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Towards the planning and design of disturbance patterns across scales to counter biological invasions

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ABSTRACT

The way in which disturbances from human land use are patterned in space across scales can have important consequences for efforts to govern human/environment with regard to, but not only, invasive spread-dispersal processes. In this context, we explore the potential of disturbance patterns along a continuum of scales as proxies for identifying the geographical regions prone to spread of invasive plant species. To this end, we build on a previous framework of cross-scale disturbance patterns, exercising the approach for the Apulia region (South Italy). We first review procedures and results introducing disturbance maps and sliding windows to measure composition (amount) and configuration (contagion) of disturbance patterns both for real and simulated landscapes from random, multifractal and hierarchical neutral models. We introduce cross-scale disturbance profiles obtained by clustering locations from real and simulated landscapes, which are used as foils for comparison to the real landscapes on the same pattern transition space. Critical percolation thresholds derived from landscape observations and theoretical works are discussed in order to identify critical scale domains. With reference to the actual land use and invasive alien flora correlates of disturbance patterns, a cross-scale "invasibility" map of the Apulia region is derived, which shows sub-regions and scale domains with different potentials for the invasive spread of undesirable species. We discuss the potential effect of contagious and non-contagious disturbances like climate change and why multifractal-like disturbance patterns might be more desirable than others to counter biological invasions in a multi-scale and multi-level context of adaptive planning, design and management of disturbance.

1. Introduction

The claimed objective of physical planning is the optimization of spatial composition (what and how much there is) and configuration (how it is spatially arranged) of landscape elements like habitats or land uses (Van Lier, 1998), focusing on land-use allocation. Since human land use is a major force driving landscape change (MEA, 2005), physical planning should ultimately adopt a landscape perspective (Turner and Gardner, 1991; Ricketts, 2001). This should be based upon the increasing understanding of landscape dynamics in the context of complex adaptive socioeconomic and ecological systems (Levin, 1998; Berkes and Folke, 1998), integrating phenomena across multiple scales of space, time and organizational complexity. In social–ecological landscapes (SELs) (Zaccarelli et al., 2008) social-economic drivers are generally imposed on biophysical components to generate change in landscape pattern (Lambin et al., 2001; Black et al., 2003; Foley et al., 2005). In particular, interactions between land ownership and landscape position have emerged as strong determinants of land-cover patterns and contagious disturbances (Mladenoff et al., 1993; Spies et al., 1994; Wear and Bolstad, 1998). In addition, non-contagious disturbances are imposed by climate change with possible cross-scale interactions with contagious disturbances (Fig. 1). In this respect, climate changes relate to two main issues of potential risks to biodiversity: rise in average temperature, and an increased fluctuation of weather conditions (weather extremes),

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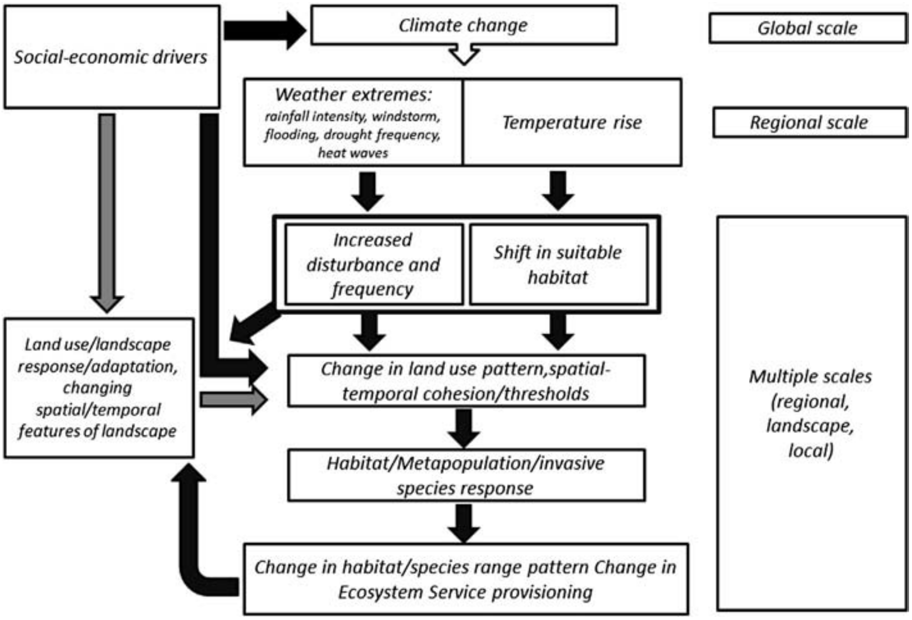

Fig. 1. Outline of response chain of changes from climate and socioeconomic drivers to habitat/species distribution pattern and ecosystem service provisioning mediated by habitat loss and change both in land-use pattern and landscape connectivity. Different spatial scales interact (modified from Opdam and Wascher, 2004) (see text).

such as rainfall intensity, windstorm, flooding, and drought frequency, which both lead to increased disturbances in landscapes (Opdam and Wascher, 2004). Such disturbances can overlap and interact in varying degrees and patterns with disturbances generated by direct human interaction with the biophysical environment. An example of this is when temperature rise can affect the extent and magnitude of contagious disturbances (e.g., a fire made worse over a larger area due to greater temperature extremes).

The crucial problem of land-use allocation in planning and design is that many different global and local human-driven processes in the landscape are competing with each other and with natural processes at multiple scales having a major effect on landscape processes and biotic compositions (Koomen et al., 2012). As a result, the effects of land-use intensity on local biodiversity and ecological functioning in SELs depend on spatial scales much larger than a single field or land use (Zurlini and Girardin, 2008).

Traditionally, disturbance is broadly defined as any event that results in a sustained disruption of ecosystem structure and function (Pickett and White, 1985). Land-use change can be deemed as a "landscape-level" disturbance underlying fragmentation and habitat loss (Hobbs and Huenneke, 1992) and is considered the greatest threat to biodiversity (MEA, 2005). At landscape scale, disturbance due to land-use intensification can be expressed through the conversion of perennial habitat to arable fields, the destruction of edge habitats, fragmenting natural habitat, giving up low-intensity land-use management, reallocation of land to increase field size, avoiding set-aside fallows, cultivating of formerly abandoned areas, and farmer specialization on one or few crops (Zaccarelli et al., 2008). Landscape-level disturbance can facilitate biological invasion, from initial introduction through establishment and spread, which can threaten native diversity (Hobbs and Huenneke, 1992; Pyšek et al., 2010). As threats to biodiversity intensify (McKee et al., 2004) and rates of species invasion continue to rise, effective sustainable planning and management requires detailed understanding of relationships between disturbance, invasion and diversity (Hulme, 2006).

