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Early warning signals of regime shifts from cross-scale connectivity of land-cover patterns

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ABSTRACT

Increasing external pressures from human activities and climate change can lead to desertification, affecting the livelihood of more than 25% of the world's population. Thus, determining proximity to transition to desertification is particularly central for arid regions before they may convert into deserts, and recent research has focused on devising early warning signals for anticipating such regime shifts. We here draw the attention to some emerging land-cover cross-scale patterns with a historical characteristic sequence of different regimes in arid or semi-arid Mediterranean regions that could indicate an impending transition to the tightening and extension of desertification processes. Inflexibility of land administration may, in turn, reinforce desertification processes, erode the resilience and promote regime shifts and collapse instead of the adaptability required to counter surprises due to climate change. Various theoretical studies have designated the increase in spatial connectivity as the leading indicator of early warning for an impending critical transition of regime shifts. We show that a potential way to address early warning signals of regime shifts to monitor and predict changes is to look at current land-cover regime within a simple framework for interpreting cross-scale spatial patterns. We provide examples of this approach for the Apulia region in southern Italy with desertification processes in place, and discuss what a cross-scale land-cover pattern could mean, what it says about the condition of socio-ecological landscapes, and what could be the effects of changing observed conditions ought to, for instance, climate change. We took advantage of the rich information provided by cross-scale pattern analysis in the pattern transition space provided by classic neutral landscape models. We show potentially dramatic shifts of connectivity at low land-cover composition below certain thresholds, and suggest that the degree to which the observed pattern departs from a particular neutral model can indicate early warning signals of regime shifts, and how those landscapes might evolve/react to additional land-cover variation. Moreover, as the land-cover pattern mostly depends on social-economic factors, we argue that we have to change societal values at the root of inflexibility.

1. Introduction

Social-economic factors have been unceasingly imposed on biophysical components of complex adaptive systems as social-ecological landscapes (SELs) (Berkes and Folke, 1998; Zaccarelli et al., 2008). As a result, SELs generally follow a historical distinctive sequence of different land-use/land-cover (LULC) pattern regimes, e.g., from pre-settlement natural vegetation to frontier clearing, then to subsistence agriculture and small-scale farms, and finally to intensive agricultural and urban areas, and confined recreational areas (Foley et al., 2005). This general trend implies the expansion of global croplands, pastures, plantations, and urban areas, with large increases in the consumption of energy, water, and fertilizer, with the drainage of wetlands and floodplain embankments, conflicts between housing and economic land use, the loss of biodiversity following habitat fragmentation by urbanization and transport infrastructure (Lambin et al., 2001; MEA, 2005). This has

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led to clearly defined spatial areas with fixed rules in many parts of the world through the increasing merging and enlarging of specific functions, like intensive agriculture, urban and recreational areas (Foley et al., 2005). Therefore, one main problem to face is how a "static" and "ordered" landscape condition in SELs, provided by the cross-scale intersections of plans and norms (order) can be made sustainable in the face of both predictable and unpredictable disturbance and change (disorder) (Zurlini et al., 2013). Instead of the adaptability required to counter surprises, inflexibility limits the ability of persons, groups, and companies to respond to new emerging issues, and some may have contributed to the collapse of ancient societies (Scheffer and Westley, 2007).

Such inflexibility is exemplarily illustrated in Pirsig's (1974) book, where the South Indian monkey trapper drills a hole in a coconut, puts a ball of rice inside and chains the coconut to a stake. The monkey smells the rice, inserts its hand to grasp the rice, and becomes trapped since its fist with the ball of rice is now too big to pass through the hole, and it will not let go of the rice. Pirsig calls this trap "value rigidity." The usually high value the monkey places on rice requires re-evaluation of this life-threatening situation. If the monkey gave up a bit of rice, it would save its life, but because of its consolidate value rigidity the monkey does not and results captured. In this metaphor, value rigidity skews the value we attach to facts and, because of value rigidity we might get stuck in a "rigidity trap" (Carpenter and Brock, 2008).

Agricultural intensification has been a worldwide phenomenon since 1961 that doubled the world's food production with only a 10% increase in the area of arable land globally (Tilman, 1999). Increasing external pressures from agricultural intensification and climate change lead to increasing desertification, affecting the livelihood of more than 25% of the world's population (MEA, 2005). Inflexibility of land administration may, in turn, reinforce such desertification processes, erode the resilience and promote regime shifts and collapse (Holling and Meffe, 1996; Allison and Hobbs, 2004; Anderies et al., 2006) in arid and semiarid regions, more susceptible to suffer dramatic changes. Consequently, the search for indicators of imminent ecosystem shifts is drawing growing attention, especially for those regions before they may convert into deserts (Scheffer et al., 2001; Reynolds et al., 2007).

If we do not have proper early warning signals of system shifts, and if we are not able to adapt through feedback mechanisms to changes in the environment, we might get stuck in a rigidity trap like the Pirsig's monkey, and we are at high risk of abrupt shifts with important ecological and economic consequences. Such shifts are documented not only in lakes and forests to rangelands and coral reefs, but also in a wide spectrum of other complex systems, including physiological systems, financial markets, and SELs like desertification in the Mediterranean region (Kéfi et al., 2014). Because of their consequences, recent research has focused on devising early warning signals for anticipating such abrupt ecologic transitions (Scheffer et al., 2009).

Theoretical studies have shown that upcoming transitions entail spatial signatures, so that spatial patterns could provide powerful indicators of regime shifts in SELs (Guttal and Jayaprakash, 2009). For not well-mixed ecosystems such as dry lands, boreal wetlands, or heterogeneous habitats, changes in spatial patterns could provide early warnings of impeding transitions (Guttal and Jayaprakash, 2009; Carpenter and Brock, 2010). For terrestrial ecosystems, changes in vegetation patchiness can be a signal of imminent transitions like the conversion into deserts of Mediterranean arid ecosystems (Kéfi et al., 2007). These studies designate the increase in spatial connectivity, in particular, as a prominent indicator of early warning for an impending critical transition of regime shifts, and that may be a generic phenomenon for a wide class of transitions (Dakos et al., 2010).

