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RESEARCH ARTICLE

Multiscale ecological assessment of remote sensing images

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Abstract In landscape ecology, the importance of map extent and resolution on the value of landscape indices is widely discussed, but the information content of the map, mostly derived from remote sensing images, is not. In this study, we sought (1) to understand the influence of changes in maps' spatial and spectral resolution of agricultural landscape elements, taking hedgerow networks as a case study, and (2) to explore how predictions of species distribution might be affected by maps' resolutions, taking two carabid species as a case study. To do so, we compared maps from different remote sensors, derived two landscape characterization variables from the maps related to patterns known to drive ecological processes, and analyzed their predictive power on biological data distribution to assess the information content of these maps. The results show that (1) the use of several methods, including landscape metrics, was useful to assess map validity; (2) the spatial resolution of satellite images is not the only important factor; changes in spectral resolution significantly alter maps; (3) the relevant definition of "hedgerow" to construct functional maps is species and process specific; thus the different maps are not either good or bad, but rather provide complementary information; (4) the more a species responds to network structure and over small areas, the less the different maps can be substitutable one to another.

Keywords Biodiversity · Carabid · Hedgerow · Landscape metrics · Satellite images

Both Vannier and Vasseur (in alphabetic order) have equally contributed to the paper and are thus joined "lead authors".

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Introduction

Mapping landscape features that may control, enhance, or impede ecological processes is a key element in landscape ecology. The interactions between ecologists, geographers, and land planners in IALE (International Association of Landscape Ecology) have fostered a wealth of initiatives to develop mapping techniques, to utilize remote sensing images (Groom et al. 2006), and to design software to analyze maps (McGarigal 2002). From the onset of landscape ecology, many authors discussed the importance of map extent and resolution

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on the value of landscape indices (Turner 1990; O'Neill et al. 1991; Gustafson 1998). However, most maps were made from remote sensing images, but the information content of maps was not discussed. Li and Wu (2004), when addressing the problem of the use of landscape indices, recognize scale dependency as a major issue. They distinguish the scale of observation and the scale of analysis. They state that "Difficulties in collecting data at multiple scales of observation have forced most studies of scale effects to concentrate on the scales of analysis". They acknowledge that "Once the data are collected, however, the scale of observation is an inherent property of the data set" and these problems inherent to the scale of observation may remain. To tackle this problem they accept that, for practical reasons, "Changing scale by manipulating data can be a surrogate for observing the landscape directly with two or more sensors (or sampling schemes) of different resolutions". More recently, (Bailey et al. 2006) analyzed the effects of thematic resolution on the outcome when computing landscape indices. They conclude that the finest resolution (many themes) is more a source of noise than information. If, in landscape ecology, the functional meaning of landscape metrics derived from maps is the task of ecologists, the analysis of the process of map-making from data is the task of geographers. Collaboration between both disciplines is a prerequisite to address the question of the information content of maps from raw data to metrics meaningful for ecological processes. The purpose of this paper is to address several issues of scale when relating species distribution to landscape maps: (1) the spatial and spectral resolution of the images to produce maps and (2) the extent of the analytical windows used to calculate the landscape metrics.

Our aim was to compare maps from different remote sensing data, to characterize internal structure of maps with landscape metrics related to patterns known to drive ecological processes, and to assess the functional information content of these maps. To do so, we concentrated on a single landscape element, "wooded hedgerow", and on the linear wooded hedgerow networks that constitute a bocage landscape. Hedgerows are present in many agricultural landscapes around the globe and distinct enough to deserve special attention (Forman and Baudry 1984). Hedgerow networks have multiple functions (Baudry et al. 2000a) such as protection of soils against wind and water runoff; they can reduce pollutant loads in runoff and mitigate the effects of discharge runoff into receiving water bodies (Merot et al. 1999). They also play a key role in the maintenance of biodiversity (Saunders et al. 1991; Burel et al. 1998). From a mapping standpoint, these linear landscape features are difficult to determine on large areas because of their thinness, spatial configuration, and the heterogeneity of the landscape around these features.

Landscape ecology shows that most species are dependent on both landscape composition and configuration (Fahrig et al. 2011). To thrive in an area, any population of plant or animal needs good conditions to grow, disperse, hide, and reproduce. This involves ability of individuals to move within landscapes and to have enough suitable landscape elements to sustain a minimum viable population. It therefore appears preferable, in order to study the relationships between biodiversity and environmental factors, to assess the suitability of landscape units of various sizes rather than to focus exclusively on the quality of local conditions (Le Coeur et al. 2002; Schweiger et al. 2005). Scale dependency in the relationships between biodiversity patterns and landscape metrics are the rule (Cushman and McGarigal 2002).

Most of the time, wooded hedgerows are digitized by hand from conventional airborne photographs or orthophotoplans over small study areas. Although all hedgerows can be represented on maps, this approach is time-consuming, labor-intensive, and the updating of maps, which depends on data availability, is often postponed. Sheeren et al. (2009) used conventional aerial photographs and implemented automatic detection of small wooded elements, while Tansey et al. (2009) used digital airborne photos and elevation data to classify hedgerows and field margins. The methodologies used in these studies have been applied to areas that cover only a few square kilometers. They produce good results, but have not yet been applied on a large scale because of the complexity of aerial photography processing. A GIS database of all the tree cluster outlines was produced in 2005 by IGN (the French administration for geography) for the whole of the French metropolitan territory using orthophotoplans and applying an automatic extraction method. Since 2005, IGN and IFN (French national forest inventory) are currently updating this database while characterizing tree clusters (forests, copses, hedgerows) (Touya et al. 2010). An evaluation of the information and the quality of this database does not yet exist. Several papers dealing with landscape features mapping from remote sensing data have shown that satellite images with high or very high spatial resolution are suitable for automatic hedgerow mapping. Thus, linear strips of wooded vegetation including hedgerows and riparian vegetation have been detected and extracted using an object-oriented method combining spectral, textural and shape criterion from SPOT 5 (Germaine et al. 2008) or Quickbird images (Aksoy et al. 2010). Vannier and Hubert-Moy (2008) compared the ability of different types of satellite imagery to estimate the proportion of hedgerow network that can be automatically extracted in using a remote sensing dataset spanning a wide range of both spatial and spectral resolutions. They show that the classification accuracy is influenced by the data used and agricultural landscape complexity and that the detection performance increases with hedge density. Lennon et al. (2000) apply a fuzzy combination of spectral and textural variables extracted from an airborne hyperspectral image with a spatial resolution at 2 m to map and characterize wooded hedgerows. In spite of the high accuracy of the results, the ability to acquire such imagery over large areas has been limited because of the costs and accessibility of the equipment and technology needed.

