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Multi-scale vulnerability of natural capital in a panarchy of social–ecological landscapes

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A B S T R A C T

Environmental security, as the opposite of environmental vulnerability (fragility), is multi-layered, multi-scale and complex, existing in both the objective physical, biological, and social realm, and the subjective realm of individual human perception. In this paper, we detect and quantify the scales and spatial patterns of human land use as ecosystem disturbances at different hierarchical levels in a panarchy of social–ecological landscapes (SELs) by using a conceptual framework that characterizes multi-scale disturbance patterns exhibited on satellite imagery over a four-year time period in Apulia (South Italy). In this paper we advance the measure of the functional importance of ESPs provided by natural areas and permanent cultivations based on their effectiveness at performing the services. Any landscape element contributes to the overall proportion of disturbance in the region, through its composition of disturbed locations (pixels), and to the overall disturbance connectivity through its configuration. Such landscape elements represent, in turn, functional units for assessing functional contributions of ES providers at different scale(s) of operation of the service. We assume that such effectiveness at performing the services will result directly affected by how much disturbance surrounds ESP locations at different neighborhoods. Multi-scale measurements of the composition and spatial configuration of disturbance are the basis for evaluating vulnerability of ecosystem services through multi-scale disturbance profiles concerning land-use locations where most of ecosystem service providers reside. Vulnerability estimates are derived from the identification of scale range couplings or mismatches among land-use disturbances related to different land uses and revealed by trajectories from the global profile to local spatial patterns. Scale mismatches of disturbances in space and time determine the role of land use as a disturbance source or sink, and may govern the triggering of landscape changes affecting ecosystem service providers at the scale(s) of operation of the service. The role of natural areas and permanent cultivations (olive groves and vineyards) in providing *disturbance regulation* across scales in South Italy has consequences for regional SELs since it may govern if and how disturbances associated with land-use intensification (sources) will affect the functional contribution of ES providers.

1. Introduction

During recent decades, worldwide losses of biodiversity have occurred on an unprecedented scale and agricultural intensification has been indicated as a major driver of this global change (e.g., Matson et al., 1997; Donald et al., 2001; Tilman et al., 2002; Stokstad, 2006). On one hand, land-use intensification has disrupted ecosystem services such as biological pest control (e.g., Matson et al., 1997; Tylianakis et al., 2004) and crop pollination (e.g., Stokstad, 2006) and, on the other hand, increased fertilizer inputs have reduced water quality (e.g., Vitousek et al., 1997), decreased the richness of plant species (e.g., Mitchell et al., 2004) and increased the occurrence of plant diseases (e.g., Vickery et al., 2001).

The services provided by ecosystems are benefits that nature provides to people, and are community or ecosystem-wide, or even landscape-wide attributes. Nonetheless these services can often be characterized by the component populations, species, functional groups (guilds), food webs, habitat types or mosaics of habitats and land uses that collectively produce them, i.e., the ecosystem service providers (ESPs) (Kremen, 2005). Agricultural intensification and land conversion represent one of the largest threats to the earth's ecosystems (Tilman, 1999; Millennium Ecosystem Assessment, 2005), which endangers biodiversity directly, but it may also

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threaten the productivity, diversity and stability of our food production systems by disrupting, for instance, pollinator communities (Ricketts et al., 2008).

Also the dynamic spatial configuration of land use in landscapes resulting from human appropriation can have a variety of ecological effects at a landscape scale. Fields have been merged and enlarged to enhance farming efficiency resulting in homogeneously farmed landscapes. Local landscape intensification may affect grassland production (Loreau and Hector, 2001), and resistance to plant invasion (e.g., Kennedy et al., 2002). New land-cover types can be juxtaposed within increasingly fragmented native land-cover types, modifying nutrient transport (Peterjohn and Correll, 1984), affecting species persistence and biodiversity (Tilman et al., 2002; Benton et al., 2003), and nurturing invasive species (With, 2004). The effects of different land-use intensities on local biodiversity and ecological functioning, i.e., the natural capital (Chiesura and de Groot, 2003; de Groot, 2006; Haines-Young et al., 2006) much depend on spatial scales much larger than a single field or land use. In this context, understanding the magnitude, patterns and mechanisms of land use dynamics, in terms of disturbance they produce at multiple scales is, therefore, crucial to the future of ESPs.

The most appropriate subjects to study for planning and management of ESPs are socio-ecological systems (SESs) (Berkes and Folke, 1998), as society has always influenced and shaped the ecological component of SESs, and processes and patterns have been interacting and co-evolving historically that it is often very hard to distinguish what is natural from what is not. SESs are deemed as whole complex, dynamic and adaptive systems hierarchically structured, and self-organizing, with historical trajectories, memory and learning capabilities, with nonlinear feedbacks, thresholds, and hysteresis effects (Berkes and Folke, 1998; Levin, 1998; Li, 2000, 2002; Cadenasso et al., 2006; Ohl et al., in press). In the real geographic world, SESs materialize as social–ecological landscapes (SELs). Within such systems different anthropogenic and natural processes are dominating and interacting across different scales (Kay, 2000; Gunderson and Holling, 2002) in a panarchy of nested levels of organization (Gunderson and Holling, 2002).