This paper advances a novel approach, drawing the attention to some emerging cross-scale patterns of land-cover largely driven by changes of socioeconomic conditions (Foley et al., 2005) that could be signs of impeding shifts in an exemplary Mediterranean semi-arid region. We argue that a potentially useful way to address regime shifts is to look at different land-cover patterns within a simple framework to interpret current spatial connectivity across scales with the aid of simulated landscape patterns. So, early warning signals could refer to the degree to which observed cross-scale patterns depart from a particular neutral landscape model. We provide examples of this approach and discuss what a cross-scale land-cover pattern could mean, what it tells about the condition of SELs, and what could be the effects of changing observed conditions. In this attempt, we exercise concepts and methods for the Apulia region (southern Italy), as an example of Mediterranean semi-arid region where water shortages and desertification processes are already in place (Frattaruolo et al., 2012; Ladisa et al., 2012). We first illustrate how different connectivity patterns can be gauged for their transitions in a suitable space (the pattern transition space), allowing us to explore their cross-scale nature. We, then, exercise the framework with real and simulated maps. Classical landscape null models (Gardner et al., 1987; Gardner and Urban, 2007) are applied as baselines for comparison to the real landscapes on the same pattern transition space. We show that connectivity of different land-covers can be used as an early warning signal for an impending critical transition to desertification, with potentially dramatic shifts in land-cover composition below certain thresholds, and this can be detected only through a cross-scale approach. This could be useful to monitor how landscapes might evolve or react to variation of land cover due to changes in climate conditions and very central to understanding the kinds of management and/or policy actions to take at various scales. Finally, we argue that we have to change societal values at the root of inflexibility, in order to manage a real transition toward more environmentally efficient and, therefore, more sustainable land-cover patterns.

2. Data and methods

2.1. A typical Mediterranean semi-arid region: the Apulia

The Apulia region (southern Italy) (Fig. 1) is presented here as an example of panarchy of nested jurisdictional SELs made up of people and nature (sensu Gunderson and Holling, 2002), where more than 82% are constituted by agro-ecosystems. The Apulia region is a typical Mediterranean highly semi-arid region according to the aridity index (Pueyo and Alados, 2007), with desertification processes already in place (Perini et al., 2009; Parise and Pascali, 2003; Frattaruolo et al., 2012; Ladisa et al., 2012) because of both unfavorable bio-physical conditions and increasing human pressure. Such factors include erratic precipitation (mainly in winter), high summer temperature with frequent droughts, poor and erodible soils, extensive human-induced deforestation with frequent wildfires and arsons, land abandonment, heavy exploitation of aquifers leading to coastal salinization, concentration of economic and tourism activities in coastal areas (Ladisa et al., 2012).

Agriculture is still one of the primary economic resource as shown by the recent trends of productive and unproductive LULCs and of main employment sectors (Fig. 1). The northern and somewhat the central part of the region include arable lands (39.8%), producing cereals and vegetables, while extensive century-old as well as intensive olive groves (22.6%), fruit orchards and vineyards (6.4%), and heterogeneous agricultural areas (13.3%) dominate the central and southern parts of the region (Zaccarelli et al., 2008), which are karst with no surface-water bodies. Major towns and small urban settlements account only for 3.8%, while natural

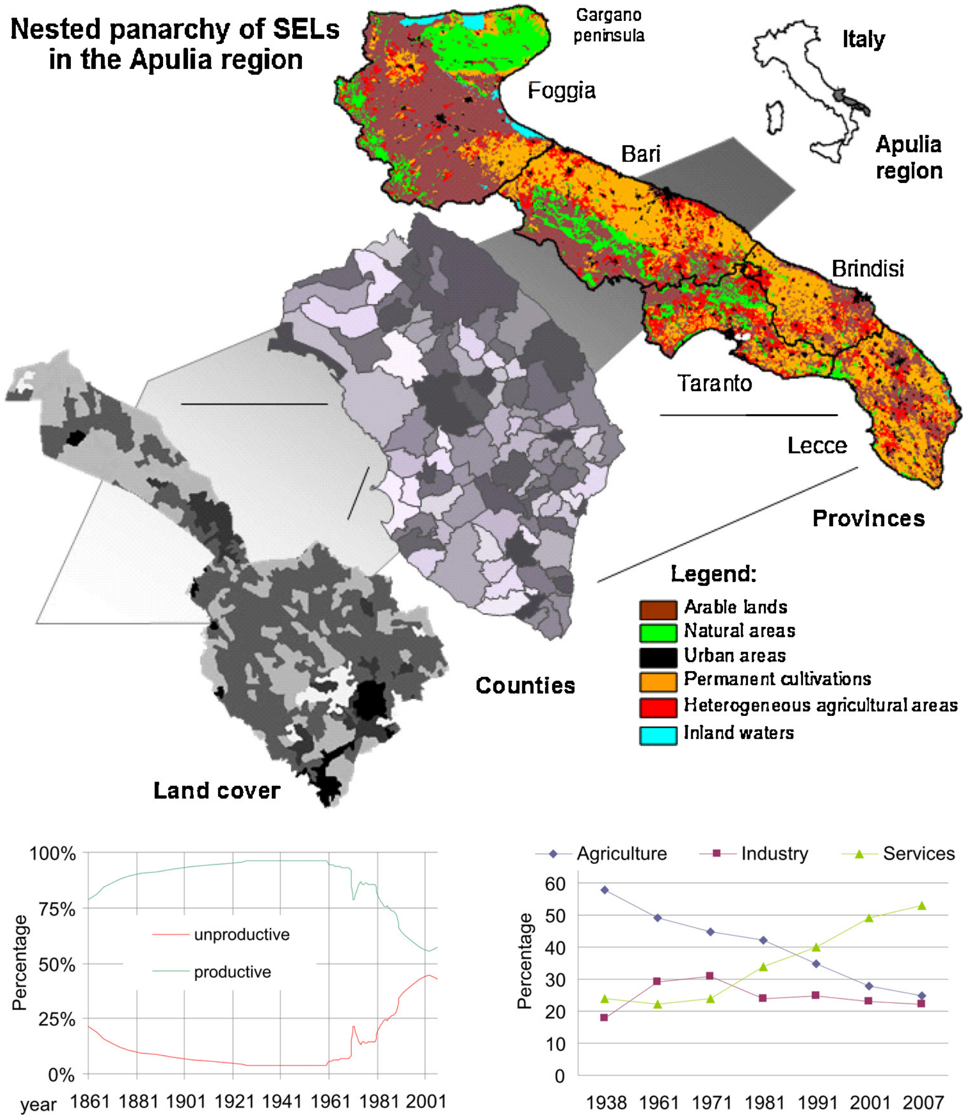

Fig. 1. Nested panarchy of SELs in Apulia (southern Italy) with main LULC composition (top) and recent historical trends of productive and unproductive land (a), and of main employment sectors (b) (source of census data: ISTAT, 2011).

habitats are unevenly distributed with forested areas (7.3%) concentrated in the Gargano peninsula.

Recent trends are characterized by a merging of arable lands, a contraction of vineyards, and the expansion of olive groves, plantations, and urban areas, with large increases in energy, water, and fertilizer consumption, along with extensive biodiversity loss (Zaccarelli et al., 2008; Petrosillo et al., 2010). Recurrence plots for 12 year (2010–2012) time series of 16-day maximum normalized difference vegetation index (NDVI) reveal that the dynamics of forests are fairly spatiotemporally predictable (highly resilient), whereas arable lands are less predictable despite self-correcting balancing feedback loops (e.g., drought-irrigation, soil impoverishment-fertilization), and urban areas show a chaotic behavior (Zurlini et al., 2014).