In this study, we have developed a methodology to compare different maps of hedgerows derived from remotely sensed data. Beyond simply the data availability or methods to transcribe a wooded hedgerow network with a varying degree of accuracy, it is the structural and functional meaning of maps derived from different types of remote sensing data that we chose to evaluate in this study. We sought (1) to understand the influence of changes in maps' spatial and spectral resolution on the characteristics of hedgerow networks of agricultural landscape, and (2) to explore how predictions of species distribution might be affected by map spatial and spectral resolutions. The approach is illustrated with various existing data from the Pleine-Fougères LTER site (osur.univ-rennes1.fr/zoneatelier-armorique) in Brittany (France). Actually this site shows a strong gradient of hedgerow density. To evaluate this methodology we chose carabids as taxonomic group model due to their contrasted responses to landscape composition and structure, i.e. a good indicator (Burel et al. 1998; Schweiger et al. 2005), in particular to hedgerows and hedgerow network characteristics. Moreover, it has been shown that the community composition vary along the hedgerow gradient of the study site, forest species being gradually replaced by open field species. Thus a forest species, *Abax parallelepipedus* (Pillet and Mitterpacher) and an open field species, *Pterostichus melanarius* (Illiger) have been selected to perform the ecological assessment of maps.

Methods

After the presentation of the landscape context of the study site ("Study site" section) we present the methodological steps of six remote sensing images evaluation, organized as follows: the hedgerow maps construction from remote sensing images ("Hedgerow maps construction" section); the hedgerow maps multiscale characterization notably involving two landscape metrics ("Structural and functional evaluation of hedgerow maps" section) and the maps ecological assessment with carabid distribution data ("Ecological assessment of maps" section).

Study site

We performed our analysis on the Pleine-Fougères LTER site (www.osur.univ-rennes1.fr/zoneatelier-armorique) in north-eastern Brittany (48°36′ N, 1°32′ W), France (Fig. 1). It is characterized by a strong spatial variation in hedgerow network density (Baudry et al. 2000b). Hedgerows and earthen banks were inventoried from field surveys conducted in 1994–1995 in three subnetworks along the hedgerow gradient (about 500 ha each, see (Baudry et al. 2000b) for details). Thus, information on characteristics of the bocage of the study site, independent from those used to construct the hedgerow maps and unbiased by remote sensing acquisition, were available. According to these data, hedgerow network density ranged from 115 m/ha in the south of the landscape gradient to 74 m/ha in the center and 44 m/ha in the north. Furthermore, if the proportion of boundaries with tree cover ranging from 50 to 75% was similar along the hedgerow gradient, the proportion of boundaries with cover of over 75% diminished from 45% on the south to 31% on the

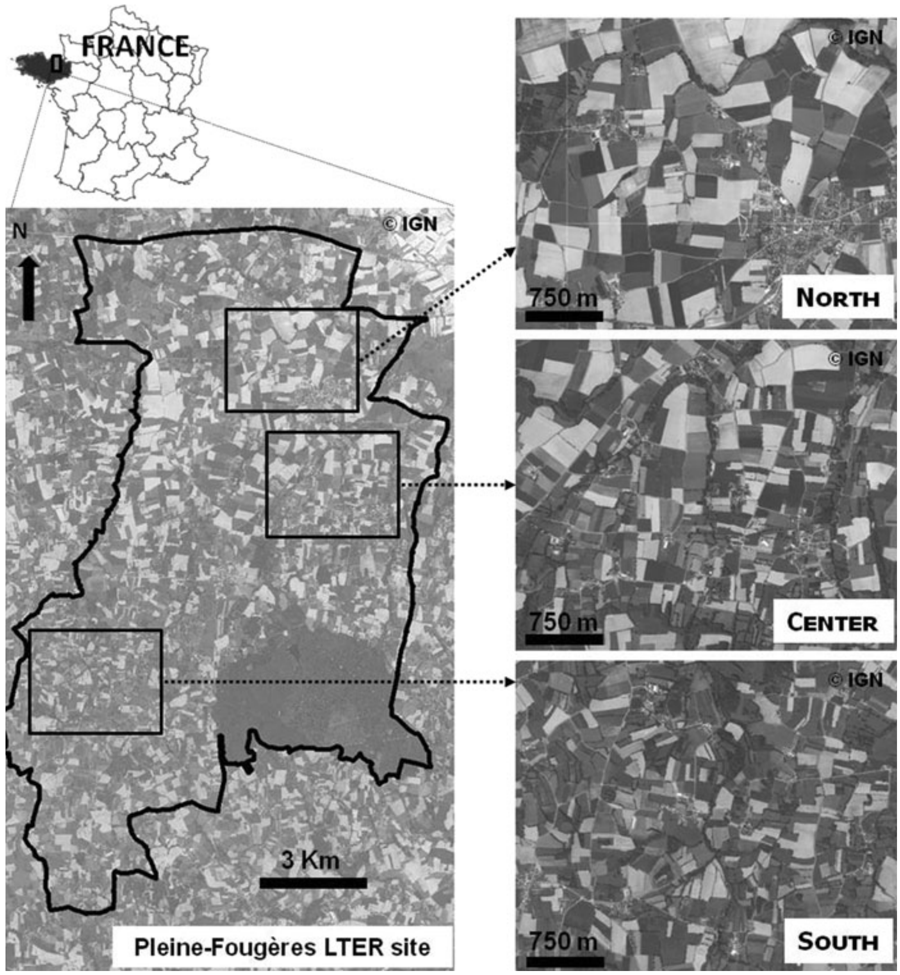

Fig. 1 Location of the study site (Pleine-Fougères, northern Brittany, France) with focus on three subnetworks along the north–south hedgerow gradient. Biological data sampling has been done in hedgerows situated in these subnetworks

center and 27% on the north. Finally, the tree cover was correlated with the canopy width (length between canopy edges): on average 5.8 m for 50–75% cover to 6.4 m for cover of over 75%. Therefore, the south of the hedgerow gradient presents much denser network and tree cover than the center and the north.

Hedgerow maps construction

Six different hedgerow maps were produced from the four different types of remote sensing images: Orthophotoplan, SPOT 5, ASTER VNIR, IRS P6 LISS III (Table 1).