Any region in the panarchy of SELs is characterized by the spatial composition (what and how much is there) and configuration (how is it spatially arranged) of landscape elements like land use/land cover. Complexity of heterogeneity increases as the perspective moves from patch type and the number of each type, to spatial configuration, and to the change in the mosaic through time (Wiens, 1995; Li and Reynolds, 1995). Any landscape element with higher land cover dynamics (disturbance) contributes to the overall proportion of disturbance in the region, through its composition of disturbed locations (pixels), and to the overall disturbance connectivity through its configuration. Such landscape elements represent, at the same time, functional units for assessing functional contributions of ES providers at different scale(s) of operation of the service. How those patches are arranged in space relative to each other increases the complexity of understanding the heterogeneity or structure of the system (Li and Reynolds, 1993), but can be the basis for assessing vulnerability of ESPs.

Understanding ESP vulnerability in SELs requires understanding how the actions of humans as a keystone species (sensu O'Neill and Kahn, 2000) shape the environment across a range of scales in a panarchy of SELs taking into account the scales and patterns of human land use as ecosystem disturbances. In this respect, consistent throughout the literature is the notion that the vulnerability of any system, like ESPs, at any scale is a function of the exposure and sensitivity of that system to hazardous conditions (disturbance) and the ability or capacity or resilience of the system to cope, adapt or recover from the effects of those conditions (Smit and Wandel, 2006). Most ecosystem services are broadly classified as operating on local, regional, global or multiple scales, and different providers of the same ecosystem service may operate across a range of spatial and temporal scales (Costanza, 2008; Ricketts et al., 2008). Because disturbances are inflicted at multiple scales, the effectiveness of various species, communities, and other ESPs linked to landscape elements like land use and habitats at performing the services, could be differentially affected by disturbances in the same place, and a potentially useful way to appreciate these differences is to look at how disturbances are patterned in space at multiple scales (Zurlini et al., 2006, 2007).

In this paper we expect that such effectiveness of ESPs at performing services could be affected by both how much disturbance (disturbance composition) surrounds ESP locations at different neighborhoods, and how such disturbance is spatially arranged (disturbance configuration) in those neighborhoods. Land uses and covers within SEL mosaics not only might be disturbed by various agents, but also might act as a "source" or a "sink" as to the potential spread of disturbance to neighboring non-agricultural areas (sink) where most of ES providers reside, as it may occur because of disturbance agents like, for instance, fire, pesticides, herbicides, pests, disease, alien species, urban sprawl. Thus, for instance, maintaining pollination services would require the conservation and management of sufficient resources like suitable nesting habitats as well as sufficient pollen and nectar resources for wild pollinators within agricultural landscapes (Kremen et al., 2007), however a decay of pollinator richness has been observed as distance from natural habitat increases (Ricketts et al., 2008). By providing adequate representation (distribution and abundance) of land units supporting ESPs, a potentially useful way to evaluate ESP vulnerability is to look at how disturbances relative to such land units are patterned in space at multiple scales. The multi-scale assessment of ESPs' vulnerability, we develop here, is spatially explicit with two main components: one related to the amount of surrounding disturbance, and the other to the spatial arrangement of that amount. This allows a much deeper understanding of the spatial interplay between disturbance and ESPs across multiple scales.

1.1. Ecosystem service providers (ESPs)

Services can often be characterized by the component populations, species, functional groups (guilds), food webs, habitat types or mosaics of habitats and land uses that collectively produce them, i.e., the ecosystem service providers (the ESPs) (Kremen, 2005). In order to maintain services, the maintenance of the component habitat types or mosaics of habitats and land uses that collectively produce them rather than management for individual taxa may be a more effective way of using limited resources to benefit the greatest number of species (coarse filter approach, Noss, 1987). The coarse filter has evolved to a concept of conserving species diversity by providing adequate representation (distribution and abundance) of land units considering the historical range of variability based upon the understanding of disturbance regimes (Haufler et al., 1996).

We can characterize ecosystem services locally by conducting a functional inventory to identify the component ESPs and measuring or estimating the importance of each ESP's contribution (Kremen, 2005). In general, the functional importance of any ESP in a specific environment will depend both on its effectiveness at performing the service, and its abundance (Balvanera et al., 2005). Both efficiencies and abundances may respond to eroded or disturbed amount and configuration of land use, predators and competitors, as well as to changing physical or biophysical parameters. Functional contributions of ESPs have been measured or estimated for disparate processes including pollination,

Table 1
Ecosystem services, classified according to the), and their direct and intermediate ecosystem service providers. Functional units refer to the unit of study for assessing functional contributions of ecosystem service providers; spatial scale indicates the scale(s) of operation of the service (based but modified from Kremen, 2005).