Highly-intensive production increased significantly because of mechanization with a decrease in the relative employment sector (Fig. 2). Olive oil, wheat, and wine (the three main agricultural productions) are critically dependent on sufficient and cheap water availability (Kapur et al., 2010). As a result, the main vulnerability of the region concerns its persistent water scarcity related to its water budget deficit (about 350 mm/year), requiring regular water imports from nearby regions and heavy exploitation of aquifers (Gualdi et al., 2011; Salvati et al., 2011).

In trying to respond to those issues, a number of plans have been developed in the last decade in the Apulia region at different jurisdictional levels, i.e., region (Regione Puglia, 2012), province and municipality (Fig. 3; Zaccarelli, unpublished data). Such plans refer to hydrogeological risk and water management, landscape and coastal area management, cultural heritage, conservation, and parks protection, regulating energy development and production, and rural development. All plans clearly define spatial patterns with fixed rules, and their very complicated intersection within and across scales often makes difficult, if not impossible, to determine whether a new particular activity can comply consistently with all the rules (Fig. 3), and this is often at the root of many conflicts.

2.2. The pattern transition space

Many authors (e.g., Li and Reynolds, 1994; Riitters et al., 2000; Neel et al., 2004; Zurlini et al., 2006, 2007; Proulx and Fahrig, 2010) suggested to study landscape pattern focusing on the two most fundamental measures of pattern, that is composition (what

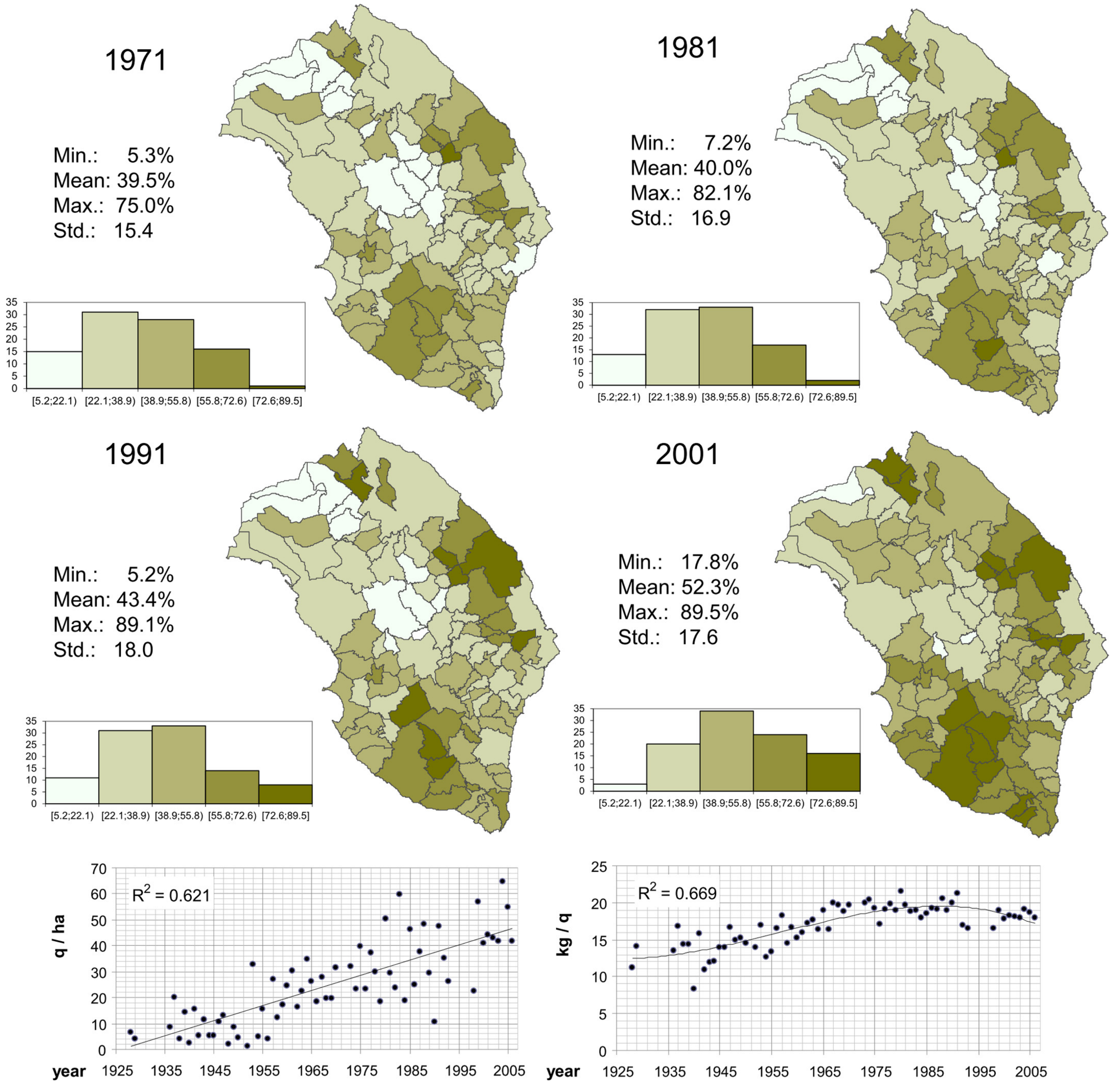

Fig. 2. Map of olive grove intensification for the municipalities of the Salento peninsula. Trends in olive yield and olive oil production efficiency are presented below; a darker color corresponds to a greater intensification of olive groves (source of census data: ISTAT, 2011).

and how much there is) and connectivity (configuration, spatial arrangement). In this respect, even simple binary maps generated by neutral landscape models (NLMs) (Gardner et al., 1987) can produce a surprisingly rich array of spatial patterns. The pattern transition space can be esemplified by a set of 25 neutral landscapes (Fig. 4) where the focal land-cover area (Pc) is related to connectivity as the degree of spatial autocorrelation among adjacent cells (H) (Neel et al., 2004). There are a number of circumstances where quite a few transitions of the focal area (black) pattern occur. There is a transition from a background matrix (top) to foreground patches (down), while, at the top, there is a transition of a perforated matrix from small or diffuse holes (left) into large or distinct holes (right). Below, there is a transition from smaller patches (left) into fewer, larger patches (right). In general, from left to right, at similar composition values, there is a transition from more to less fragmented landscapes with increasing connectivity, and from less to sharper contrast with the non-focal cover type.

Even though NLMs do not adequately represent linear features such as rivers and hub-and-spoke landscape patterns within agriculture and urban landscapes (e.g., Jones et al., 2013), the emphasis on focal class aggregation of neutral models is justified because changes in class aggregation are a major, if not the dominant, component of the fragmentation process at the landscape level (Neel et al., 2004; Li et al., 2004).