The image dataset was chosen to span a wide range of spatial resolutions and different spectral resolutions. Spectral resolution refers to the number of bands provided by the sensor, as well as their spectral bandwidths (Chuvieco and Huete 2009). Spatial resolution roughly corresponds to the smallest unit that can be detected on an image (Chuvieco and Huete 2009) i.e. the size of a pixel that is recorded in a remotely sensed raster image. Map resolution can be defined as the size of the smallest feature that can be represented on a surface and as the accuracy at which the location and shape of map features can be depicted for a given map scale. The spectral resolution of the dataset ranged from one panchromatic band (orthophotoplan), to multispectral bands from visible to near infra-red wavelengths; the spatial resolution ranged from 0.5 to 23 m (Table 1). All images were acquired during the vegetation season between 2001 and 2005 approximately at the same time of day with small view angles (no more than 20° from nadir) to avoid shadows created by the canopy. Although images are from different years, only very

Table 1 Characteristics of remote sensing data

	Orthophotoplan	SPOT 5	SPOT 5	ASTER VNIR	IRS P6 LISS III
Date	08/14/2001	09/24/2002	09/24/2002	09/09/2004	05/27/2005
Spatial resolution (m)	0.5	5	10	15	23
Spectral bands (μm)	Panchromatic	P: 0.51–0.73	B1: 0.50–0.59	B1: 0.52–0.60	B1: 0.52 –0.59
			B2: 0.61–0.68	B2: 0.63–0.69	B2: 0.62 – 0.68
			B3: 0.78–0.89	B3: 0.78–0.86	B3: 0.77 – 0.86
			B4: 1.58–1.75		B4: 1.55 – 1.70

small changes occurred in the hedgerow network during this 4-year time period; less than 2% of hedgerows were removed and 12% pruned (Lofti et al. 2010). We made the assumption that this dataset made possible the detection of different types of hedgerow elements from the tree-crown to the micro-landscape.

One map, the hedgerow reference map (named *MD*), was produced from a manual digitization of the orthophotoplan in a geographical information system (GIS) using ArcGis 9.2 software. In the resulting map each hedgerow is represented by a polyline, the common way to represent hedgerows (Forman and Baudry 1984). Hence, and unlike the other maps, this map indicates the hedgerow network length and its position in the landscape, but it does not provide information on the tree canopy width or internal structures of hedgerows (number or length of gaps, type of trees, etc.).

For the five other maps we used an object-oriented approach to classify wooded hedgerows from the remote sensing dataset (Burnett and Blaschke 2003; Benz et al. 2004), using eCognition software (Definiens Imaging, Munich) as described in (Vannier and Hubert-Moy 2008). The object-oriented approach consisted in classifying homogeneous groups of pixels using spatial concepts and contextual information (Blaschke and Strobl 2001). Radiometric correction of the imagery was performed applying the 5S model (Tanré et al. 1990), and geometric correction was undertaken using ArcGIS 9.0 (ESRI Inc.). All data were georeferenced based on the Lambert 2 conformal conic system, the Root Mean Square Error was less than 0.5 pixel. Note that the SPOT 5 image includes two types of spectral resolutions (Table 1): multispectral bands were merged with the panchromatic band using the HLS model (Hue Lightness Saturation), in order to obtain a 5 m pan-sharpened image (Vrabel 1996). All maps were then processed in two stages that were a multi-criteria segmentation and a membership classification. The segmentation process generates objects based on scale, shape and reflectance of the image pixels. Thus, we classified objects in two classes, "hedgerow" and "no hedgerow", using a supervised classification algorithm based on membership functions (brightness index, mean and ratio derived from objects reflectance).

All classifications of remote sensing data result in different kinds of errors that can affect subsequent landscape pattern analysis (Pontius 2000; Shao and Wu 2008). Thus classification accuracy needs to be evaluated (Wu and Hobbs 2007).We first calculated *Kappa* index which expresses the proportional reduction in error generated by a classification process compared with the error of a completely random classification (Congalton 1991). Based on an error matrix between samples of hedgerow objects selected by photo-interpreting the orthophotoplan and classified objects, the *Kappa* index allows to estimate the percentage of well, over and under-detected objects of a classification. However limits of such methods to evaluate map accuracy, particularly for ecological purposes, have been recently pointed up. As highlighted by Pontius (2000), this standard index only gives a classification quantification error i.e. only informs about "the quantity of cells of a particular category in one map that is different from the quantity of cells of that category in the other map". Thus, others complementary methods detailed in the following "Structural and functional evaluation of hedgerow maps" section have been used too for maps evaluation.

Then, a post-processing procedure using the *MD* map was applied for removing overestimated elements and to generate final maps (underestimated elements were not re-introduced). Consequently, the "finest" wooded hedgerow element represented in all maps corresponds to the "hedgerow definition" used for the *MD* map which is "a field boundary with a range of wooded elements composed of three trees minimum with gaps no longer than 10 m (IGN)".

Finally, six hedgerow maps were produced: *MD* (from manual digitization) and *Ortho*, *Spot5*, *Spot10*, *Aster*, and *Irs*, from the classifications of the remote sensing images, respectively the orthophotoplan, the SPOT 5 merged data, the SPOT 5 original data, the ASTER VNIR and the IRS P6 LISS III. Each of them differs in the characteristics of hedgerow structure and hedgerow network detected and represented. While a "hedgerow" is most of the time considered by authors as a tree range along a field boundary (Forman and Baudry 1984), in this study we sought to define functional attributes of hedgerows by analyzing the ecological relevancy of each map.

Structural and functional evaluation of hedgerow maps

Pontius (2000) emphasized the need to judge GIS-based, spatially explicit, classification on its ability to produce accurately both quantities and locations of categories of grid cells in a map. An error of location occurs when "the location of a category in one map is different from the location of that category in the other map" (Pontius 2000). As mentioned before, the spatial structure of the hedgerow network is of a great importance for various ecological processes. Consequently it makes the goodness of the representation of land-uses spatial properties crucial to evaluate. Moreover, structural and ecological characteristics of elements which are well, over and under-detected also need to be characterized. Consequently the different subsequent methods have been used to access to the structural and functional content of maps.

Global evaluation of map structures

A global quantitative evaluation of well-detected hedgerows was performed at the site level, function of the landscape context (i.e. along hedgerow gradient) to evaluate the error of location. In the northern, center and southern part of the site, we calculated a global precision index (GPI) i.e. the percentage of the total hedgerow length contained in the reference map that was well-detected by remote sensing classifications. Therefore, the intersection of the *MD* map was performed with all other maps using a GIS database.

In addition, a qualitative information evaluation of the maps was realized: it consisted in the orthophotoplan photo-interpretation that aimed to highlight the structural characteristics of well-detected wooded elements and the omitted ones by other remote sensing sensors.

Multiscale characterization of internal structures

We characterized the multi-scale internal structure of those maps by constructing landscape gradients thanks to landscape measures performed in windows of different size (100, 250, 1000 m).

We used two network characteristics: hedgerow density (named *HD*) and the network grain (named *LG* for landscape grain) that is the size of the mesh of the network from many small elements (fine grain) to few large ones (coarse grain). The first metric is straightforward, but grain has no specific metric, so we proposed a novel one that enabled us to describe gradients of structures. One problem with the density of any element, or percent cover, is that when the element is scarce, many spatial arrangements are possible. For instance, in a landscape with few hedgerows, they can be evenly distributed or clumped, which may create different ecological conditions. Few clumped hedgerows can maintain a high hedgerow influence in part of the considered landscape. The general principle is as follows: every pixel of the raster map was classified according to its distance from the closest hedgerow. Four *distance classes* were used: (0) for "hedgerow", (1) less than 50 m, (2) 50–100 m and (3) more than 100 m (Fig. 2a). These *distance classes* were chosen for their relevance in climatology, hence as a proxy of microclimatic conditions (Caborn 1955). The pattern of distances changes for example between square and rectangular fields; for the same length of hedgerows (perimeter) fewer points are in the third *distance class* for rectangular fields than square fields (Fig. 2b).