Since disturbances may be inflicted not just at one single scale, both habitats and native and invasive alien species may differentially respond to disturbance in the same place at different scales. A potentially useful way to appreciate these differences is to look at how disturbances are patterned in space based on a map of disturbance at multiple scales (Zurlini et al., 2006, 2007; Zaccarelli et al., 2008; Petrosillo et al., 2010).

Nassauer and Opdam (2008) expanded the field of landscape ecology to include research into a third aspect of pattern and process: design. Then, a crucial question might be how to optimize human-driven processes (disturbances) associated to land uses, and how to arrange them across multiple scales of space, time and organizational complexity both to favor native species and, meanwhile, to counter biological invasions.

The main aim of this paper is to draw attention to how disturbance patterns from human land use are patterned in space along a continuum of scales, and discuss some implications of such patterns for efforts to plan and govern human/environment relationships in the light, but not only, of countering biological invasions. Despite disturbance patterns having been successfully explored in many theoretical and practical ecological contexts (e.g., Moloney and Levin, 1996; With and King, 1997; Johst and Drechsler, 2003; With, 2004), little theoretical or practical work has explicitly addressed the implications of scaling of disturbance patterns for the purpose of physical planning and design of SELs (Jones et al., in press).

To this end, we address a spatially explicit approach to quantify landscape-level disturbance in the geographical real world domain along a continuum of scales, based on previous results (Zurlini et al., 2006, 2007; Zaccarelli et al., 2008), with the aim to characterize and interpret spatial patterns of cross-scale disturbances in the Apulia region (south Italy), exhibited on satellite imagery over a four-year time period.

We first briefly review procedures and results from our previous work introducing the disturbance map based on satellite imagery of the Apulia region, and the use of sliding windows (Milne, 1992) to measure composition (amount) and configuration (contagion) of disturbance patterns, Such measures are obtained both for real and simulated landscapes from random, multifractal, and hierarchical neutral landscape models (NLMs). Then, we introduce profiles of disturbance at multiple scales performed by clustering locations along a continuum of scales either for real and simulated landscapes using a sliding window approach. We compare real and simulated cross-scale disturbance patterns on the same pattern space also in the light of well-known associations of invasive flora with specific land uses. Finally, we discuss the implications of observed disturbance patterns for the potential physical planning of disturbance also in the light of climate change, as well as the potential of disturbance patterns to be utilized as pattern of reference for the intentional planning and design of disturbance patterns to counter biological invasions.

2. The background

2.1. The map of disturbance

The area of interest is Apulia, an administrative region of 1,936,000 ha in southern Italy, inhabited for thousands of years, with a typical semi-arid Mediterranean climate characterized by hot and dry summers and moderately cold and rainy winter seasons. Overall, more than 82% of Apulia contains agro-ecosystems (Fig. 2). Change detection on satellite imagery is needed to produce a map of disturbance as input to the analysis of disturbance patterns (Zurlini et al., 2006). Cloud-free Landsat imagery with a 30-m pixel resolution (0.09 ha) in the same period of vegetation phenological cycles in two different years, i.e. June 1997 and June 2001, has been processed. Since landscape mosaic is mostly defined by vegetation cover, as response variable we use changes over time in NDVI (normalized difference vegetation index), defined as the difference between the visible (red) and near-infrared (nir) bands, over their sum. NDVI is broadly recognized as a robust indicator of vegetation photosynthesis, with built-in relationships to social–ecological processes such as habitat conversion or crop rotation (Young and Harris, 2005).

We measure disturbance by any detectable alteration of land cover reflecting significant NDVI changes, mainly assignable to human-driven disturbances (EC, 1999), as captured by a “narrow” 4-year time window. To this end, we derive a binary (disturbed, undisturbed) map of the region, for which we choose relatively extreme percentiles of 10% at both tails of the distribution (i.e. overall 20%) of NDVI standardized differences for both real and simulated cases. By doing so, we reduce the chance of analyzing either the pattern of “background noise” that could be obtained with much higher (e.g., 40%) percentiles, or of emphasizing a few local extreme values (e.g., 1% or less).

As we focus on land cover dynamics, disturbances turn out to be mostly associated with agricultural expansion and intensification, conversion of perennial habitats and vineyards to cultivation fields and new olive grove tillage, farming practices such as fire and crop rotation, and urban sprawl. The geographical spatial pattern of disturbance at regional level derived from the 4-year time window (1997–2001) does not vary significantly in time since locations of multiple drivers of disturbance are typically constrained within bounds established by planning at different jurisdictional levels (Petrosillo et al., 2010). Thus, we can use such disturbance map to characterize the disturbance regime of the region.

Patterns across scales can be measured in several ways (e.g., Grossi et al., 2001). Here we use an overlapping pixel-level sliding window whereby ‘scale’ is varied by changing the size of the window (Milne, 1992; Kerkhoff et al., 2000). Such an approach may limit the capacity to capture and map narrow linear features (e.g., natural land cover riparian buffers) in developed landscapes (Jones et al., in press). Still, through this procedure, it is possible to capture most of the significant human-driven disturbances detectable at the resolution of satellite imagery, which can be significant for potential invasive spread. However, there might be cases where occasionally NDVI does not capture disturbance when it is in fact there like, for instance, agricultural fields that went from one crop