Structural connectivity and fragmentation can be estimated for real landscapes, for example, using the proportional adjacency of a

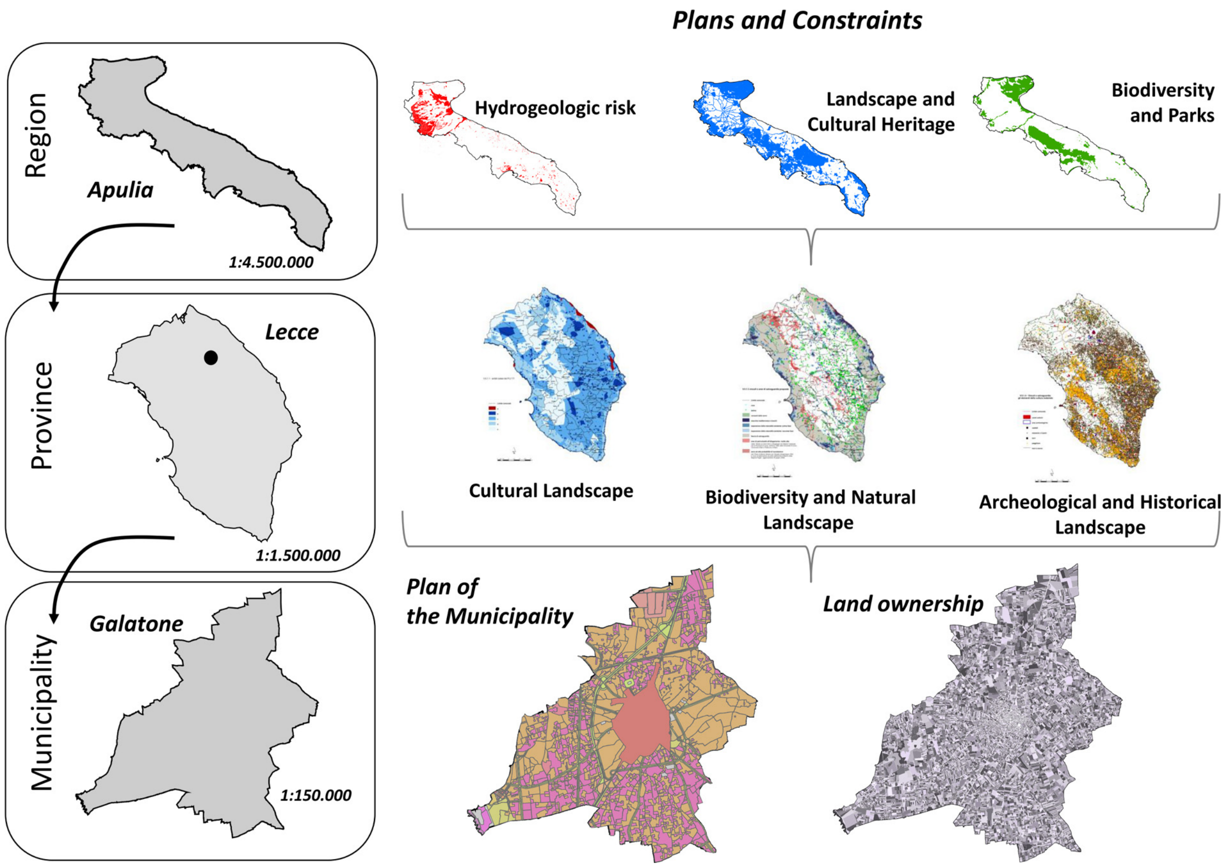

Fig. 3. Example of overlay of plans and constraints at different jurisdictional levels in the Apulia region (source of data: Regione Puglia, 2012).

focal cover type pixel, i.e., the conditional probability that a pixel is adjacent to another pixel of the same land-cover type (Pcc) (Riitters et al., 2000). One advantage of using it as a structural connectivity measure is that it can be easily calculated for both real and simulated binary landscapes and, therefore, can be used for generating the same pattern transition space for both real and simulated landscape patterns. Another advantage is that it represents an image ‘texture’ which is one of the fundamental aspects of pattern measured by popular pattern metrics (Riitters et al., 1995).

One way to derive land-cover patterns across scales uses an overlapping moving window device to measure map composition, i.e., the proportion of focal cover type (Pc) for different window sizes over the entire region. We use the adjacency (Pcc) for structural connectivity within a window with the same set of window sizes both for simulated and real maps (Zurlini et al., 2006). As a result, we can characterize a pattern transition space [Pc, Pcc] at different scales resulting from different-sized spatial windows. Taken together, they can describe wide-ranging spatial patterns that are encountered on real maps for different focal land surface features including habitats, LULC types, disturbance regimes, and any other focal feature (Riitters et al., 2000; Zurlini et al., 2006; Zaccarelli et al., 2008; Petrosillo et al., 2010).

2.3. Real and simulated cross-scale patterns

As to real landscapes, we set few broad focal LULC categories from the 2006 forth level CORINE land-cover of the Apulia region (www.sit.puglia.it). Data were converted from vector to raster with 100 m pixel size. This was the thematic base level for the whole regional panarchy, including Forests, Olive groves, and Arable lands summing up to 93% of the entire region. We also generated 1000 random, multifractal, and two level hierarchical landscape pattern maps of size 1024 × 1024 cells (pixels) using the RULE model (Gardner, 1999). Then, we measure the connectivity of simulated maps by proportional adjacency.

A critical component of this approach is the ‘convergence point’ (CP), which represents the global [Pc, Pcc] value that is exactly equal to the extent of the entire map. For any smaller window, the value of [Pc, Pcc] will necessarily depart from the CP of reference if the local pattern at the scale of the window size is different from the global pattern. With decreasing window size at a given geographic location, the profile away from the CP in [Pc, Pcc] space describes the cross-scale ‘profile’ of pattern surrounding that location at different window sizes (Zurlini et al., 2006, 2007).

Such pixel-level profiles are clustered to eight main groupings of cross-scale pattern’s sizes (Zurlini et al., 2007). Any two geographic locations with the same cross-scale cluster profile experience the same pattern at different neighborhood sizes. Land-cover CPs can shift in the pattern transition space according to corresponding changes in global [Pc, Pcc] values (Zurlini et al., 2006).

3. Results

3.1. Simulated cross-scale patterns

A random map, by definition, has no local domains at any scale 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 transition space (Zaccarelli et al., 2008).