Then we constructed a *LG* gradient for each map at the study site scale (named *reference space*): we computed the number of pixels of the different classes contained in square windows centered on equally spaced points (20 m). A correspondence analysis was performed on matrices of windows of

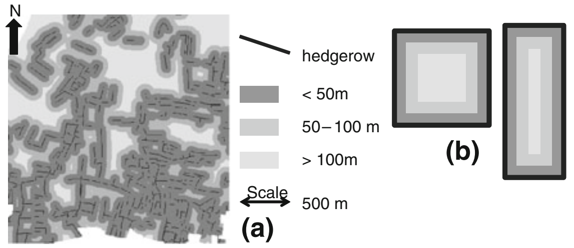

Fig. 2 **a** Example of a distance map (from the *MD)* with four distance classes (0) hedges, (1) less than 50 m, (2) 50–100 m and (3) more than 100 m); **b** Illustration of *LG* variation with field shape with equal perimeter (hedgerow length): the area in *distance class 3* covers 25% of the area in the square and only 14% in the rectangle

4 distance classes × *sampled points.* The first axis of the CA constitutes the *LG* gradient (i.e. the *reference space*). A *reference space* of each map was thus created using the same method for three sizes of windows (100 × 100, 250 × 250 and 1000 × 1000 m); this allowed us to create eighteen *reference spaces* from each specific map and window size (scale of analysis).

Then, to measure the *LG* variables characterizing carabid sampling points we considered them as supplementary points in the *reference space* i.e. their coordinates in the factorial space were calculated a posteriori using the coordinates of the *distance classes* in this space and the relative abundance of the different *distance classes* characterizing each window centered on a carabid sampling point (Benzécri and Benzécri 1984).

To evaluate internal structures of maps we first calculated for *Ortho, Spot5, Spot10, Aster and Irs*, the number of carabid sampling points that were not situated on hedgerows due to sub-detection. Then, using Pearson correlation test, we tested correlations between *HD* and *LG* for all maps. The relationships among metrics were established at the three spatial scales and only for windows around carabid data. Note that *HD* and *LG* have different properties: density depends only on the hedgerows present in the window, i.e. the density of pixels assigned as "hedgerow" whereas the grain is affected by hedgerows surrounding the window. If a hedgerow is right outside a window, the space at the border within the window will be in the <50 m class, while if the hedgerow is at 100 m, this space will be in the >100 m class. At 100 m, due to the fact that the window includes only a part of the hedgerow sampled, *HD* mainly characterizes the width of the hedgerow and *LG* the presence or absence of the hedgerow on the map. Moreover, we hypothesized that when the window size increases, the number of hedgerows included increases, leading to a weakening of each hedgerow's relative weight in favor of greater sensitivity to the total length of hedgerows. This may lead to a higher correlation between the two variables at larger scales. Finally the descriptive comparison of (*HD*/*LG*) correlations coefficient of each map allows evaluation of the effect of maps and landscape metrics interactions on landscape pattern analysis.

Ecological assessment of maps

Model species

To develop and test the methodology of maps functional meaning assessment, we chose two carabid species as model species. Carabids are widely used to study the state of biodiversity in agricultural landscapes (Kromp 1999) and have been studied in Pleine-Fougères for their association with landscape structure (Burel et al. 1998; Aviron et al. 2005). The ecology of this two species is well known: *Abax parallelepipedus* is a stenocious forest species that reproduces and lives in wooded habitats such as dense hedgerows while *Pterostichus melanarius* is a field species that reproduces in arable fields and overwinters in field margins. For the former, hedgerows are corridors facilitating movement (Charrier et al. 1997), while for the latter they are barriers (Thomas et al. 1998). A high *HD* and fine grain landscapes favor *A. parallelepipedus* because of both the climatic conditions (shade and less wind) and the higher connectivity, while *P. melanarius* prefers open spaces with both coarse grain and narrow hedgerows easier to cross. Their presence and relative abundance in hedgerow has been shown to be different in contrasted landscape units and to vary along the hedgerow gradient of the study site (Burel et al. 1998; Millán de la Peña et al. 2003; Aviron et al. 2005). Moreover they differ in their dispersal power (maximum daily displacement distance: 10 m for *A. parallelepipedus* (Charrier et al. 1997) and 73 m for *P. melanarius* (Lys and Nentwig 1992)). Thus they are expected to respond at contrasted scales to the hedgerow network structure. According to its good dispersal ability and its generalist status, *P. melanarius* distribution is expected to respond to larger scales and be less determined by local conditions than *A. parallelepipedus*.

Biological data

The carabid data were collected in the three subnetworks along the hedgerow gradient that have been used in previous studies (Le Coeur et al. 1997; Burel et al. 1998). These subnetworks have been demonstrated to represent contrasted landscape contexts as well as different species assemblages in particular for carabids; and moreover they are informed with supplementary independent data on hedgerow characteristics (see "Study site" section). Sampling units (i.e. three pitfall traps each) were placed at the top of earthen banks, in hedgerows (23 in the northern, 26 the central and 25 in the southern subnetworks, i.e. 74 sampling units in total), and were collected weekly for 5 weeks in May and June 1997. This set-up was chosen to represent a diversity of hedgerow structures and adjacent land use (Baudry et al. 2003).

Statistical analysis of the biological dataset

The predictive power of the landscape gradients of each map was tested for each species by logistic regression. Separated models were created for each combination of species, type of landscape gradient, (*HD* and *LG*) and window size (100, 250 and 1000 m), i.e. 36 models per species. The abundances distribution of each species was analyzed using generalized linear mixed models (GLM) with a log link function. A negative binomial error distribution was used to account for overdispersed count data (Lehvävirta et al. 2006) typical of carabids (i.e. clumped abundance distributions). All the analyses were performed in the R 2.9.0 software package (R Development Core Team 2010). For the significant variables only, the performance of the models in fitting beetle data was compared using the amount of total variance explained.

Results

Hedgerow maps validation

Maps statistical accuracy, assessed by *Kappa* Index, was ranged from 0.75 to 0.95. It means that classification processes have avoided at least 75% of the errors that were generated by a completely random classification. It is an indication of a good or excellent degree of agreement in terms of aspatial quantitative error (Fielding and Bell 1997).