Service	Direct and intermediate ecosystem service providers (ESPs)/organization level	Functional units	Spatial scale
Aesthetic, cultural	All biodiversity, landscape land use/cover	Species, populations, communities, habitats, landscapes	Local–global
Ecosystem goods	Diverse species, supporting landscape land use/cover	Species, populations, communities, habitats, landscapes	Local–global
UV protection	Biogeochemical cycles, micro-organisms, supporting landscape land use/cover	Biogeochemical cycles, functional groups, landscape	Global
Purification of air	Micro-organisms, plants, landscape land use/cover	Biogeochemical cycles, populations, species, functional groups	Regional–global
Flood and drought mitigation	Landscape land use/land cover	Communities, habitats, landscape	Local–regional
Climate stability	Landscape land use/land cover	Communities, habitats, landscape	Local–global
Pollination	Insects, birds, mammals and supporting landscape land use/land cover	Species, populations, functional groups, communities, habitats, landscapes	Local
Pest control	Invertebrate parasitoids and predators and vertebrate predators and supporting landscape land use/cover	Species, populations, functional groups, communities, habitats, landscapes	Local–regional
Purification of water	Landscape land use/cover, soil micro-organisms, aquatic micro-organisms, aquatic invertebrates and supporting landscape land use/cover	Species, populations, functional groups, communities, habitats, landscapes	Local–regional
Detoxification and decomposition of wastes	Leaf litter and soil invertebrates; soil micro-organisms; aquatic micro-organisms and supporting landscape land use/cover	Species, populations, functional groups, communities, habitats, landscapes	Local–regional
Soil generation and soil fertility	Leaf litter and soil invertebrates; soil micro-organisms; nitrogen-fixing plants; plant and animal production of waste products and supporting landscape land use/cover	Species, populations, functional groups, communities, habitats, landscapes	Local
Seed dispersal	Ants, birds, mammals and supporting landscape land use/cover	Species, populations, functional groups, communities, habitats, landscapes	Local
Disturbance regulation (includes human disturbances, invasive species)	Landscape land use/cover, supported parasitoids and vertebrate predators	Species, populations, functional groups, communities, habitats, landscapes	Local–regional

bioturbation, dung burial, water flow regulation, carbon sequestration, leaf decomposition, disease dilution (Kremen, 2005). One of the few functional contribution of ESPs measured on landscape level across multiple spatial scales is, to our knowledge, the disturbance regulation provided by natural areas and permanent cultivations in Apulia as shown by Zaccarelli et al. (2008).

Ecosystem services, classified according to the Millennium Ecosystem Assessment (2005), have been revised in Table 1 after Kremen (2005) with a landscape perspective, and their direct and intermediate ESPs are given. Functional units refer to the unit of study for assessing functional contributions of ESPs (Kremen, 2005), and spatial scale indicates the scale(s) of operation of the service. The appropriate ecological level for defining the components is service-dependent and scale-dependent. Most ESPs result directly or indirectly related to landscape land use/land cover (Table 1).

2. Materials and methods

We exemplify concepts and methods with reference to the recent works (Zurlini et al., 2006, 2007; Petrosillo et al., 2009; Zaccarelli et al., 2008) with a view towards understanding how disturbances across scales might impact biodiversity and ecosystem service providers through land use and habitat modification. Since landscape mosaic is mostly defined by vegetation cover, we use land cover change as a measure of disturbance and historical stress. Landscape elements we consider are based on European CORINE land cover classification (Heymann et al., 1994) that permits a biophysical identification of ecosystems (sensu Tansley, 1935), based on vegetation cover, physiognomy, soil types and land forms, and an integration of biotic and abiotic components extremely related, historically and evolutionary, like habitats and syntaxa (Usher, 1991). The need for management action is so urgent that the lack of detailed inventory for most taxa in all regions can be deemed less important; thus CORINE land covers can be used as a ‘‘coarse filter’’ approach (Noss, 1987) to ESPs with no observed distribution data (Zurlini et al., 1999). Nonetheless, species passing through the mesh of the coarse filter can still be recovered by higher resolution assessment of high-priority ESP areas for conservation in the panarchy of SELs. In this context, the idea of natural capital is a useful framework in which one can consider as a whole, the output of goods and services associated with an entire landscape, viewed as a mosaic of different land cover elements (Haines-Young, 2000).

We detect and quantify the scales and spatial patterns of human land use as ecosystem disturbances at different hierarchical levels in a panarchy of SELs by using a conceptual framework that characterizes multi-scale disturbance patterns exhibited on satellite imagery over a four-year time period in the Apulia region (South Italy) (Zurlini et al., 2007; Zaccarelli et al., 2008) as representative of the disturbance regime of the region. Overall, more than the 82% of Apulia contains agro-ecosystems. Multi-scale measurements of the composition (amount) and spatial configuration (arrangement) of disturbance are the basis for evaluating vulnerability of ecosystem service through multi-scale disturbance profiles concerning land-use locations where most of ecosystem service providers reside. Vulnerability estimates are derived from the identification of scale range matches or mismatches among disturbances relative to different land uses and revealed by trajectories from global to local spatial patterns.

2.1. Disturbance of what, and to what

Disturbances have been defined as ‘‘any relatively discrete event in space and time that disrupts ecosystem, community, or population structure and changes resources, substrates, or the physical environment’’ (Pickett and White, 1985). Land cover change is a disturbance because converting forest to agriculture land, or vice versa, alters soil biophysical and chemical properties and associated animal and microbial communities, and agricultural practices such as crop rotation or fire alter the frequency of these disturbances.