Multifractal maps do not exhibit convergence, and none of the profiles reaches the CP (Fig. 5). By definition, a multifractal is constructed to have the higher moments grow increasingly with scale, making for nonstationary parameters. This implies that cluster

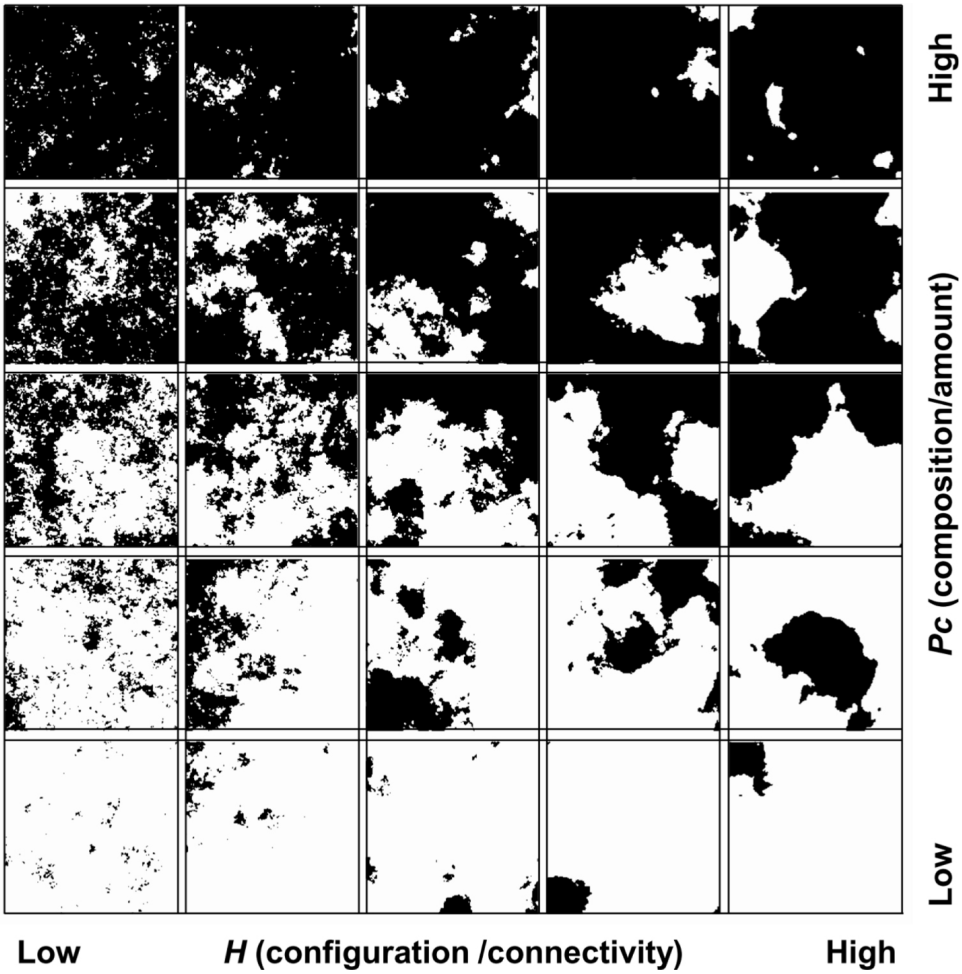

Fig. 4. Pattern transitions illustrated by twenty-five binary multi-fractal neutral landscape maps (256 × 256 cells – pixels) generated by the computer program RULE (Gardner, 1999) and ordered by the amount of the focal land cover type (Pc) and connectivity as the degree of spatial autocorrelation among adjacent cells (H) (modified after Neel et al., 2004).

profiles will not converge to CP except asymptotically, and this occurs both for the real and simulated landscape (Fig. 5, profiles for Pc and Pcc, below). Multifractal patterns arise from the alternation of various elements scattered in the landscape across a range of scales (Fig. 4); they are very common and similar to patterns of many real phenomena we can observe in the geographic world (e.g., Milne, 1991; Li, 2000; Halley et al., 2004; Zurlini et al., 2007; Fig. 5).

As for hierarchical patterns, they do exhibit a convergence at intermediate window sizes with a typical fish-bone scaling pattern of structural connectivity (Pcc, Fig. 6). Cluster profiles of hierarchical maps look like strings of a "frayed rope" starting at local scales from different regions and then quickly aggregate along scale to form a common "rope" with variations in composition but with connectivity that seems rather steady at certain scale ranges (Zurlini et al., 2007).

In general, hierarchical patterns are characterized by fewer, larger patches with clearly defined boundaries and a sharp contrast with the non-focal cover type (Fig. 4, lower right-hand corner).

3.2. Real patterns

Cross-scale profiles obtained from broad LULC classes like Forests, Olive groves, and Arable lands of the study area seem to follow hierarchical-like patterns (Fig. 6). Such patterns arise because some land cover (large fields, industrial and urban areas) and land covers (conservation areas, natural parks) are typically constrained within the bounds established by planning actions and/or economic necessities (Fig. 3). Along with the expansion of industrial and residential areas, fields have been merged and enlarged to enhance farming efficiency resulting in rather homogeneous farmed landscapes (e.g., arable lands, Figs. 1 and 6). In addition, even planning for conservation both on land and sea, has implied the identification and confinement of land and coastal areas in fewer, larger portions to make management easier and mitigate the negative effects of fragmentation and habitat loss on species persistence (e.g., Forests, Fig. 6). As to olive groves, the trees are well adapted to the Mediterranean climate and karst conditions and require little water in its natural state. Whereas a traditional olive farm is made of large, ancient, widely spaced trees providing cover for grass and grazing animals, the trees in recent plantations are tightly packed, scrubbier and usually grow in shallower soil. Such intensive cultivation has been merged and enlarged (Figs. 2 and 6), producing up to 20 times as many olives as a traditional grove at the expense of much more irrigation.

3.3. Composition and structural connectivity across scales

The cross-scale path of land-cover CPs (Fig. 7) is derived from observed distributions and is approximately represented by the two extremes cluster profiles (e.g., C1 and C8, in Fig. 6). For multifractal patterns, connectivity increases at higher composition