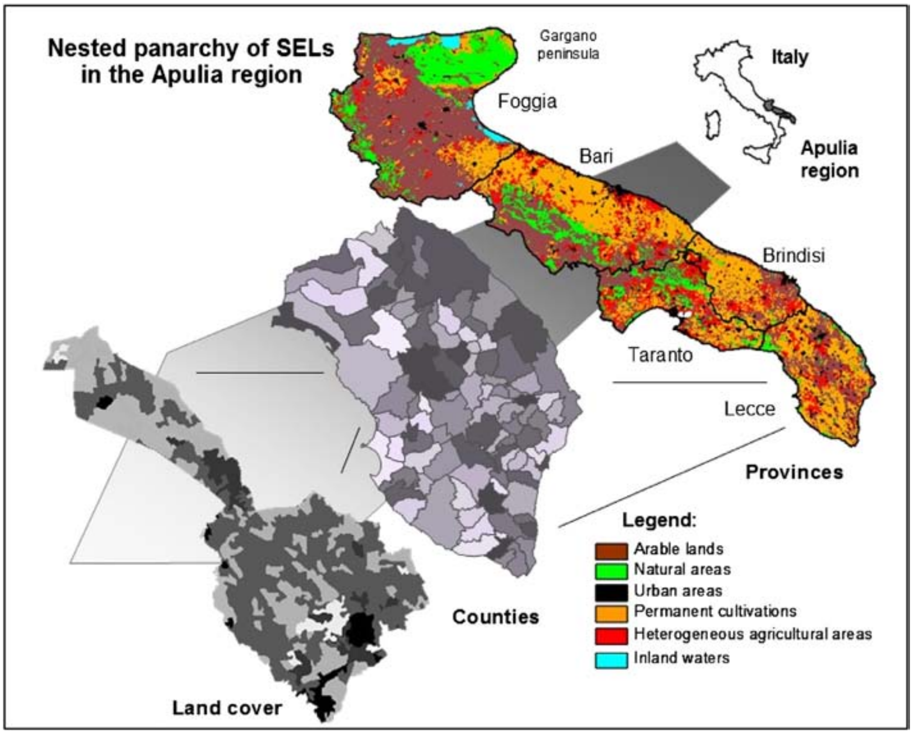

Fig. 2. Panarchy of nested jurisdictional levels defined as clearly bounded and organized political units in Apulia in southern Italy. Three main levels of the panarchy are identified (region, province, and county) with six broad land-use/land-cover classes (top) and a simplified example of Corine Land cover map for one county (down) Modified after Zaccarelli et al., 2008.

to the same or another but retained occasionally exactly the same NDVI. On the contrary, it would be very unlikely that this procedure does capture disturbance when it is not there.

2.2. Disturbance patterns across scales

A wide array of metrics for landscape composition and configuration has been developed for categorical data (Li and Reynolds, 1994). In this paper, what and how much is present (composition) refers to landscape-level disturbance, that is the response variable we choose to directly measure the result of human interactions with the biophysical environment.

In the sliding window approach, composition is expressed within a given window as the probability of disturbance (P_d), and is estimated by the proportion of pixels that are disturbed. Configurationis measured by the adjacency of disturbance within a window, given by the probability that a disturbed pixel is adjacent (by the four-neighbor rule) to another disturbed pixel (P_{dd}), so it is a measure of clumping (contagion). Composition (P_d) and contagion (P_{dd}) can be used to define a pattern transition space [P_d, P_{dd}] (Riitters et al., 2000; Zurlini et al., 2006, 2007) that further describes cross-scale disturbance patterns that are encountered on real maps like in the Apulia region (Fig. 3). Four simple examples of different combinations of P_d and P_{dd} are represented by locations a, b, c, d in pattern transition space [P_d, P_{dd}] (Fig. 3): (a) highly disturbed but perforated by undisturbed areas (i.e. perforated disturbance), (b) highly disturbed but with clumped undisturbed areas (i.e. edge disturbance), (c) low level and highly fragmented disturbance (i.e. spread disturbance), and (d) low level and clumped disturbance (i.e. patchy disturbance).

We measure the composition and contagion of disturbance for each pixel (location) in the map with ten window sizes, in pixel units, of 3 × 3, 5 × 5, 9 × 9, 15 × 15, 25 × 25, 45 × 45, 75 × 75, 115 × 115, 165 × 165, and 225 × 225, spanning from 0.81 to 4556.3 ha. A critical component of our approach is the convergence point, labeled CP, in Fig. 3, which represents the global [P_d, P_{dd}] value at the upper scale limit that is equal to the extent of the entire map that, in our case, is the Apulia region. Hence, CP represents both the proportion of disturbed pixels (P_d), and the measure of overall contagion (P_{dd}) at regional level. For any given location (pixel), the profiles of disturbance composition and contagion over window size describe the local spatial pattern of disturbance surrounding that location across-scales (Milne, 1992) up to the regional CP value. We group location profiles with an unsupervised *k*-means algorithm (Legendre and Legendre, 1998) over the entire range of window sizes, and derive eight clusters to provide a broad array of disturbance patterns after experimenting with different alternatives. We then plot the resulting mean cluster profiles in the [P_d, P_{dd}] pattern transition space along with the CP. Along a cluster profile, a small window with high disturbance amount combined with a large window with low disturbance amount implies a local heavy disturbance embedded in a larger region of lighter disturbance.

3. Neutral landscape models (NLMs) and percolation theory

NLMs have received thorough treatment elsewhere (e.g., With and King, 1997; Andrén, 1994; Fahrig, 2002), and have evolved from simple random landscape maps (Gardner et al., 1987) to maps with hierarchical structure (e.g., Lavorel et al., 1993), up to the analysis of structural aspects of pattern from mathematical morphology (Riitters et al., 2007). Patterns have been simulated as a random process, or as fractal distribution with different degrees of spatial contagion, or as processes within nested map layers to mirror a hierarchical patch structure (Lavorel et al., 1993). NLMs have been used to identify critical thresholds in landscape pattern with regard to the spread of organisms or disturbance across a landscape (e.g., Gardner et al., 1989).

As to disturbance, percolation theory (Stauffer, 1985) helps on random maps, to identify critical values of the proportion of disturbed locations (p) critical for the percolation of invasive species. Species percolate on an infinite random map of disturbance when $p > 0.59275$. Such threshold, however, is limited to the specific assumptions regarding the spatial distribution (infinite random), the square grids with “site” percolation, and the movement rule (the four-neighbor rule) (With and King, 1997). Nevertheless, a landscape size of 256 × 256 pixels like we use is apparently sufficient for achieving the degree of connectedness of like patch types that are predicted from percolation theory (Gardner et al., 1992).

A more general model, bond percolation based on graph structures, still results in thresholds in connectivity that depend on dispersal ability (Keitt et al., 1997; Ferrari et al., 2007). This result is supported when a fractal, rather than random, distribution of patches is used, resulting in thresholds at $0.29 < p < 0.50$, depending on habitat arrangement (e.g., Hill and Caswell, 1999; Fahrig, 2002). Riitters et al. (2007) have shown that on random neutral binary raster maps, critical thresholds from mathematical morphology could not be the same as predicted by percolation theory because such theory pertains to overall map composition (p), whereas mathematical morphology considers structural aspects of pattern that are not included in that theory.

4. Simulated cross-scale patterns and critical threshold range

We use the classical RULE software (Gardner, 1999) to generate simulated random, multifractal and hierarchical landscape pattern maps of size 1024 × 1024 pixels with the same composition (P_d). In the multifractal model, the degree of spatial clumping (parameter H) is adjusted to produce realistic patterns that are relatively dispersed ($H = 0.0$). For the hierarchical model, the RULE parameters describe the number of units (m_i) at each level i, and the fraction of focal habitat or disturbance units (p_i) at each level. We test one three-level map for which (m_i, p_i) = (16, 0.5), (8, 0.5), and (8, 0.8) and one two-level map for which (m_i, p_i) = (16, 0.8), (4, 0.25) and (16, 1.0) (Zurlini et al., 2007). On each simulated map, composition and contagion are scaled by ten window sizes and clustered as for real maps in order to compare real and simulated disturbance profiles.