To detect change, we applied a standardized differencing change detection technique based on the use of the NDVI "greenness" index (Normalized Difference Vegetation Index; Pettorelli et al., 2005; Zurlini et al., 2006). From a set of Landsat TM 5 images for June 1997 and June 2001, after registration, calibration, and atmospheric correction, we derived NDVI values for each pixel and calculated the standardized difference NDVI image. A pixel is considered to be "changed" or "disturbed" whenever it falls within a predefined upper or lower percentile of the empirical distribution of the standardized difference values (Zurlini et al., 2006). In other words, we define disturbance as any detectable alteration of land cover reflecting significant and relatively frequent vegetation changes which are mainly assignable to fast human-driven processes.

In this study, a change in a farming practice is like the use of a prescribed fire which most ecologists would agree is a disturbance even if it did not change the land cover. The justification is that observed changes in NDVI can clearly demonstrate that not only agricultural fields could be more dynamic than other types of land-cover systems, but also that, agricultural fields could spread disturbance agents in the landscape to other neighboring land uses like natural areas or permanent cultivations where most of ES providers reside (Zaccarelli et al., 2008). In Apulia, typical contagious disturbances are related to land use or land cover and reflect changes associated with urban sprawl, conversion of grasslands to cultivation fields, new olive grove tillage, and farming practices such as fire, herbicides, pesticides, fertilizers, and crop rotation. Unlike other disturbances such as storms and hurricanes, or clear cutting, the extent and duration of contagious disturbance events in Apulia are dynamically determined by the interaction of the disturbance with the landscape mosaic.

In summary, taking into account the different sources of error, we believe that it is possible by this procedure to capture most of the significant real human-driven disturbances detectable at the resolution of Landsat imagery. It is worth to note that multi-scale disturbance patterns very similar to those shown here can be obtained for other four-year periods before and after the period considered in this paper, providing the same geographically coherent disturbance regions. So, what we consider here is a rather persistent disturbance regime in Apulia through a four-year time window. There might be cases where occasionally NDVI does not capture disturbance when it is in fact there, for example in agricultural fields which went from one crop to the same or another crop but retained exactly the same NDVI. On the contrary, it would be very unlikely that this procedure captures disturbance when it is not there (Zaccarelli et al., 2008).

3. Results and discussion

Decision hierarchies of social systems are intertwined with the hierarchies found at the ecosystem or landscape level (Gunderson and Holling, 2002). Anthropogenic disturbances such as changes in land use are determined by the social components of SELs which consist of groups of people organized in a hierarchy at different levels (e.g., household, village, county, province, region, and nation). Within this panarchy (Gunderson and Holling, 2002), the participants have differing views as to which system states are desirable at each level. Any given land use system in the panarchy is likely to overlap multiple ownership and jurisdictional boundaries, and fall under at least three levels of administrative decision and control (e.g., Apulia in Fig. 1).

Europe is a good place to test models because European landscapes are the result of consecutive reorganizations of the land for a long time to adapt uses and spatial structures to meet

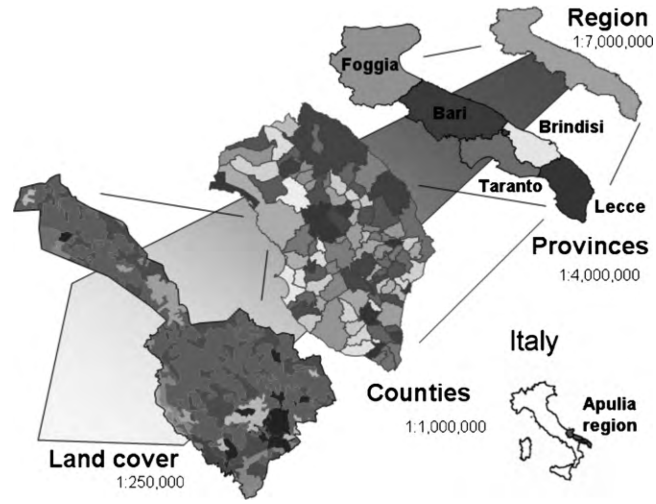

Fig. 1. An example of a panarchy of nested SELs in Apulia, an administrative region in southern Italy. Three main levels of governance hierarchy can be identified (one region, five provinces and 258 counties) embodying different social, economic, and cultural constraints. The entire region and each sub-region can be described in terms of their unique social–ecological landscapes based on land use/land cover composition supporting ecosystem service providers.

changing societal demands (Antrop, 2005). Human influence dominates landscape dynamics in space and time (O'Neill and Kahn, 2000), thus defining limiting constraints at "higher scales" and altering the detailed functioning of ecological processes at "lower scales". So, land-use decisions affect both ecological and social structures and processes, and vice versa.