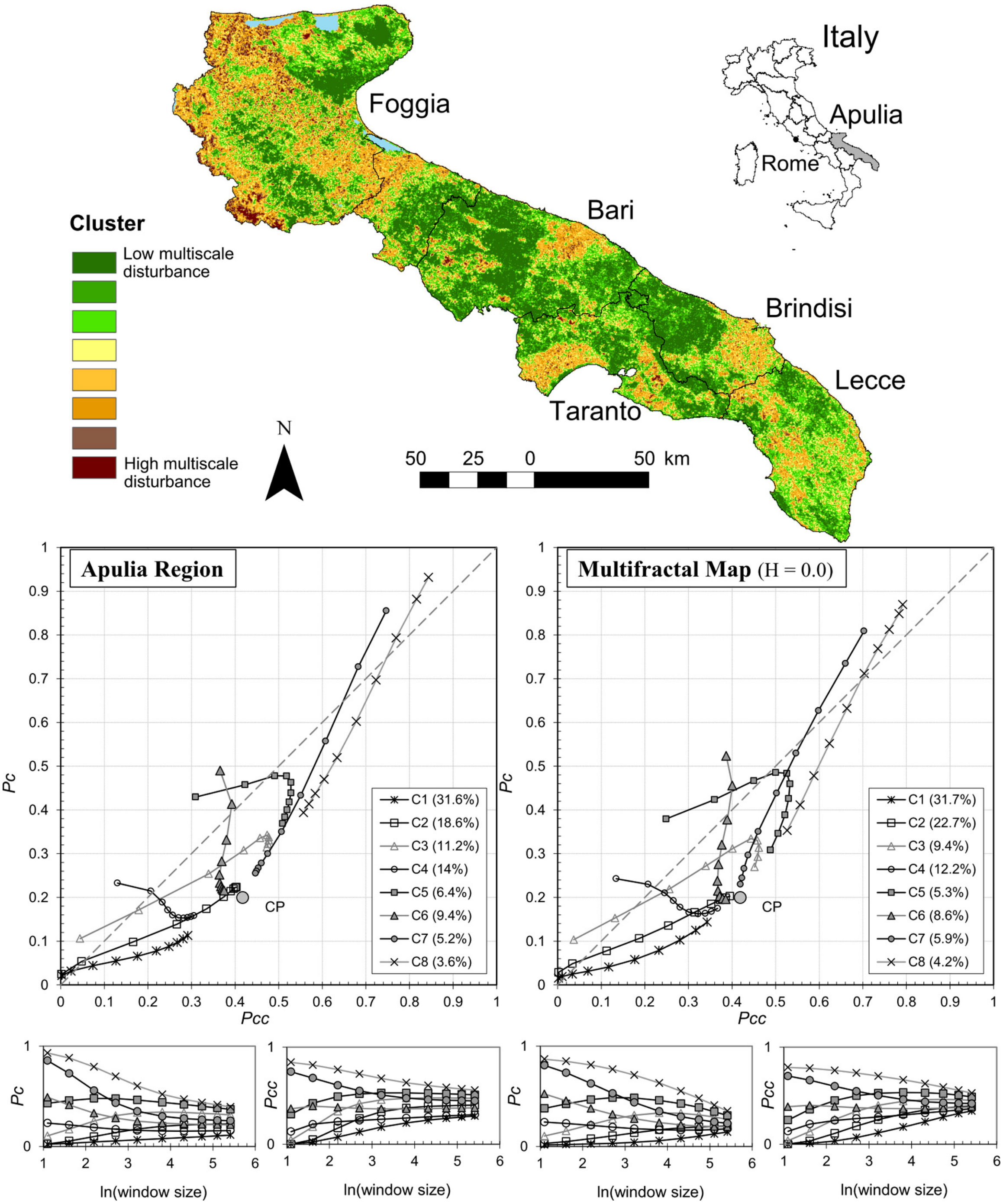

Fig. 5. Example of cross-scale cluster profiles in the Apulia region and their geographical representation (Pc and Pcc refer to disturbance; modified after Zurlini et al., 2007; Zaccarelli et al., 2008). Real (left) and simulated multifractal (right) profiles. Percentages refer to the number of pixels for each cluster profile (C) with respect to all pixels of the entire region.

values almost proportionally to composition (Fig. 7, top right). On the other hand, in highly fragmented maps (Fig. 7, bottom left), an increase of focal cover, for example, from 0.0 to 0.2 (20%) results in a 45% increase in connectivity. Within these two opposite situations, transitions between multifractal patterns entail a corresponding smaller increase in connectivity for each unit of a percentage increase. So, 45% of the overall structural connectivity reside in the first 20% of land-cover composition.

In hierarchical patterns, connectivity at higher composition values can vary much less than proportionally with composition (Fig. 7, top right). On the other hand, at lower composition values (Fig. 7, bottom right), a reduction of focal cover from 0.2 to 0.0 (20%) results in a remarkable 90% decrease in structural connectivity. Thus, Forests and Olive groves could be highly vulnerable to habitat loss at very low composition since a small amount of habitat reduction (e.g., less than 7%) may disrupt structural connectivity up to 73% (Fig. 6). At low forest composition (about 7%) there is a sharp shift at 73% connectivity that can be deemed as a critical threshold (Fig. 6).