Structural and functional evaluation of hedgerow maps

Global evaluation of map structures

The global precision index (GPI) was quite good for all maps ($\geq$70%), except for the Irs map (28%). It was slightly higher for the *Spot5* map (88%) than for the *Ortho* and the *Aster* maps (74 and 70% respectively). Moreover, the error of detection is spatially structured at the study site level (error of location). Indeed, the detection performance increased along the north-south hedgerow gradient of the study site (Table 2). In addition, the coarser the map, the more marked this spatial pattern of error i.e. the more important the difference of performance in the north and the south: it was quasi-null for *Ortho* and on the contrary strongly marked for *Irs*.

The qualitative evaluation showed that each map contained different information (Fig. 3). The *MD* map portrayed field boundaries indicating the presence of tree range in a boundary but without providing information on the structure of the hedgerows. The *Ortho* map portrayed precisely the shape of tree canopies and part of shadows. The *Spot5* and *Spot10* maps contained most of the wooded hedgerows and network structure. The *Aster* map portrayed coarse wooded hedgerows and omitted narrow hedges. It included large spatial structures and closed landscapes. The *Irs* map portrayed part of closed landscapes composed of woods, shrubs, wooded hedges, small grasslands, fallows. It represented coarse landscape structures of closed areas with many wooded hedgerows and grasslands.

Thus, fine-scale maps (*MD*, *Ortho*, *Spot5* or *Spot10*) depicted density and spatial distribution of hedgerows with a good accuracy whereas coarser-scale maps (*Aster*, *Irs*) represented macro-structures (i.e. wooded hedges gathering).

Multiscale characterization of internal structures

The number of sampling points not situated on a hedgerow increased with the coarseness of the map: 8 out of 74 for *Ortho*, 27 for *Spot5*, 28 for *Spot10*, 40

Table 2 Percentage of well detected hedgerows of each map compared with the *MD* map in different landscape context (i.e. hedgerow network density decrease from the south to the north)

	MD	*Ortho*	*Spot5*	*Spot10*	*Aster*	*Irs*
South	100	76	95	91	74	46
Center	100	74	87	86	62	29
North	100	74	82	74	64	10
Mean	100	74	88	84	70	28

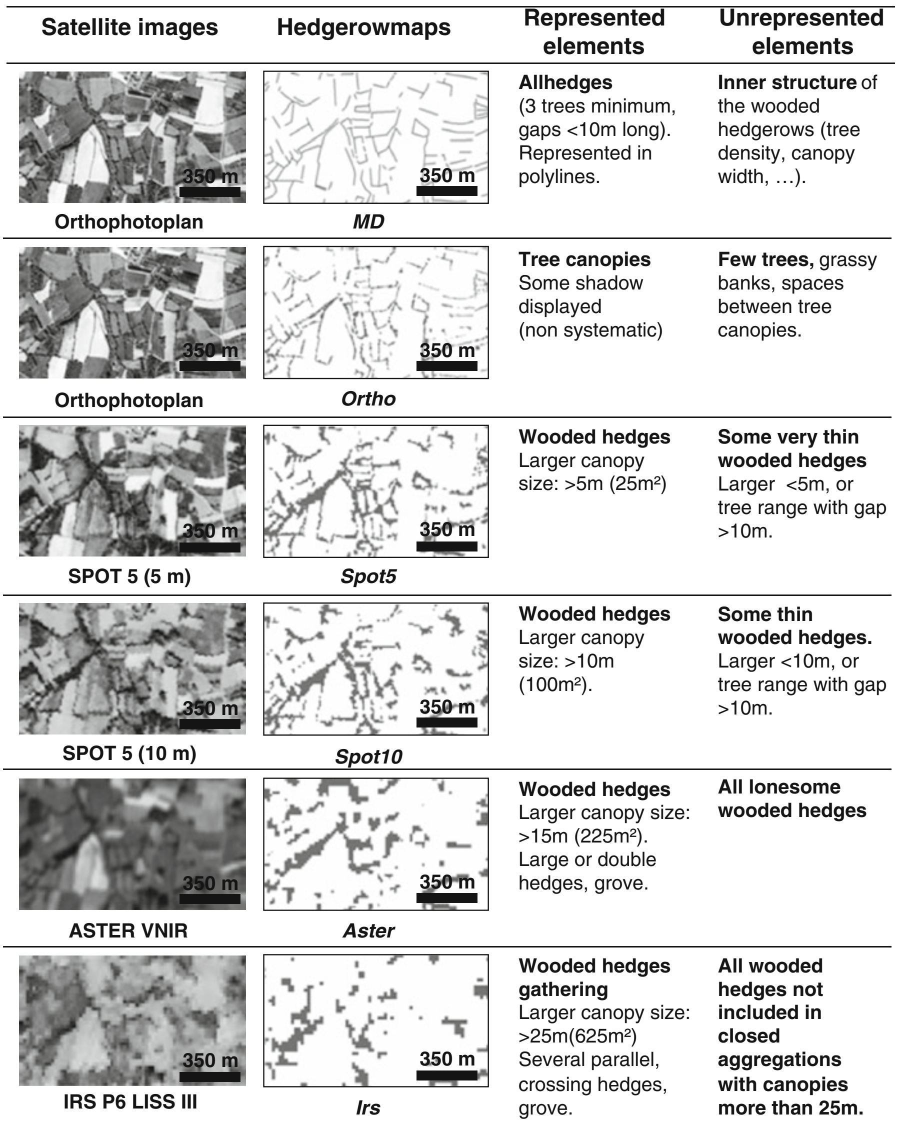

Fig. 3 Summary of characteristics of well-detected wooded elements and unrepresented ones on the different hedgerow maps

for *Aster* and 60 for *Irs*. For *MD*, they are on a hedgerow by construction (see "Biological data" section). This led to several outliers in the relations between variables for the other maps.

The two *landscape gradients* (*HD* and *LG*) were always negatively correlated. For all maps, the *HD*/*LG* correlations increased with the window size increase, 0.26 ± 0.11, 0.47 ± 0.15, 0.91 ± 0.05 in average at 100, 250 and 1000 m respectively (Table 3). For maps integrating the amount of tree cover, this window size effect was more marked as the spatial resolution of the map is high. That was explained by stronger dissimilarities between *HD* and *LG* variables at finest scales for these maps. These results suggested that these metrics uncovered landscape differences at fine scales between fine maps but became highly redundant for all maps at the 1000 m scale. This seemed not depend only on hedgerow width detection but also on landscape characteristics.

Considering each landscape gradient, *HD* as *LG*, all pairwise comparisons of maps (Table 4) showed increasing correlations with window size. Both gradients were very different between maps at 100 m, even between fine maps (*MD*, *Ortho*, *Spot5*) but were similar at 1000 m. At 100 m and 250 m window sizes, maps were more similar in terms of *HD* than *LG*. However, both gradients are well correlated between *Spot5*, *Spot10* and *Aster* even at 100 m.