We hypothesize that the characteristic scales of particular phenomena like anthropogenic changes should entrain and constrain ecological processes that produce services, and be related to the scales of human interactions with the biophysical environment (e.g., Holling, 1992). If the patterns or scales of human land use change, then the structure and dynamics of SEL as a whole can change accordingly, leading to transitions between alternative phases, when the integral structure of the systems is changed (Kay, 2000; Li, 2002). In human-driven landscapes, evaluating the disturbance patterns of land use at multiple scales clearly has potential for quantifying and assessing environmental condition, processes of land degradation, subsequent impacts on ES providers and human resources in SELs.

4. Effects of multi-scale disturbance patterns on ESPs

Many authors (Li and Reynolds, 1994; Riitters et al., 1995) have suggested focusing on a few key measures of pattern and, particularly, on the two most fundamental measures of pattern that are composition and configuration. Therefore, we characterize landscape patterns of disturbance in terms of the amount (composition) and spatial arrangement of disturbance (configuration or connectivity).

We make use of moving windows to measure composition (Pd, the proportion of disturbed pixels within a window) and configuration (Pdd; contagion as the proportion of shared edges between disturbed pixels on changed pixels edges within a window) of disturbance patterns at multiple scales (i.e., window sizes), as detected on satellite imagery. The measurements were made for each pixel at multiple scales by using 10 square arbitrary chosen window sizes in pixel units of 3, 5, 9, 15, 25, 45, 75, 115, 165, and 225 thus the window area ranges from 0.81 ha to 5852.25 ha. For each pixel a profile of Pd or Pdd is defined by the set of values measured at different window sizes. Profiles were aggregated (i.e., averaged) and a mean profile derived applying a

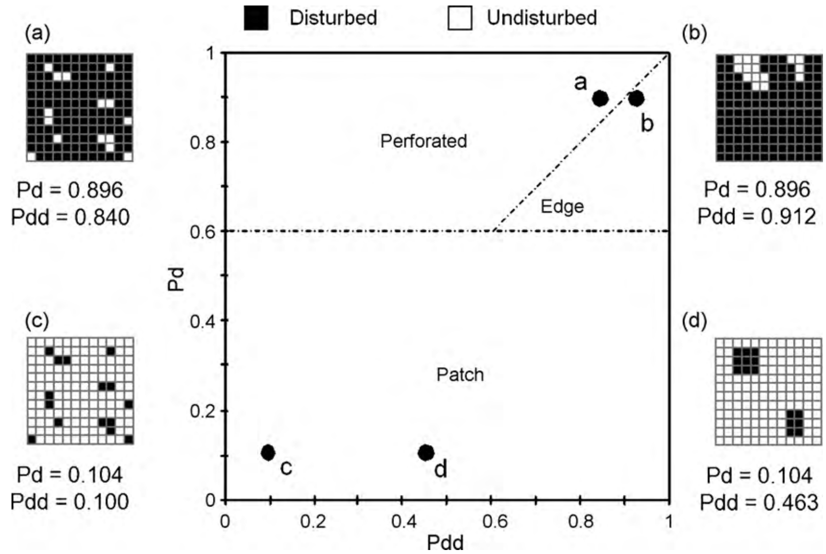

Fig. 2. The graphical model used to identify disturbance categories from local measurements of Pd and Pdd in a fixed-area window. Pd is the proportion of disturbed and Pdd is disturbance connectivity (modified after Riitters et al., 2000). Four simple examples of binary landscapes (a–d) are presented by the side of the [Pd, Pdd] space for different combinations of composition and configuration: (a) highly disturbed but perforated by undisturbed areas (perforated disturbance), (b) highly disturbed but with clumped undisturbed areas (edge disturbance), (c) low level and highly fragmented disturbance (spread disturbance), and (d) low level and clumped disturbance (patchy disturbance) (modified after Zurlini et al., 2006).

broad land use type classification spanning the whole SEL mosaic except for urban areas. We considered four classes roughly matching the second level of the European CORINE classification and in particular: arable lands (CORINE code 2.1), permanent cultivations (CORINE code 2.2), heterogeneous agricultural area (CORINE codes 2.3 and 2.4) and natural areas (CORINE codes 3.1, 3.2, 3.3 and 4.1).

Differently from our earlier work (Zurlini et al., 2006), we include land use composition of the SEL by developing the mean accumulation disturbance profiles at multiple scales for each location (pixel) part of specific land use.

The [Pd, Pdd] phase space (Fig. 2) and the calculation of the convergence point (CP; an asymptotic point for a window exactly equal to the entire study region) to represent SELs, can be very useful to provide the appropriate dynamic representation of different SELs in the panarchy, as traced by their recent disturbance history (Zurlini et al., 2006, 2007; Zaccarelli et al., 2008).

For any given location (pixel) in each land use, the trajectory converging to the CP in [Pd, Pdd] space describes the accumulation profile of disturbance pattern at increasing neighborhoods surrounding that location. If trends in [Pd, Pdd] space were similar for two different locations, then both locations have experienced in their surrounding landscapes the same "disturbance profiles" in terms of amount and configuration. For example, at a given geographic location, the trend in Pd with increasing window size can be interpreted with respect to the disturbances experienced by that location at different spatial lags. A small window (local scale) with high Pd combined with a large window (large scale) with lower Pd implies a local heavy disturbance embedded in a larger region of lighter disturbance. Locations characterized by constant Pd over window size experience equal amounts of disturbance across spatial scales.

