied over a larger area, where multiple mosaicked images are necessary. Clearly, in this case, a rigorous radiometric correction is needed in order to discriminate among really or misleadingly spectrally different sites. Otherwise, spectral distances among objects could be due to different values of the same habitat type within different images.

To summarize, time and cost efforts of plant species inventorying could be seriously reduced, or at least planned in a more efficient way, by using multispectral satellite data with high spatial resolution, and this approach can be profitably applied to face biodiversity assessment at a detailed scale from a remotely sensed perspective.

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