Ecological assessment of maps of hedgerow maps

Pterostichus melanarius

Both *HD* and *LG* explained the *P. melanarius* distribution, negative and positive correlations respectively, at the three spatial scales. However, at all scales, *HD* was more informative than *LG* and for both the best gradient was obtained at 250 m with *Ortho* for *HD* gradient and *MD* for *LG* gradient (36.3 and 30.3% of variance explained respectively) (Fig. 4). Finest maps (*MD*, *Ortho*, *Spot5*) gave more informative *HD* gradients than coarser maps at 100 and 250 m, *Spot5* being by far the best at 100 m (22.8% of variance explained), all three being quite equivalent at 250 m (variance explained between 34.5 and 35.6%). At 1000 m, *Spot5* and *Spot10* had less informative *HD* gradients than all others (despite their correlations always higher than 80% with other maps, see Table 3), *Aster* giving the best one (23.7% of variance explained).

Predictive power of *LG* gradients was independent from the spatial resolution trend of maps at 100 m: *MD* and *Irs* were the only ones significant (12.2 and 9.7% of variance explained). At 250 m, *MD* was by far the best, followed by *Ortho* and *Irs* (30.3, 16.1 and 16% of variance explained), others explaining less than 5% of variance. At 1000 m, all maps were quite as much informative, *Irs* and *Spot10* being slightly worst than fine maps and *Aster* being the best one (20.8% of variance explained).

Table 3 Matrix of correlation between *HD* and *LG* gradients of each map at 100, 250 and 1000 m window sizes (both variables have been constructed only with windows around biological sampling units)

HD/LG correlations (R^2 values)	100 m	250 m	1000 m
MD	0.37	0.62	0.94
Ortho	0.10	0.36	0.92
Spot5	0.21	0.35	0.90
Spot10	0.22	0.40	0.94
Aster	0.28	0.38	0.88
Irs	0.40	0.70	0.85

Values in the table are *coefficients of determination* (R^2); all correlations are significant (Pearson correlation test, $P < 0.05$, $N = 74$)

Abax parallelepipedus

The spatial distribution of *A. parallelepipedus* was positively explained by *HD* and negatively by the *LG*, at 100 and 250 m. At both scales, *LG* gradients were more informative and for both gradients the best map were *Spot5* at 100 m (15.4 and 19.4% of variance explained by *HD* and *LG*) (Fig. 4). *Spot10* were the most informative map at 250 m. At 1000 m, none of map gave a significant landscape gradient, for *HD* as *LG*. And contrary to *P. melanarius* some maps were never explanatory, the coarsest (*Irs*) and the finest one (*MD*). High similarities between *Spot* (*5* and *10*) and *Aster* maps, previously revealed by high gradients correlations (see Table 4), explained why *Aster* was a relatively well informative map for this species.

Discussion

Different aspects of maps accuracy have been evaluated thanks to complementary metrics: hedgerow elements quantity (*Kappa* index), hedgerow network length (GPI), the error of hedgerows location (GPI and photo-interpretation), density and spatial patterns of hedgerow network (*HD* and *LG* metrics). Evaluation of hedgerow length and spatial structure

Table 4 Matrix of correlation between *HD* gradients, and between *LG* gradients, of the six maps at 100, 250 and 1000 m scales

Determination coefficients (R^2 values)	*HD*						*LG*					
	MD	*Ortho*	*Spot5*	*Spot10*	*Aster*	*Irs*	*MD*	*Ortho*	*Spot5*	*Spot10*	*Aster*	*Irs*
100 m												
MD	1.00						1.00					
Ortho	0.41	1.00					NS	1.00				
Spot5	0.33	0.57	1.00				NS	NS	1.00			
Spot10	0.26	0.32	0.64	1.00			NS	NS	0.91	1.00		
Aster	0.10	0.32	0.41	0.25	1.00		0.05	0.19	0.82	0.70	1.00	
Irs	NS	0.13	0.07	NS	0.08	1.00	0.11	NS	0.16	0.13	0.21	1.00
250 m												
MD	1.00						1.00					
Ortho	0.88	1.00					0.67	1.00				
Spot5	0.79	0.83	1.00				0.51	0.37	1.00			
Spot10	0.80	0.80	0.88	1.00			0.47	0.21	0.90	1.00		
Aster	0.65	0.60	0.71	0.68	1.00		0.52	0.44	0.92	0.84	1.00	
Irs	0.64	0.69	0.66	0.55	0.52	1.00	0.45	0.27	0.33	0.28	0.44	1.00
1000 m												
MD	1.00						1.00					
Ortho	0.99	1.00					1.00	1.00				
Spot5	0.97	0.96	1.00				0.95	0.95	1.00			
Spot10	0.93	0.90	0.98	1.00			0.97	0.97	0.96	1.00		
Aster	0.93	0.96	0.90	0.81	1.00		0.96	0.94	0.97	0.94	1.00	
Irs	0.93	0.96	0.94	0.87	0.97	1.00	0.95	0.96	0.88	0.95	0.88	1.00

Values in the table are *coefficients of determination* (R^2); only coefficients of significant correlations are presented (Pearson correlation test, $P < 0.05$, $N = 74$). *NS* non-significant correlations

of hedgerow network are particularly important for maps used for ecological applications. Actually, these bocage landscape characteristics are more often quantified in ecological studies than the hedgerow quantity.

Even though the *Kappa* index give overall good accuracy of hedgerows classifications of all remote sensing images, evaluation of the hedgerow maps content shows that (1) important hedgerow sections were not well extracted from IRS P6 LISS III, (2) more generally the error of detection is spatially structured by landscape context gradients and (3) quantitative and qualitative content differ between maps. The ecological assessment showed that all remote sensors provide maps with ecological relevancy, including IRS P6 LISS III. Essentially the different maps represent complementary tools for ecologists due to ecological complementarity of objects that are detected or missed in the different maps.

Note that hedgerow network modifications during the 4-year time period separating the more distant remote sensing images probably slightly explain these differences between maps. Only 2 and 12% of hedgerow were removed and pruned respectively (Lofti et al. 2010) while errors of hedgerow detection of the different remote sensor are from 12 to 72% on average. Thus we are confident that qualitative results as well as general implications of the methodology remain valid. This opens novel avenues to analyze the relationships between cartography and ecology.

Map accuracy validation and uncertainties analysis

The analysis of GPI, the photo-interpretation and the landscape metrics brought to results on the interactions between image resolution and landscape structure on the one hand and image resolution and landscape metrics on the other hand.