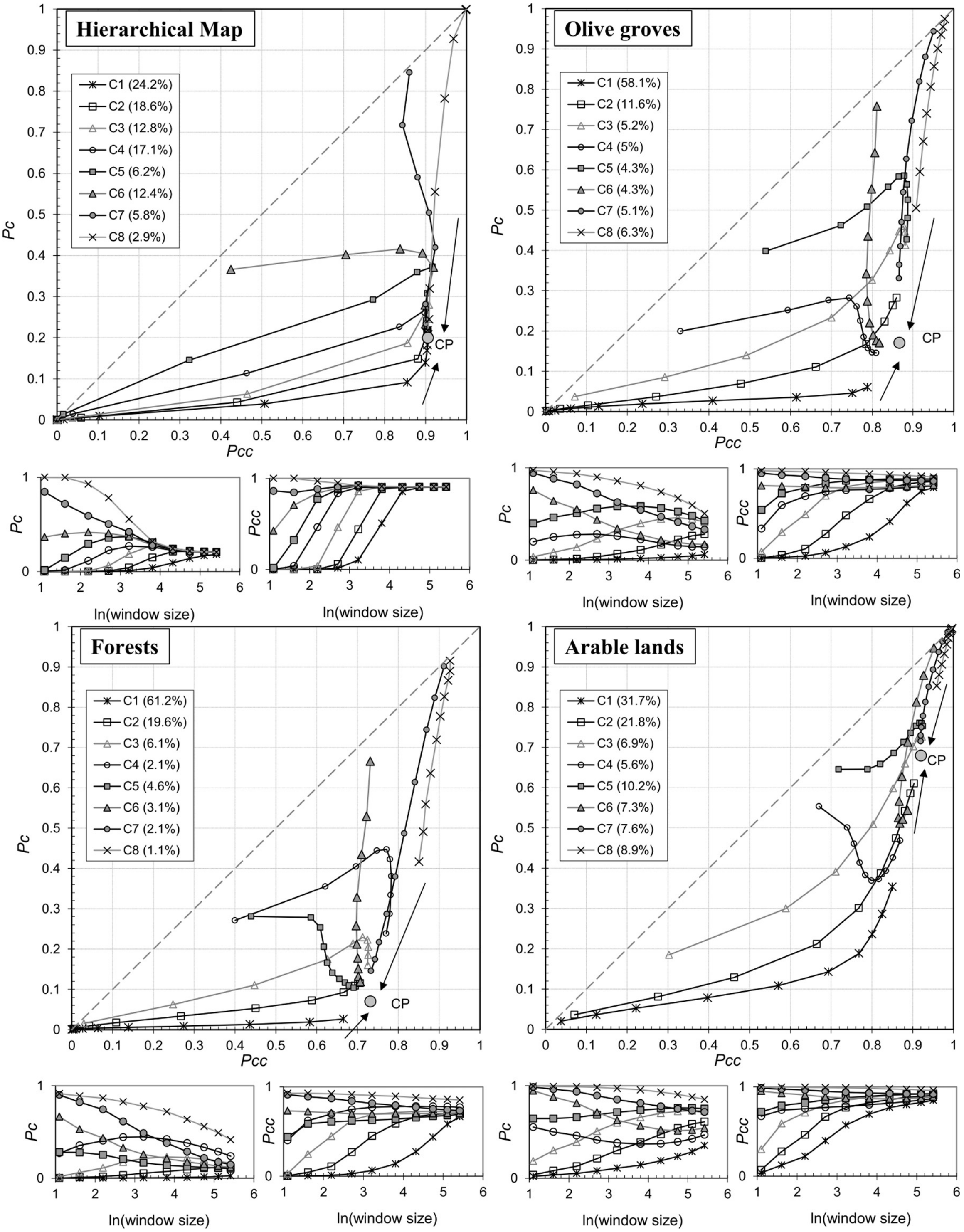

Fig. 6. Simulated hierarchical patterns (top left) and real cross-scale patterns for Olive groves, Forests, and Arable lands in Apulia. LULC composition patterns are clearly additive and sum up to 93% of the entire available regional land. C stands for clusters as in Fig. 5.

We can then identify three main types of relationship between composition and structural connectivity with some invariant properties at particular scale ranges in the pattern transition space of CPs (Fig. 7): *Build up (or break down)*, where the first 10% of the composition of focal land cover builds up almost 35% of total connectivity for multifractal patterns. In hierarchical-like patterns 10%, for example, of Forests and Olive grove composition provides more than 70–80%, respectively, of relative total structural connectivity; *Resistance*, where a unit of a percentage increase in composition determines a parallel much lower increase in connectivity (about 50% for multifractal and very much less for hierarchical patterns); *Linear change* between composition and connectivity only for multifractal patterns at higher composition values. An idea of underlying patterns at any location in the pattern transition space is provided by simulated maps (Fig. 4).

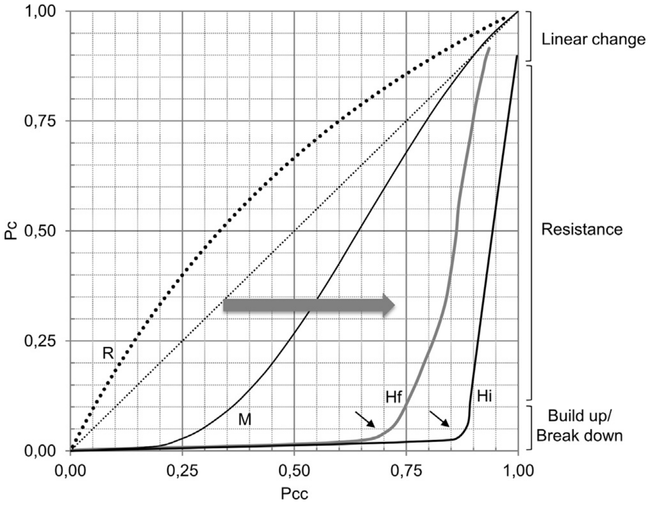

Fig. 7. Summary of results for random, multifractal and hierarchical patterns in the pattern transition space defined by composition (Pc) and configuration or connectivity (Pcc): R, pattern of simulated random maps; M, general pattern of simulated and observed multifractal maps (Fig. 5); Hf, observed hierarchical-like pattern of Forests (Fig. 6); Hi, simulated hierarchical maps. Black arrows indicate thresholds. The gray arrow indicates the direction of connectivity transition.

4. Discussion

4.1. Rigidity traps

A robust and consistent picture of climate change over the Mediterranean emerges, consisting of both a pronounced decrease in precipitation, especially in the warm season, and a marked warming, with its maximum in the summer season leading to a greater occurrence of extremely high temperature events (Giorgi and Lionello, 2008). Meanwhile, economies of scale seem largely responsible on the ground for the current, observed trend in southerly Europe in merging and increasing farm sizes and, thus, fewer farms and farmers (Metzger et al., 2006).

In ecology, such merging increases connectivity between metapopulations or metacommunities and is often considered advantageous for promoting resilience and recovery; however, connectivity is a two-edged sword, and more connections between human-managed ecosystems can also spread disease, introduce new species, increase harvesting and soil and water stress gradually eroding resilience (Van Nes and Scheffer, 2005). The introduction of new farm machinery, strains of cereals and tree crops, along with the overexploitation of water resources for irrigated agriculture, and extensive application of fertilizers represent the main social-economic drivers in charge of the desertification and soil erosion in the Mediterranean Europe (Briassoulis, 2003) as well as in the Apulia region (Perini et al., 2009). Besides, time series highlight that during the second half of the 20th century the regional Apulia climate has become moderately warmer and drier (Gualdi et al., 2011) and responsible for a significant proportion of the inter-annual production variability in olive oil (15%) and wheat (16%) (Gualdi et al., 2011). The net irrigation requirements for major crops in the region are expected to increase in the next hundred years with a maximum of 65% for intensive olive groves with further over pumping of aquifers (Kapur et al., 2010). This will increase water stress by the intensity, extent, timing, and duration of changes in normal water resource availability (Acosta-Michlik et al., 2008).

As a result of overlaying plans and constraints (Fig. 3) and the increasing spatial aggregation of intensive agriculture, olive groves, and urban areas (Fig. 4), a rather inflexible structure with hierarchical-like pattern is emerging across scales. The arrow in Fig. 7 indicates the general trend of pattern transition in connectivity from multifractal-like to current hierarchical-like patterns (e.g., Fig. 2), with the potential local increase of soil and water stress, fewer capacities to dissipate it, and dramatic break-downs of connectivity at low land-cover composition below certain thresholds (e.g., Forests, Hf in Fig. 7). Whenever changes to land cover cross those thresholds recoveries can be difficult, expensive and slow. In particular, forests actually drive the water cycle on land promoting precipitations, so that their further reduction can be particularly critical to water scarcity (Makarieva et al., 2014).

The interplay among the inflexibility of plan constraints, the general agricultural intensification, and climate change, can give rise to a "rigidity trap", which is formally characterized by spatial patterns with low heterogeneity and higher aggregation and connectivity of entities, a great capacity to focus on a singular approach, low capacity to explore alternatives, and little capacity to dissipate stress (Holling, 2001; Carpenter and Brock, 2008). Such trap is constituted by a pathological loop of resource degradation and stress (soil and water), followed by social-economic response aimed at reestablishing or maintaining productivity of the resource-degrading activity (social inflexibility), with consequent further land degradation and erosion of the system adaptive capacity to cope with shocks and surprises. This can dramatically enhance desertification processes and be detrimental to the necessary adaptability of landscape elements and biodiversity. This can alter, in turn, the vegetation and the patterns of regional climate variables like temperatures and precipitation (Pielke, 2005; Makarieva et al., 2014) with adverse effects on the ability of ecosystems to support the water cycle on land. We argue that this adverse circumstance can become typical in many different human-dominated semi-arid areas like the Apulia region.