Interestingly, for the assessment of ESP vulnerability, the trajectories of disturbance accumulation profiles at multiple scales on the [Pd, Pdd] state space also indicate whether and where land-use disturbances might act as a "source" or a "sink" across scales respect to their potential spread to neighbor areas. If a mean profile is always larger than the CP of reference and has a convex trend downwards to the CP (e.g., arable lands in Fig. 3), land use acts as a potential disturbance source to the neighbor mosaic because of local heavy disturbance embedded in a larger region of fewer disturbances.

Conversely, if a mean profile of a land use is below the CP with a concave trend upwards to the CP (e.g., natural areas in Fig. 3), land-use locations can be potentially affected by neighbor disturbances (sink) because of local low disturbance embedded in a larger region of heavy disturbances. Disturbance profiles at multiple scales for the four land uses in three different provinces of Apulia region, and province convergence points (CPs) are shown in Fig. 4.

Theoretically, spatial "mismatches" are expected when the spatial scales of management and the spatial scales of ecosystem processes are not aligned, possibly leading to disruptions of the SEL, inefficiencies, and/or loss of important components of the ecological system (Cumming et al., 2006). In practice, within SEL mosaics, each land use and land cover has its own disturbance due to human management, even in the case of natural areas because of the presence of fields and human settlements. Thus, spatial scale mismatches in [Pd, Pdd] space can occur for differences in both disturbance accumulation profiles related to the management of different land uses and accumulation rate of disturbance clumping at different spatial lags. Any two geographic locations with the same accumulation trajectory in [Pd, Pdd] space experience the same multi-scale disturbance profile with no spatial scale mismatches, as it might occur in some cases for permanent cultivations and natural areas (Figs. 3 and 4). Conversely, dissimilar trends imply differences in spatial profiles of disturbance with consequent scale mismatches of disturbance (Figs. 3 and 4). Social processes that can lead to mismatches are primarily inherent in land occupancy, which constitutes the hierarchy of social institutions that run the allocation, use, and management of land resources (Fig. 1).

The differences of Pdd values between window points tell us about the cross-scale spatial accumulation rate of disturbance clumping of each land use. Such differences are more pronounced and range from natural areas to arable land (Fig. 3), meaning that fields have been merged and enlarged to enhance farming efficiency, resulting in almost homogeneously farmed landscapes (e.g., Foggia, Fig. 4).

Arable lands and heterogeneous areas (source) generally show at the same scales not only higher disturbance composition (Pd),

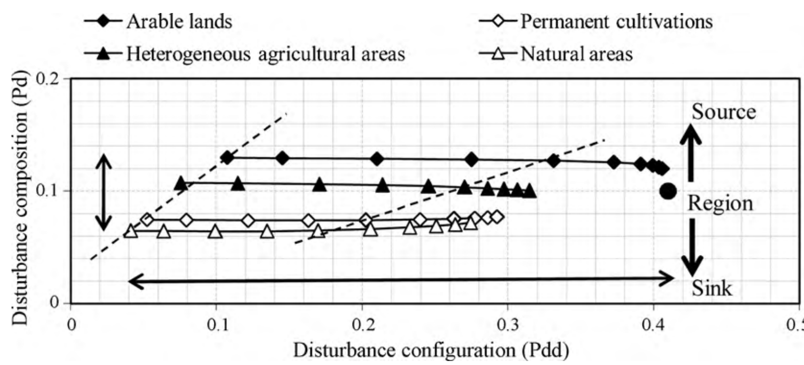

Fig. 3. Disturbance trajectories for the four broad land-use classes of Apulia at multiple scales (10 window sizes in increasing size order from left to right) at regional Pd = 0.10 are represented in the same space [Pd, Pdd] presented in Fig. 2. Initial Pdd values, and regional convergence point (black dot) are shown at the regional hierarchical level. The dotted lines attempt to connect identical window sizes among different land uses to exemplify cross-scale disturbance mismatches, e.g., between arable lands and natural areas. Source (upwards arrow) and sink (downwards arrow) trajectories are identified respect to the regional CP. Left–right and up–down arrows indicate the vulnerability components of ESPs, one due to disturbance configuration, the other to disturbance composition.

but also cross-scale contagion accumulation increments in disturbance higher than those for permanent cultivations and natural areas (sink).

Distances in the [Pd, Pdd] state space between two land use profiles at the same window size (scale; Fig. 4) draw directly the attention to spatial scale mismatches of disturbance among land use that can lead to their reciprocal potential role as disturbance source or sink at the same and cross-scales, with possible consequent changes in the structure and dynamics of SELs.