In multifractal models critical thresholds vary with the degree of spatial contagion given by the parameter H, which is the Hurst exponent of the fractional Brownian motion (Gardner, 1999). In this case, percolation based thresholds of habitat (disturbance) can be defined for each H at p when the mean percolation frequency (*pf*), that is the number of percolation cases over the total, exceeds a predefined cutoff level usually 0.5 or 1 (Ferrari et al., 2007).

For the sake of simplicity in this demonstration, we considered a percolation threshold range of disturbance composition at $0.3 < P_d < 0.4$ related to $0.0 < H < 0.25$ (Ferrari et al., 2007), with reference to the conservative $p_f = 1.0$ (O’Neill et al., 1988), that is when all cases percolate. The upper limit 0.25 for H is chosen because at P_d fixed to 0.2, $H = 0.3$ generates multifractal patterns with very unrealistic contagion (Zurlini et al., 2007).

This threshold range is consistent with the general range predicted by NLMs (Table 1), complex meta-population models (e.g., Lande, 1987; Fahrig and Jonsen, 1998; Hill and Caswell, 1999; Fahrig, 2002), and also with the range observed in real landscapes (e.g., Andrén, 1994; Gibbs, 1998; Bascompte and Rodriguez, 2001; Newcomb Homan et al., 2004; Radford et al., 2005).

With (2004) generated random and fractal spatial patterns by classic NLMs representing a gradient of landscape disturbance and

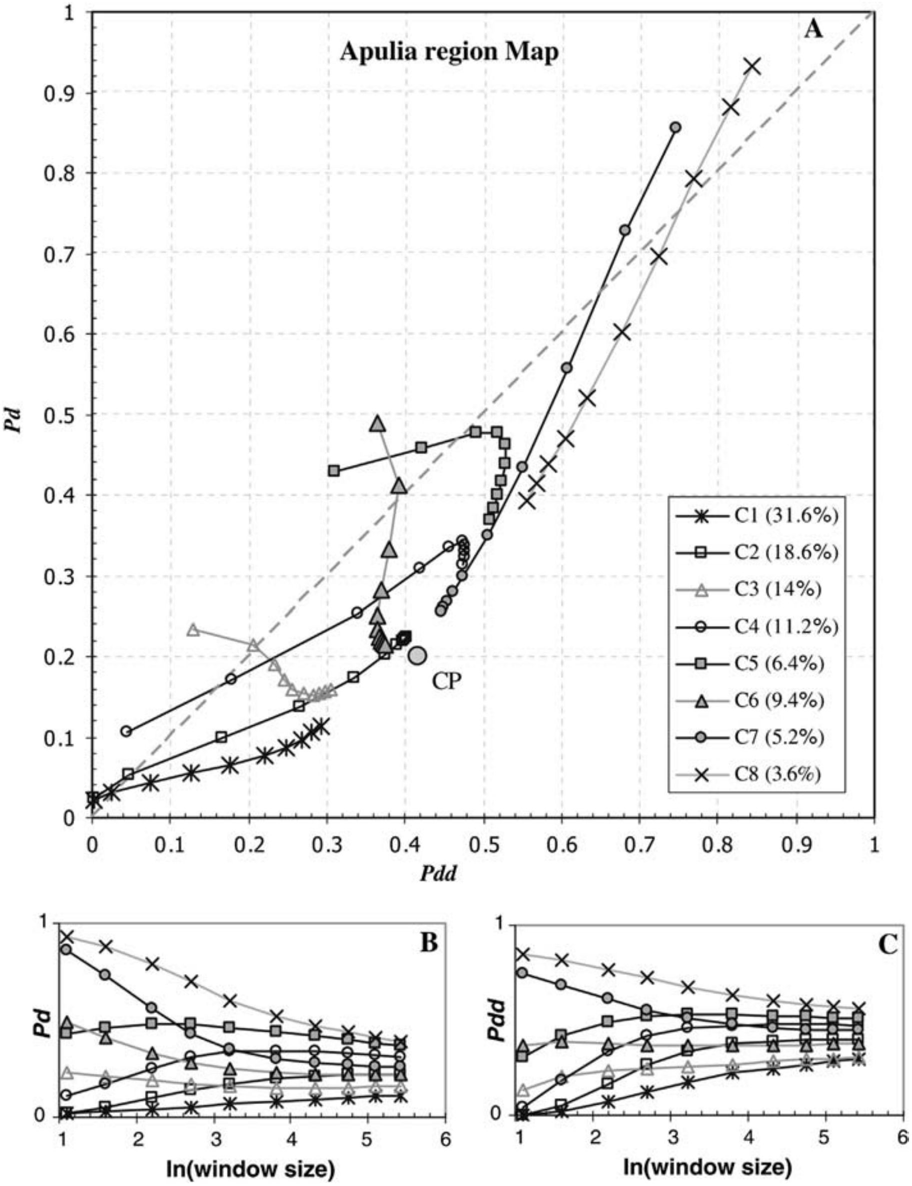

Fig. 3. Top, pattern transition space [P_d, P_{dd}] of disturbance composition (P_d) and contagion (P_{dd}) and profiles for eight clusters (C1–C8) of disturbance in Apulia at ten window sizes (scale) in the period 1997–2001. In the legend are pixel percentages in each cluster. Below, single cluster profiles of disturbance composition and contagion vs window size are also shown, See text; modified from Zurlini et al., 2007.

fragmentation, and argued that if the invasive species has better dispersal and gap-crossing abilities, e.g., single pixels of undisturbed habitat, then invasive spread on landscapes with small and randomly localized disturbances is more likely to occur when only $p = 0.26$ of the landscape has been disturbed (cf. Pearson et al., 1996). Invasive spread of species dispersing through adjacent disturbed habitats occurs at a lower level of disturbance when disturbances are large or clumped in distribution on the landscape, whereas for species capable of crossing gaps, invasive spread is more likely to occur on landscapes in which disturbances are small and randomly localized (With, 2004, Table 1).

Table 1
Summary of the critical percolation thresholds given by the proportion of disturbed locations (P_d) in the landscape according to With (2004).

Disturbance	Percolation threshold for poor dispersers (P_d)	Percolation threshold for better dispersers (P_d)
Small and localized	0.57	0.26
Large and clumped	0.43	0.48

5. Comparing real and simulated cross-scale patterns

A relevant question is how we can compare disturbance patterns as single cluster profiles in [P_d, P_{dd}] space are not strictly comparable either within, or between NLMs, or with real patterns.