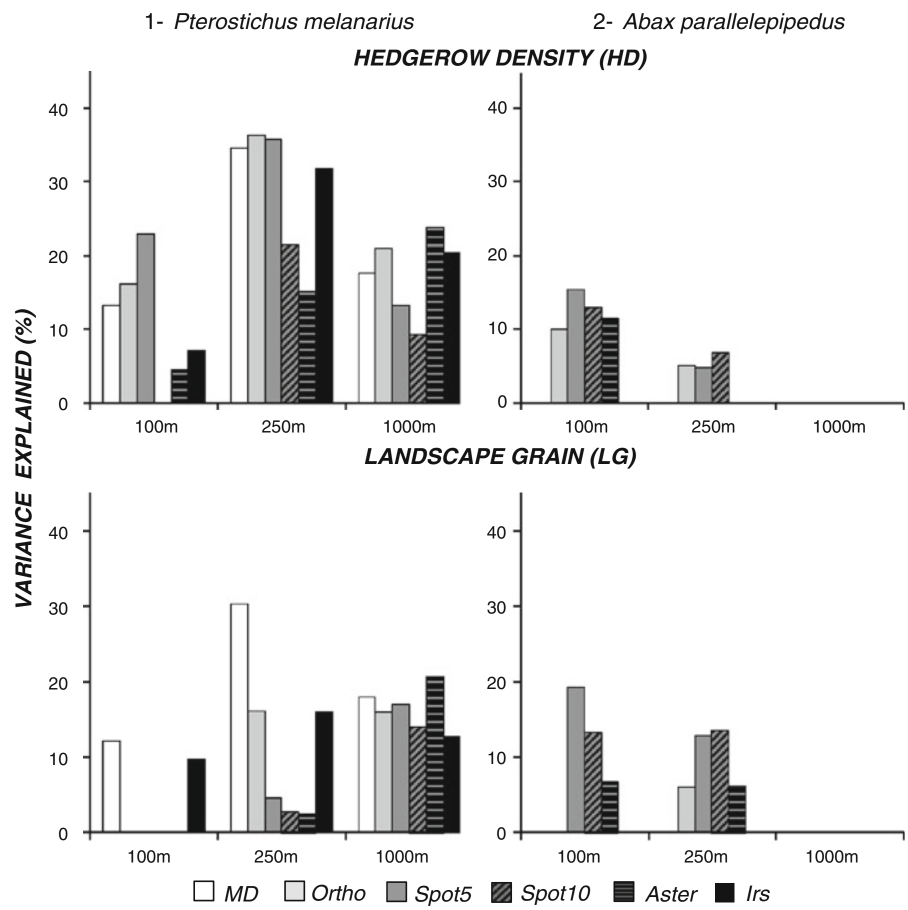

Fig. 4 Ecological explanatory power of landscape gradients (*HD* and *LG*) of each map at 100, 250 and 1000 m scales: values represent the proportion of variance explained of the (1) *Pterostichus melanarius*, and (2) *Abax parallelepipedus* abundance distribution. Only significant gradients are represented (GLM, $P < 0.05$; $N = 74$)

(1) Interactions between images resolutions and landscape structures

Hedgerows and networks detection can be strongly affected by landscape context which is characterized by:

a- The contrast between hedgerow and the adjacent land cover (maize, wheat, grass…). In this case, the north had more maize than the center and the south (32, 22 and 19%); and the orthophotoplan that had a low spectral resolution may be overall less efficient because of confusion between hedgerows and maize in the north and between hedgerows and grass in the south.

b- The density of hedgerow networks (dense networks produce coarse grain of wooded structure). These coarse grain structures were the only one well extracted from coarser remote sensor, particularly from IRSP6LISSIII or ASTER.

c- The hedgerow structure, partly determined by the management regime: on the study site hedgerows are mainly composed of shredded trees that are pruned every 10–12 years, asynchronously from one tree to another. One or 2 years after pruning the canopies are very small and may not be detected. Lofti et al. (2010) find that more hedgerows are pruned on the south, than on the center and the north. Thus, on the south, we found nearby both, the widest (see "Study site" section) and the narrowest hedgerows. This explains too the relatively seeming poor performance of *Ortho* compared to *MD* that consider discontinuous canopies as a continuous hedgerow. This is a key point as "standard" hedgerow mapping focus on drawing lines to extract networks. It explains the lower performance of *Aster* and *Irs* produced from images that do not detect narrow or isolated hedgerows. The overall ability of *Spot5* is due to the high spatial resolution of SPOT 5 images that make this sensor the less biased by hedgerows and landscapes characteristics discussed above.

(2) Interactions between maps and landscape metrics

Landscape variables failed to distinguish the network density and structure at fine-scale in coarser maps (particularly *Irs*). It is partially explained by the strong *bias of data* constituting maps related to landscape context characteristics (see above). Moreover, coarser maps do not explicitly preserve the spatial structure of the network; they detect only hedgerow intersections (nodes) or emphasize network closure aggregating nearby hedgerows. Information about spatial structure becomes spatially implicit in the map and constitutes a *bias of representation* of maps. Consequently, measuring network structure in this case is meaningless. Finally, spatial hedge density compensation for coarse maps can occur i.e. a substitution of “wooded” pixels losses from undetected fine hedgerows by those from width amplification of the detected ones. This *bias of construction of variables* leads to (1) an increase of *HD* and *LG* correlations for coarse maps, (2) an increase of correlation between fine and coarse maps of *HD* only, but not of *LG*. It has been indeed observed until 250 m, which must correspond to the landscape scale at which the study site combines fine and coarse hedgerows.

Consequently maps evaluation shows that hedgerow information content of maps from the different remote sensors is different and the contrasts of landscapes in the study site (i.e. landscape gradients length) can be strengthened by spatial structured errors. The development of methods to characterize the different kinds of uncertainties has been pointed out as one of challenging research priorities in landscape ecology (Pontius 2000; Wu and Hobbs 2007; Shao and Wu 2008). As these authors, we highlight the necessity to no hide maps associated errors, and to evaluate the classification information with various criteria. Actually, the use of classical coefficients (like the *Kappa* index) to validate a remote sensing classification, does not inform about the map quality. These classical methods give *quantification error estimation* instead of *location error estimation* which seems to be more appropriate for spatial pattern analysis (Pontius, 2000). Moreover, they are non informative about the structural and functional content of the maps. The evaluation method that we have proposed to evaluate maps quality and spatial structure of the errors combines useful complementary metrics: GPI (global percentage index), photo-interpretation, and landscape metrics. For the assessment of the ecological information content of maps, we need to develop others evaluation methods discussed in the following section.

Selection of maps in landscape ecology researches

(1) Species sensitivity to maps resolutions

Both carabids species were explained by both, hedgerow network density and structure. However, *Pterostichus melanarius* distribution is better explained by the hedges density unlike *Abax parallelepipedus*, better explained by tree density at both, hedgerow and network scales. It is consistent with previous knowledge of the strong dependency of the latter to microclimatic conditions (Petit and Burel 1998). Moreover, *A. parallelepipedus* is confirmed to respond to finer scales. Globally, due to these ecological characteristics, all maps explained more or less well *P. melanarius* distribution. Moreover, the gap of variance explained by fine and coarse maps decreases with the spatial scale of the window making all maps substitutable at 1000 m, particularly for the *LG*. On the contrary, some maps (*MD* and *Irs*) are not explanatory at all for *A. parallelepipedus*. These results confirm that the more a species is sensitive to the spatial arrangement of the network, or responds to fine landscape scales, the higher its sensitivity to the resolution of the data source (maps). The fact that different species react to landscape patterns at different scales is well established (Riitters et al. 1997); changing resolution is usually done in the analytical phase. Chust et al. (2004) did not find any difference between two sensors (LANDSAT TM: 30 × 30 m, and SPOT: 20 × 20 m) in the analysis of landscape/species relationships, perhaps because the difference in resolution is not high enough. The use of maps at different spatial and spectral resolution must be further explored to better understand how landscape patterns affect species distribution.