4.1. ESP vulnerability across multiple scales

Ecosystem services can often be characterized by the component populations, species, functional groups (guilds), food webs, habitat types or mosaics of habitats and land uses that collectively produce them, i.e., the ecosystem service providers (the ESPs). Because disturbances are inflicted at multiple scales, species, functional groups, food webs, habitats, landscapes could be differentially affected by disturbances in the same place, and a

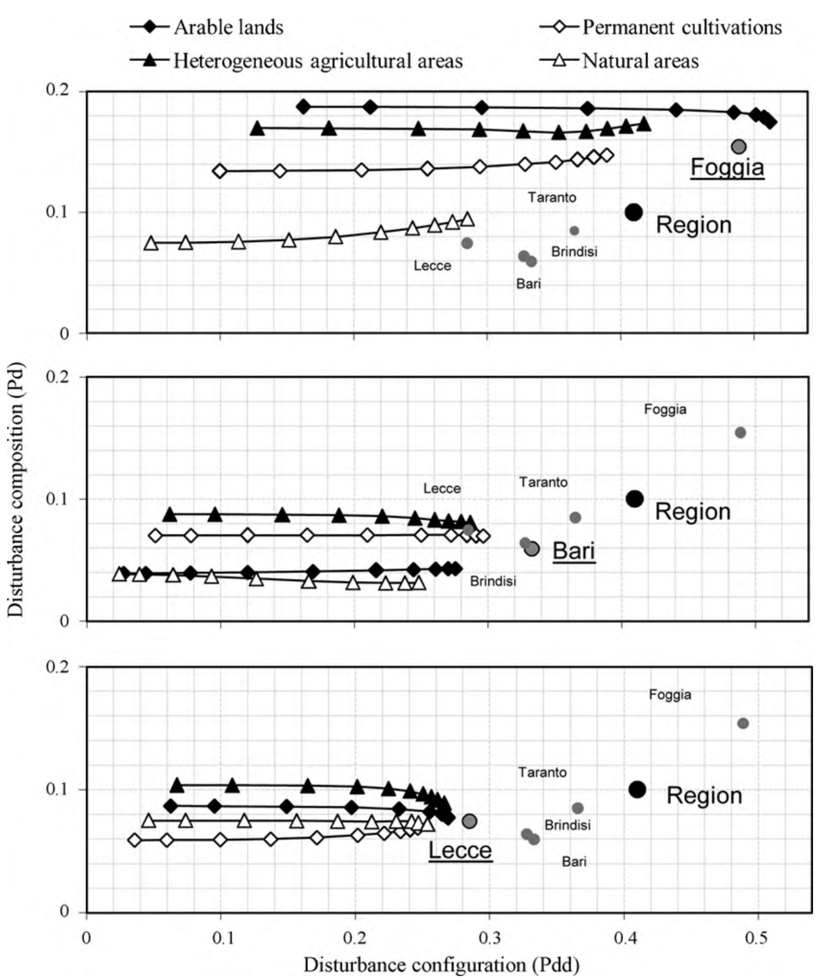

Fig. 4. Trends of disturbance profiles at multiple scales (10 window sizes in increasing order from left to right) of the four land uses for three different provinces of Apulia (Foggia, Bari and Lecce) are presented to show their reciprocal source–sink role. Convergence points for the five provinces and for the Apulia region are shown for comparison.

potentially useful way to appreciate these differences is to look at how disturbances are patterned in space at multiple scales (Zurlini et al., 2006, 2007).

All land-use disturbance trajectories in Apulia panarchy are located near the lower left corner in the [Pd, Pdd] pattern space (Figs. 3 and 4), with a certain invariance of disturbance composition (Pd) at increasing disturbance clumping (Pdd). Land uses have distinct disturbance profiles at multiple scales with paths fairly parallel to the Pdd axis almost up to the CP value of entire region, and with increasing disturbance composition (Pd) usually ranging from natural areas to arable land (Figs. 3 and 4).

For an environmental security (sensu Müller et al., 2008; Zurlini and Müller, 2008; Makarieva et al., 2008) interpretation of the [Pd, Pdd] space, we have to look not only at the disturbance accumulation profiles at multiple scales (context) of various land use and land cover locations, but also at the role those profiles might play as "source" or "sink" across scales within SEL land use mosaics respect to the potential spread of disturbance agents to neighbor areas.

The [Pd, Pdd] pattern space has already been interpreted in terms of vulnerability/fragility independently of single location membership to a definite land use (Zurlini et al., 2006); in this case, vulnerability could be higher for scale domains where disturbance is more likely and clumped for trajectories of location clusters.

In our case, we reasonably assume that ESPs reside in natural areas and permanent cultivations, which as a coarse filter supporting most of component populations, species, functional groups (guilds), food webs, habitat types or mosaics of habitats and land uses that collectively produce ecosystem services. In Fig. 3, black arrows indicate the extent of vulnerability components for ESPs, one due to disturbance composition, the other to disturbance configuration. While the first component of vulnerability (disturbance composition) is rather straightforward to evaluate, the second deserves more attention with regard to the specific traits of ESPs. For the first component, the higher the contrast and the difference between arable land disturbance profile (source) and natural area disturbance profile (sink), the higher will be the vulnerability of ESPs residing in natural areas, because there will be the chance of a location with ESPs surrounded by high disturbances.