A random map, by definition, has no local domains at any scale in either pattern metric space or in real geographic space so every location on the random map experiences the same pattern. Simulated CPs at various disturbance compositions are always located above the main diagonal in the [P_d, P_{dd}] space (insert in Fig. 4) showing an over-dispersed behavior.

Multifractal maps do not exhibit convergence and none of the disturbance profiles reaches the CP (Fig. 4). By definition a

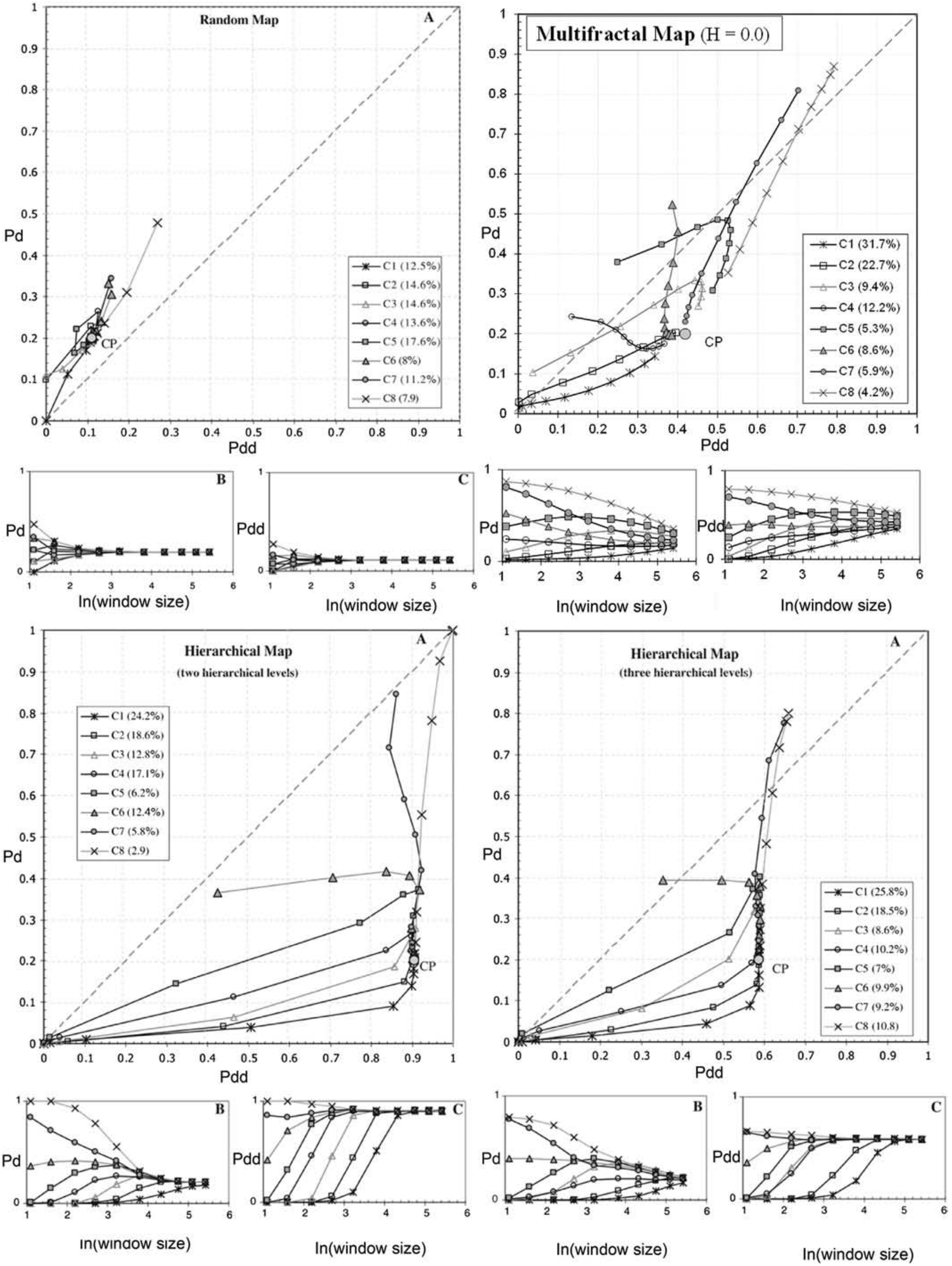

Fig. 4. Simulated random, multifractal and hierarchical patterns across scales. Random patterns and multifractal patterns (top); hierarchical patterns with two hierarchical levels and hierarchical patterns with three hierarchical levels (down) (see text).