4.2. Early warning pattern indicators of impeding transitions

Because of increasing desertification, the search for indicators of imminent ecosystem shifts is drawing growing attention in Mediterranean arid and semi-arid regions. Thus, for example, the distribution of vegetation patch size can be described by a power law over a wide range of environmental conditions (Kéfi et al., 2007; Scanlon et al., 2007), and deviations from such a distribution under high grazing pressures, could be used as indicators of approaching desertification (Kéfi et al., 2007).

In a similar way, our simple example suggests that land-cover pattern and, in particular, connectivity, can be used to provide early warning signals of regime shifts in Mediterranean semi-arid region like Apulia, according to the degree to which observed cross-scale patterns depart from a particular neutral landscape model. In this respect, the convergence point (CP) represents a regional value responding to both connectivity and composition (Fig. 6). Therefore, CP can be used as a cross-scale early warning indication of regime shifts at certain thresholds (Fig. 7). This because we can reasonably guess where the CP is in the pattern transition space for the area of interest, whether a particular landscape pattern scenario will shift the CP, and how its path could be across multiple scales and its environmental consequences (Fig. 7). Thus, for instance, the CPs of Forests and Olive groves (Fig. 6) are currently rather proximate to the critical threshold (Fig. 7). That means that even a further reduction of those land covers, accounting for about 30% of the region, might lead to dramatic shifts in connectivity/fragmentation with effect on the water cycle on land (Makarieva et al., 2014); on the other hand, an increase could be healthy for the water cycle whereas connectivity would not benefit much from this (Fig. 7). An increase of Arable lands would increase water and soil stress but not connectivity that is already high.

Italian forest area and fragmentation across scales remained apparently unchanged over the 10-year period (1990–2000), however, significant changes were observed in the Apulia region at certain scale intervals (Zaccarelli et al., 2006). This clearly calls for a cross-scale approach, and the goal could be then to build in a safety factor whenever the CP is observed or expected to shift, to help identify where and at which scale issues could be addressed with a more coordinated, cross-scale approach in adaptive design and management.

5. Conclusions: perspectives in adaptive design and management

Managing a transition toward more environmentally efficient and, thus, more sustainable land use implies better information on consequences of land-use decisions from local to global scale, the creation of proper incentives for agents, a greater capacity to adopt new LULC patterns and practices (Lambin and Meyfroidt, 2011). To this end, we need change beliefs, analyses or hunches that can make hard to learn new facts like for Pirsig's monkey and to recognize important facts, or not, in line with our established values (Armson, 2011). Self-sealing beliefs can be self-correcting when extreme events such as wildfires or hurricanes foster change in long-established rules and practices like planning and management (Schusler et al., 2003). However, events like desertification processes may also provoke other feedback processes working to maintain the status quo, such as the financial and/or political support that accompanies the continued crisis management. So we might, nevertheless, get stuck in a trap through the pathological loop of resource degradation even when resource managers recognize that things would improve if they approached their work differently (Repetto and Allen, 2006).

The priority in combating desertification processes in arid and semi-arid regions should be the implementation of preventive measures based on early warning signals like those presented here, for lands that are not yet degraded, or, which are only slightly degraded, even though severely degraded areas clearly need concern too. An adaptive approach still provides a fundamental framework for the implementation and adaptation of management and policies over time as more information is collected (Walters, 1986; Vernier et al., 2009; Cushman and McKelvey, 2010). A crucial issue then could be developing landscape planning and management (e.g., restoration) that might accommodate for surprises (Scheffer et al., 2001) and for change in land-cover pattern (Fig. 7) as humans will change land-use and land management to adjust to climate change.

In this respect, new conceptual strategies for the design of SEL sustainability are emerging (e.g., Olsson et al., 2004; Folke et al., 2005; Musacchio, 2009; Opdam et al., 2009; Ostrom, 2009; Benayas and Bullock, 2012; Zurlini et al., 2013; Jones et al., 2013). Such strategies can involve the design and management of landscape structure and processes such as to promote a shift of land-cover CP in the opposite direction to that of the arrow in Fig. 7. This implies, for example, the strategic conservation of forests and placement of managed and semi-natural ecosystems to reduce water and soil stress intensity, and such as to enhance the services of natural ecosystems (e.g., commodities, water availability, pollination, reduced land erosion, soil formation) (Jones et al., 2013).

Land separation and land sharing are examples of such strategies (Benayas and Bullock, 2012). The first involves restoring or creating non-farmland habitat in agricultural landscapes through, for example, riparian habitats (Jones et al., 2010), woodlands, natural grasslands, hedgerows, wetlands, and meadows on arable lands (Benayas and Bullock, 2012) to benefit wildlife and to prevent water scarcity. Land sharing involves the adoption of biodiversity-based agricultural practices, learning from traditional water-saving farming practices, transformation of conventional agriculture in organic agriculture and of "simple" crops and pastures into agro-forestry systems. In contrast to agricultural intensification, traditional farmers provide cultural and ecological services including the preservation of traditional farming knowledge, local crop and animal varieties, and native forms of sociocultural organization (Altieri, 2004). Some existing small-scale farming systems already have high water, nutrient, and energy-use efficiencies and conserve resources and biodiversity without losing yield (Kiers et al., 2008).

A key aspect is to implement monitoring programs to evolve iteratively as new information emerges and research and managing questions change according to environmental changes (Lindenmayer and Likens, 2009). This helps evaluate how environmental targets and ecosystem services, like precipitations on land (Pielke, 2005; Makarieva et al., 2014), respond to specific landscape pattern designs (Ahern, 1999; Jones et al., 2013), and whether or not certain landscape patterns at multiple scales (Fig. 7) result in synergies and trade-offs among different types of ecosystem services (Wu and Hobbs, 2002; Naidoo et al., 2004).

Our understanding of these phenomena is still far from complete and perhaps overly simplistic and multi-scaled LULC patterns will not be easier to manage, but having such knowledge will be necessary for multiple stakeholders in the panarchy of SELs to cooperate in social networks within and among organizational levels for managing SEL resilience under uncertainty and change (Walker et al., 2002; Olsson et al., 2004). This because, changing circumstances demand to reappraise values like it should be for the Pirsig's monkey and his rice. Cross-scale collaborative planning networks can facilitate overcoming the rigidity traps that prevent resource management agencies from responding to complex cross-scale problems (Butler and Goldstein, 2010). The intentional induction of cooperation could be promoted across the panarchy of SELs through the establishment of social initiatives that increase the perception of similarity within and among stakeholders to reach a minimal level that makes cooperation advisable (Fischer et al., 2013). In other words, we must be fully aware that we might get stuck in a rigidity trap to appreciate the similarity of our common condition and to start real cooperation.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2014.05.018. These data include the Google map of the most important areas described in this article.

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