(2) Implications to future map selection process

Ecological assessment of map relevancy shows that:

a- The most relevant maps are different for both species: *MD* and *Irs* not explanatory for *A. parallelepipedus*, are among the best ones (even the only ones sometimes) for *P. melanarius.*

b- The most explanatory maps change with the spatial scale characterized. In particular all fine maps do not always lead to the most predictive variable even too at finest scales. One reason is the map information content depends not only on spatial but also on spectral resolution of remotely sensed data used to extract hedgerow networks. Rocchini et al. (2007), using high spatial resolution Quickbird data, demonstrate that the visible spectral bands are not informative to assess plant richness, contrary to near-infrared bands. Vannier and Hubert-Moy (2008) have shown that despite their very high spatial resolution, orthophotoplans are not the most suitable data to extract automatically wooded hedges, insofar as their spectral resolution is low, and besides they cover only the visible spectrum. Thus, some objects cannot be identified from these data: for example, from a spectral point of view, hedgerows are very similar to other landscape elements like cornfields or shadows which lead to increased classification errors. For that matter, coarser resolution remotely sensed imagery like SPOT 5 data, thanks to their rich spectral information, can provide better classification accuracies. Thus, maps generated from these data constitute the most suitable mapping of the wooded hedgerows' finest elements. Moreover, we can question about the meaning of the manually digitized map and be careful about this high resolution "reference data". In fact, most of the time hedgerow reference maps are generated from aerial photographs or orthophotoplans and hedges are symbolized with lines. However, we have shown that this data choice and this mapping mode is not necessarily the most appropriate from an ecological perspective. Indeed, aerial photographs are not the most informative data as far as hedgerow mapping is concerned, and also some relevant information describing the hedgerow network (shape, distribution and size of canopy, tree-type…) is not represented with a line format. Finally, we have shown that the coarser spatial resolution data like IRS P6 LISS III or ASTER VN IR images are not the most suitable for precise detection but the information produced is really meaningful, including at finest scales (100 m). Network maps generated from these data represent macro-structures in the landscape which are closed areas composed of woods, shrubs, wooded hedges, small grasslands, fallows. In fact, this detection of contrasted landscape units seems to be very relevant for *P. melanarius* that typically correspond to unsuitable habitats for this crop species (Aviron et al. 2005).

c- The combination of spatially uncorrelated maps with contrasted resolutions (*MD* and *Irs*) probably bring ecological complementary information; this must be tested.

d- Finally, ecological knowledge of species can be refined from maps results comparison. In 100 m windows *P. melanarius* abundance is negatively associated with the presence of a hedgerow as shown by the good *MD* explanatory power. Supplementary information given by *Ortho* and *Spot5* about hedgerow structure is much more informative. Moreover, the coarser perception of hedgerows in *Spot5* i.e. a more restrictive definition of hedge according to the width of the tree canopy, is enough and more relevant for this species at local scale. In fact, according to *P. melanarius* good dispersal ability it is not surprising to find it even in suboptimal conditions i.e. hedgerow with intermediate canopy width, but far from dense forest-like canopies that are very unsuitable. At 250 m scale, maps provide information on the possibilities of population exchanges that are diminished by close networks. We conclude that the network information given by *MD* map is sufficient and more relevant. Indeed, more than the tree row or tree canopies itself it may be the associated bank (and ditch) that make a barrier. Moreover, at this scale the complementarity of the exact network representation given by *MD* and the binary representation of habitat units given by *Irs* seems to be interesting for this species. For *A. parallelepipedus* which prefers shady, forest-like environments, distribution is better explained by intermediate to coarse-scale maps that detect canopy cover (*Spot5*, *Spot10* and *Aster*) than by fine-scale maps. Thus only coarse variation of canopy cover density is relevant for this species given that most of all missed discontinuous or narrow hedgerows have been proved to be unsuitable habitat (Petit and Burel 1998).

Therefore, what information (structure and function) is provided by the map? We know now that maps are not simply either good or bad, but rather provide complementary information. It is by the combination of data that we can transcribe a landscape. Indeed, maps produced from very high spatial resolution are highly correlated with the presence of hedges and can be used to obtain information on some hedge parameters related to their canopy size and shape, or tree arrangement within hedgerows. Coarser maps derived from lower spatial resolution data but with a high spectral resolution can provide information on landscape structures (patches composed of closed areas including hedges in mixed landscape units) and their spatial distribution.

Changes in the scale of analysis showed that, while the different maps provided a different information at fine-scale (100 m windows), this information was quite homogeneous at coarse-scale (1000 m). This means that remotely sensed images at coarse spatial scale can be used to differentiate landscapes within a region, which represents less work. Therefore, landscape analysis can be conceived at several scales. For larger areas, coarse images can be used, then within selected areas intermediate scale images may bring in finer information; finally at fine-scale (to design field work), orthophotoplans can be used to accurately locate hedgerows.

Conclusions

Our main conclusions are: (1) Contrarily to the assumption of Li and Wu (2004), the spatial resolution of satellite images is not the only important factor; changes in spectral resolution significantly alter maps and has to be considered for mapping in the future; (2) Contrarily to our initial hypothesis, the coarse spatial scale map obtained with IRSP6LISSIII may provide some meaningful ecological information; (3) More generally, map selection relevancy or their substitutability depend closely on species ecological characteristics; and thus the selection of data source must be reasoned and constitute the first step of an ecological study protocol, (4) the relationship among the metrics derived from the different sensors change with landscape characteristics. Thus this interdisciplinary approach between ecologists and geographers (i.e. testing sensors at different scale with biological data) should be generalized to establish classes of relationships between landscapes types and remote sensing images, and define the domain of validity of remote sensing images. It implies that geographers and ecologists develop together relevant set of metrics to detect maps differences.

Overall our results emphasize the need to consider scale effects in landscape data, species distribution and analysis of their interactions, they open new methodological avenues for exploring landscape patterns in landscape ecology: (1) The comparison of results from different data source help to access to species-specific functional definition of hedgerow, and can constitute a first analysis step to built functional maps; (2) Some substitutability of fine-scales images by coarse-scale ones provide to extrapolate ecological patterns over large regional extents. Moreover, those coarse-scale maps are interesting for backtracking to the 1980s and trace back landscape structure. Due to its different implications, this interdisciplinary approach is promising and needs to be developed.

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