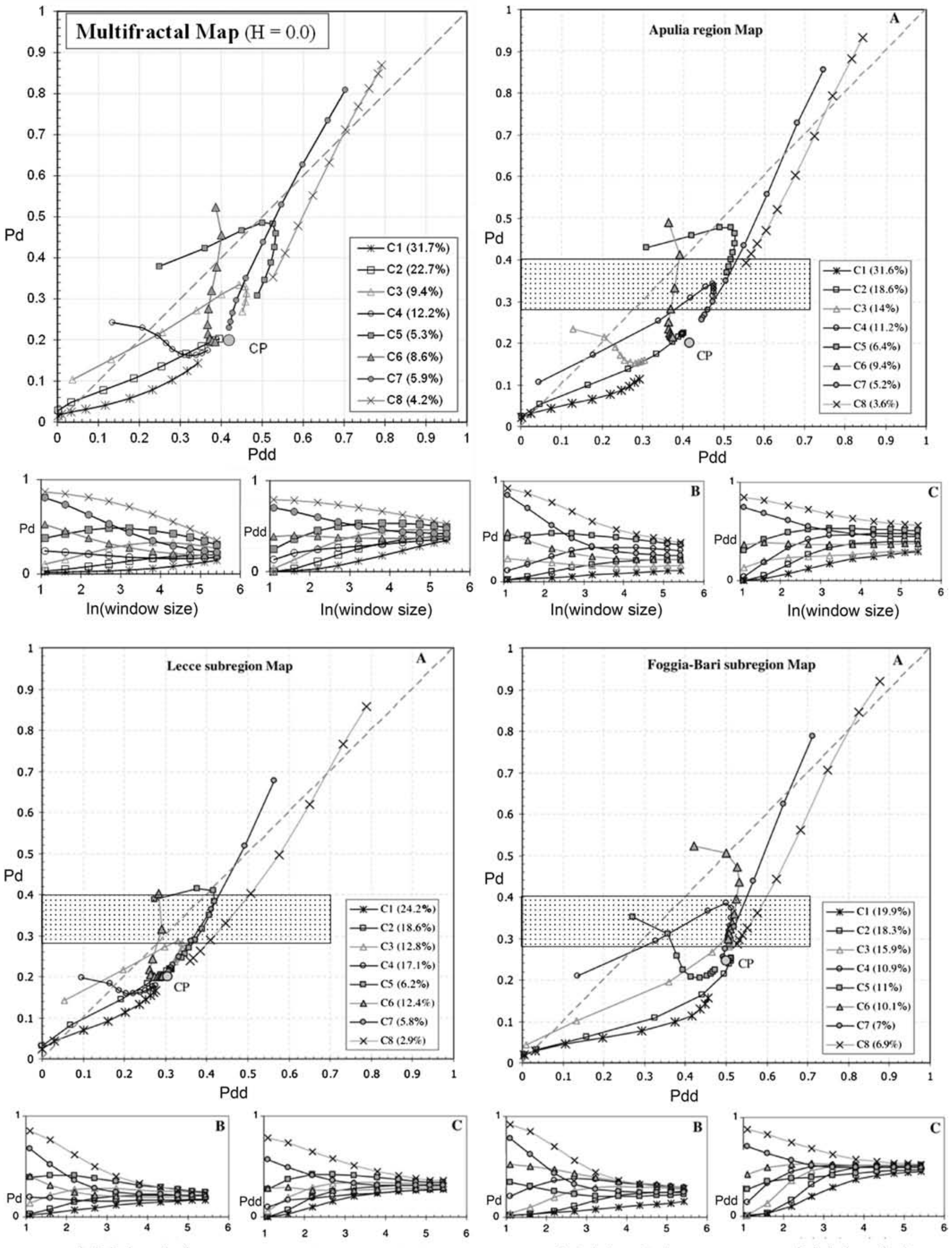

Fig. 5. Top, comparison of simulated multifractal map with the real disturbance map at multiple scales of the Apulia region with the critical percolation threshold range; down, Lecce and Foggia-Bari sub-regions (see text).

multifractal is constructed to have the higher moments grow increasingly with scale, making for non-stationary parameters, which implies that cluster strings will not converge to CP except asymptotically.

The hierarchical maps do exhibit a convergence at intermediate window sizes (Fig. 4). Cluster profiles of hierarchical maps look like strings of a frayed rope starting at local scales from different regions and quickly aggregate along scales to form a common rope ("rope effect") with variations in composition but with contagion almost constant with a remarkable cross-scale effect. Single composition and configuration cluster profiles present a typical "fish-bone" structure (Fig. 4, bottom). Hierarchical patterns of cluster profiles for contagion over the range of scales (Fig. 4) suggest that the most disturbed clusters (C8–C7) do not seem to change much along scales, whereas the less disturbed cluster profiles reach the rope from below in a clear sequence of increasing composition.

We can appreciate whether the real CP and cluster profiles in the $[P_d, P_{dd}]$ space show a behavior similar to some NLM of reference. In particular, how composition and contagion converge along scales is of decisive importance to assist in performing comparisons, together with the CP value and the frequency distribution of pixels among the eight clusters.

Real disturbances across scales are not random, but exhibit strong similarity to multifractal patterns (Fig. 5). In the real world, fragmentation tends to produce areas of different sizes with irregular edges that often turn out to be fractal in nature (Milne, 1988; Palmer, 1988; Sole and Manrubia, 1995). This, naturally, does not imply that the generating processes are the same. For multifractal maps, the domains of disturbance seem to describe local features like the cores of patches, which are distributed contagiously over the map so that convergence is obtained in $[P_d, P_{dd}]$ space only asymptotically at the ideal window that is exactly equal to the entire geographic region. In this case, the domains of disturbance seem to describe convex and concave edges (Riitters, 2005).

On the contrary, hierarchical-like patterns are only found for certain nested regions of interest (ROIs) in the Apulia region with highly contrasting contagious disturbance patterns (Zurlini et al., 2007) like, for instance, in the Foggia-Bari sub-map where convergence is achieved like in hierarchical neutral models. In this case, domains of disturbance seem to identify local features (e.g., the edges of patches) and convergence is obtained because these local features are distributed more or less uniformly over the map (Zurlini et al., 2007). The Lecce map is characterized by small and scattered disturbances, whereas the Foggia-Bari map has clear geographic differences in disturbance (Fig. 5). The Foggia-Bari map is at the border between two provinces with two contrasting disturbance patterns, which could lead to a "rope effect." In contrast, three cluster strings join in the Lecce map but rope formation is doubtful. On this basis, it is possible to hypothesize that there is a multifractal structure in the overall disturbance pattern of the Apulia region, and a hierarchical structure in disturbance pattern in sub-regions like Foggia-Bari but not in the Lecce map.

6. Land use and invasive alien species correlates of disturbance patterns

If land use were the only factor determining disturbance profiles, then each land use would tend to appear in only a few clusters. However, disturbances among land uses turn out to be significantly different from a random distribution (Zurlini et al., 2007) suggesting it is worthwhile to interpret geographical patterns of disturbance in terms of the geography of land use.

The four least disturbed clusters (C1–C4) (Fig. 3) represent 75.4% of the Apulia region. The lower disturbances that do occur, for instance, in C1 and C2 are widespread and isolated, and common in the relatively less-populated Gargano National Park and the Murge protected area (Fig. 2). It is within these clusters that the dominant regional trends are least likely to apply. On the other hand, C7 and C8 including the pixels of the most intensive agricultural areas like, for example, Foggia, have large mean disturbance composition for small windows (Fig. 3). Locations contained in those clusters are themselves disturbed, and for these clusters the decrease in mean disturbance composition is rapid at increasing window size, also implying that the disturbances tend to be widespread and isolated with increasing scales. Other transitional disturbance clusters generally comprise pixels that are not themselves disturbed, but occur more or less near disturbed pixels.

Table 2
Exotic floristic species in the Apulia region according to their mode of dispersal

Exotic flora in the Apulia region	Occasional	Naturalized	Invasive	Total	%
Anemochory	11	5	6	23	12
Barochory and vegetative multiplication	74	26	4	104	57
Endozoochory	25	2	2	29	15.8
Myrmecochory	10	5	2	17	9.2
Epizoochory	3	4	–	7	3.8
Hydrochory	1	1	2	4	2.2
Total	124	43	16	183	100

From Medagli et al., 2010.

Now, it is a matter of fact that invasive alien (exotic) flora in the Apulia region is significantly associated with human-disturbed areas like cultivated lands and anthropic ruderal environments (Medagli et al., 2010). A comprehensive checklist of the invasive alien floristic species (183) exists for the Apulia region also with reference to their mode of dispersal (Medagli et al., 2010, Table 2). There is also a very detailed checklist for the Salento peninsula (Mele et al., 2006), in southern Apulia (Fig. 2). Here, out of 1340 species present, 80 (6%) are exotic (Table 3), and the well-known association of exotic species with specific land use/land cover has been reported in detail by Mele et al. (2006) (Table 3). The great majority results associated with specific human-disturbed areas (Mele et al., 2006, Table 3). This suggests that it is worthwhile to interpret geographical patterns of disturbance also in terms of land use and its observed association with invasive alien flora distribution.

7. Landscape disturbance patterns and the map of potential invasive spread

Landscape disturbance pattern can act as a scale-dependent "filter" acting differentially on the movement of species with different degrees of vagility or spread (Keitt et al., 1997). The effect

Table 3
Association between land cover and the 80 non-native (invasive, exotic) species reported in the Salento Peninsula

Invasive plants	Land cover					
	Anthropic ruderal environments	Cultivated and abandoned land	Roadsides, edges	Dune and sandy soils	Humid habitats	Total
Grassland	32	12	3	5	9	61
Shrubby	3	1	–	2	–	6
Woody	6	1	3	1	2	13
Total	41	14	6	8	11	80

Original data from Mele et al., 2006.

Table 4
Percentage of major land-cover classes of the Apulia Region for the potential dispersal areas for three classes of disturbance. Major land-cover classes are obtained by aggregating third level CORINE classes for the year 2006 (see text).

Corine land-cover class	Profile			Total
	$P_d < 0.3$	$0.3 < P_d < 0.4$	$P_d > 0.4$	
Urban and industrial areas	3.1%	0.6%	0.1%	3.8%
Arable lands	24.5%	9.3%	8.6%	42.4%
Complex cultivation patterns	6.0%	3.1%	1.5%	10.5%
Permanent cultivations	1.3%	2.9%	2.9%	7.2%
Olive groves	19.1%	2.2%	0.6%	21.9%
Forests	5.1%	1.4%	0.8%	7.4%
Grasslands and pastures	3.7%	0.7%	0.4%	4.8%
Shrub/Herbaceous vegetation	1.0%	0.2%	0.1%	1.3%
Other land-cover types	0.4%	0.1%	0.1%	0.7%
Total	64.3%	20.6%	15.2%	100.0%

of disturbance configuration can vary according to the life history or with the mode of seed dispersal (Dupré and Ehrlén, 2002); for instance, plant species that are habitat specialists and clonal perennials that produce fewer seeds are more likely to be affected negatively by patch isolation.

For mobile organisms (but also for seedling dispersal by wind), the effects of isolation may appear only in landscapes with very fragmented habitat (Andrén, 1994). The negative effects of patch size and isolation on the original sets of species may not occur until the landscape consists of only about 30% of the original habitat (Andrén, 1994).

Generally, for locations with fixed disturbance composition, a low disturbance contagion and highly spread disturbance would be better for 'edge' dispersers whereas patchy disturbance would be better for 'interior' dispersers. These differences can be mapped as different clusters according to our conceptual model, and landscapes that do not occupy certain parts in [P_d, P_{dd}] space would be less likely to experience some types of dispersal.

For hierarchical-like disturbances (e.g., Foggia-Bari maps; Fig. 5), the "rope effect" spans the critical threshold percolation range ($0.3 < P_d < 0.4$) in a region where whatever is undisturbed is clumped and where disturbances are large or concentrated in space. In the "rope" area different disturbance clusters aggregate into geographic regions where invasive species can experience a large undisturbed matrix perforated by patches of disturbance with the same contagion for a wide scale range of disturbance composition (Fig. 5). In general, in such area invasive species capable of long-distance dispersal will be less impacted by gaps in disturbance distribution than will species with short-range dispersal, so they will cross occasional gaps of, e.g., single pixels of undisturbed habitat, and invasive species will spread over large areas of the landscape.

In the Apulia region, typical contagious disturbances are related to land use or land cover and reflect changes associated with conversion of grasslands to cultivation fields, new olive grove tillage, and farming practices such as herbicides, pesticides, fertilizers, fire, and crop rotation (Zaccarelli et al., 2008; Petrosillo et al., 2010). The most disturbed clusters (C7 and C8) in Fig. 3 include the majority of locations with large mean disturbance composition for small windows belonging to the most intensive agricultural areas and ruderal environments (Zaccarelli et al., 2008), where most of non-native floristic species are usually recorded (Medagli et al., 2010). The percentage distribution of three cross-scale disturbance classes over broad Corine land covers potentially associated with different potential percolation of invasive species is shown in Table 4. Even if we use very broad land-cover classes, RxC tests of independence using G-test (Sokal and Rohlf, 1995) clearly show that disturbance composition classes are highly significantly dependent on land-covers ($p < 0{,}01$) and that such dependence is different among land-covers ($p < 0.01$).

Based on cross-scale disturbance patterns observed, their significant connections to specific land-covers associated with non-native floristic species, and the percolation threshold range adopted, we can identify coherent geographic areas associated with

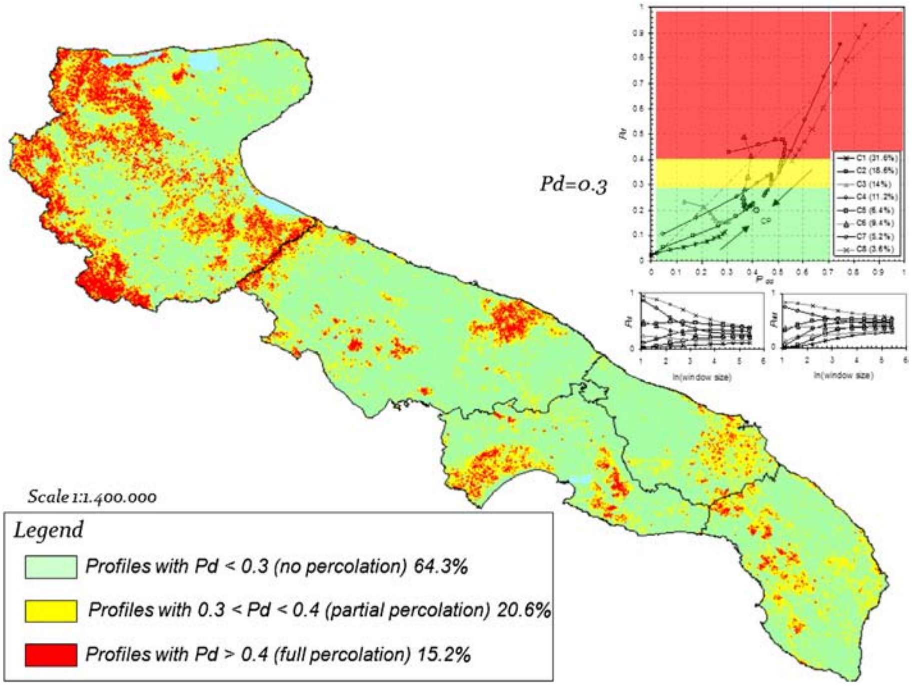

Fig. 6. Invasibility map relative to the potential dispersal of invasive species showing regions including cross-scale disturbance profiles in the Apulia region according to their full, partial or no percolation (see text).

foremost sources of disturbances that are potentially more exposed to the dispersal of invasive species (Fig. 6). Such “invasibility” map shows a clear spatial coherence of cross-scale disturbance classes (Fig. 6). Profiles with full percolation ($P_d > 0.4$; Fig. 6) are actually those profiles of the two most disturbed clusters (C7 and C8) including pixels of the most intensive agricultural areas and ruderal environments (Fig. 3; Table 4). Such “red” class is typically represented by highly intensive arable lands, vineyards and orchards, new olive grove tillage, and complex cultivation patterns including ruderal environments. The “yellow” transitional class (partial percolation) is also represented by these kinds of land cover. The “green” class (no percolation) is represented mainly by less intensive arable lands, such as protected areas, traditional farming, and ancient olive groves in the central and southern parts of the region. Sand beaches, dunes, and inland waters are included in ”other land-cover types” (Table 4) contributing to the “green” class.

A relevant question is if the different disturbance patterns across scales in the region are consistent and scaled respect to the dispersal distances involved in plant invasions. For invasive plants, seed release and vegetation height greatly affect dispersal ability but wind dispersal tends to dominate dispersal mechanisms. Most invasive plants have evolved in early successional habitats, where animals are scarce and a large amount of seed is required to rapidly colonize the disturbed environments (Soons et al., 2004). According to the wind velocity of 22 m/s or 28 m/s, for some grassland plants the maximum dispersal distances for species with plumeless seeds like *Centaurea jacea* (Asteraceae) and *Succisa pratensis* (Dipsacaceae) vary from 1.2 to 1.7 m and from 11 to 30 m respectively (Soons et al., 2004). The same authors found, for species with plumed seeds like *Hypochaeris radicata* and *Cirsium dissectum* (both Asteraceae), maximum dispersal distances from 2300 to 3900 m and from 3400 to 6000 m respectively. *C. jacea* and *H. radicata* are also present in Apulia (Mele et al., 2006). The maximum dispersal distances for grassland plumed seeds are consistent with the maximum seeding distance of some woody plants reported by He and Mladenoff (1999). Thus, the potential dispersal of grassland seeds from invasive plants in the Apulia region could be well captured by the spatial scales of our disturbance analysis at 30-m pixel resolution (“grain”), and ten window sizes from 90 to 6750 m.

An increase of overall disturbance in the region could cause a corresponding increase of spatial correlation of patch destruction (disturbance connectivity) that could be generally advantageous for long-term non-native species persistence. Thus, following an increase in the amount of disturbance due, for example, to climate change the CP of the global disturbance pattern is expected to shift upward in the pattern transition space (insert in Fig. 6) with a corresponding rise in structural connectivity of disturbance in the region. Such increasing spatial aggregation of the disturbance regime, always decreases habitat occupancy of native species, increases extinction risk, and expands the threshold amount of habitat required for persistence, with more marked effects on species with short dispersal distances (Kallimanis et al., 2005).

8. Conclusions

Alien plant species are well known to disrupt ecological services provided by native ecosystems, change the composition of native habitats, and often to lead to the extirpation of native flora and fauna (Williamson, 1996; Myers and Bazely, 2003). Understanding the patterns of alien species spread in urban, semi-natural and natural landscapes is then critical to the task of managing ecological integrity (Aronson et al., 2007). However, historical data to derive rates of species invasion are not usually available and do not exist for the Apulia region. Results from experiments studying different factors determining “invasibility” (e.g., land use, disturbance, biotic interactions) at different spatial scales are mainly used in isolation, probably because a methodology for integration is lacking. Recent studies show that factors, which affect “invasibility” most likely do so in a hierarchical manner, with different factors acting more strongly at different spatial scales (Milbau et al., 2009). The map of cross-scale disturbance patterns to address the potential dispersal of invasive species would help evaluate the effect of overlaid non-contagious disturbances like climate change, and identify the scales of operation of contagious disturbances and their possible cross-scale interactions with non-contagious disturbances (Zurlini et al., in press).

In this context, normative scenarios (Nassauer and Corry, 2004) embodying hypotheses about landscape functions are quite helpful as they rely on science to design landscape patterns that may not be imaginable to stakeholders, but that are hypothesized to have certain ecological, economic, or cultural effects (Fry, 2001). In changing SELs to accommodate for multiple drivers of change, multifractal-like disturbance patterns might be more desirable than other patterns to counter biological invasions in a multi-scale and multi-leveled context of disturbance planning and design. The main reason is that disturbance cluster profiles will not converge to CP except asymptotically, thereby assuring that in SELs different regions with different disturbance pattern (composition and contagion) can be identified and confined across scales. Although that pattern will not impede invasive alien arrival (Mack et al., 2007), it might contrast the invasive spread through the whole landscape, as it might occur for random or for hierarchical patterns. So, it might be helpful to confine invasive establishment intentionally only within particular regions of SELs characterized by certain disturbance patterns.

With (2004) suggested that land planning should concentrate disturbances from socio-economic drivers within particular regions to reduce the risk of invasive spread for species with “limited dispersal abilities”, whereas, for “better dispersers”, planning should generate fragmented pattern of disturbance across the landscape to serve as a barrier to control their spread in a similar way to what it is done to prevent fire across landscapes.

For adaptive planning, design and management, we could “learn from what has already been done” (Jones et al., in press) as patterns we can already observe in the real geographic world look very similar to multifractal patterns (e.g., Milne, 1988; Palmer, 1988; Sole and Manrubia, 1995; and Fig. 5). Such patterns arise without premeditation or even awareness that they are taking place. Therefore, multifractal planning and design of disturbance would be even more workable as such patterns may already have emerged in many regions as a result of many interacting processes.

SEL design and management efforts can prevent unintentional introductions and subsequent detrimental impacts of invasive species by targeting the initial dispersal stage, and that is likely to be the most effective management option (Puth and Post, 2005). The knowledge of multi-scale disturbance patterns as a proxy for identifying the geographical regions of potential invasive spread may improve the effectiveness and efficiency of the adaptive management, for example, of non-native plant invaders, by targeting the areas and the driving processes in SELs related to land uses that can contribute to the success of the invader. Restoration or rehabilitation scenarios might enable planners to use these and other sources of information to enhance desired native species endurance and spread while establishing barriers to reduce spread of invasive species in the landscape.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2013.05.006.

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