The reading of [Pd, Pdd] space in terms of vulnerability gradients (or its reverse, environmental security), where vulnerability is highest anywhere disturbance regime is most likely and clumped, is justified by evidence coming, for instance, from metapopulation simulations which show that increasing spatial aggregation of the disturbance regime always decreases habitat occupancy of 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). This will help interpret the vulnerability component due to disturbance configuration (Fig. 3). This is particularly central also to the dispersal of alien species and therefore to the spatial distribution of risk of competition from alien species. Poor dispersers spread more in landscapes in which disturbances are concentrated in space ('contagious' disturbance), whereas good dispersers spread more in landscapes where disturbances are small and dispersed ('fragmented' disturbance) (With, 2004).

The same interpretive framework can be used to compare portions of the SEL such as provinces in the [Pd, Pdd] space (Fig. 4), as to their CP, given by its overall Pd and Pdd values. In this way, provinces can be ranked according to the relative vulnerability of ESPs. Thus, the ESPs of the province of Foggia turn out to be the most vulnerable (Fig. 4). We can also compare the vulnerability of each single land use at multiple scales among different provinces by looking at its disturbance profiles. In this case, differences in disturbance due to traditional, low-intensity, local land-use practices of agriculture and forestry can be revealed, which have greatly promoted habitat diversity in the European human-dominated landscapes during the last centuries.

Natural areas and permanent cultivations, being ESPs, highlighted a higher potential for regulating landscape dynamics and compensating for disturbances in the SELs of Apulia. Consequently, natural areas and permanent cultivations must be considered intrinsically more vulnerable for two different reasons: (1) as they can be affected by internal disturbances, and (2) as a whole, because they act as a sink of disturbance potentially produced by arable lands (Figs. 3 and 4).

5. Conclusions

A landscape perspective of disturbance source–sink patterns at multiple scales is ultimately required to evaluate how changes in landscape structure, e.g., habitat fragmentation, may affect the potential spread of disturbance agents and invasive species. That is essential to assess the vulnerability of ESPs according to their ecological characteristics.

Any region in the panarchy of SELs is characterized by the spatial composition (what and how much is there) and configuration (how is it spatially arranged) of landscape elements like land use/land cover. Any landscape element contributes to the overall proportion of disturbance in the region, through its composition of disturbed locations (pixels), and to the overall disturbance connectivity through its configuration. Such landscape elements represent, in turn, functional units for assessing functional contributions of ESPs at different scale(s) of operation of the service. In Apulia, elements with higher land cover dynamics (disturbance) like arable lands might act as a source of the potential spread of disturbance to neighboring non-agricultural areas (sink) where most of ESPs reside.

This study points out that management of disturbance in the study region will primarily depend more on broader-scale than local-scale patterns of the drivers of disturbance (Fig. 3), and clarifies how natural areas and permanent cultivations (olive groves and vineyards) will act in the interplay of disturbance patterns within SELs, regulating landscape mosaic dynamics and compensating for disturbances across scales in South Italy. The roles of natural areas and permanent cultivations in providing *disturbance regulation* across scales in South Italy have consequences for regional SELs since they may govern if and how disturbances associated with land-use intensification (sources) will affect the functional contribution of ES providers.

Many ecological phenomena demonstrate nonlinear threshold effects (Levin, 1999), and this has implications for the economics of land-use planning. For decision-making, we need to know the additional (marginal) value of ecosystem services produced by conserving another unit of habitat (Dasgupta et al., 2000). Armsworth and Roughgarden (2003) recommend basing land-use decisions not simply on the marginal value of ecosystem services added by an additional unit of habitat, but also on the additional stability to ecosystem services that another unit of habitat would add. We argue that the spatial configuration of conservation efforts (which unit and where to conserve) is essential to provide a more effective additional value and stability to ecosystem services. Therefore, it is important to understand not only the relationship between ecosystem service and habitat area, but also the relationship between the distribution of ecosystem service providers and landscape configuration of disturbance at multiple scales, another relationship that may demonstrate nonlinearity.

The [Pd, Pdd] space helps to draw attention to spatial scale mismatches among land uses for disturbance accumulation profiles which can determine their reciprocal role as disturbance source or sink at across scales, because of their potential spread to neighbor areas with possible consequent changes in the structure and dynamics of SELs.

Even though we attribute to arable land most of the disturbance observed, we acknowledge that agricultural land-use intensification might not only mean a decrease in habitat occupancy with consequent higher extinction, but it could also make occasionally more resources available to enhance populations of some species, since the higher productivity of land use compared with generally less productive natural systems may provide more resources such as vegetation biomass, and fruits for birds, mammals and butterflies (Tscharntke et al., 2005).

Understanding the spatial and temporal scales at which ecosystem services and human disturbance operate is essential to developing landscape-level conservation and land management plans. So, for instance: how should patches of natural habitat be distributed within an agricultural landscape to provide pollination and pest control services for crops? Or, how should patches of natural habitat and disturbances be distributed within an agricultural landscape to reduce the spread of invasive species? Tentative answers to these questions can be formulated based on observed and simulated disturbance pattern in the Apulia region (Zurlini et al., 2007) to establish how much and how set-asides should be arranged, and land zoned for different land uses and land covers, in order to protect and manage the service.

Current approaches to conserving biodiversity may benefit by incorporating greater understanding of how people and nature interact within complex adaptive systems (Gunderson and Holling, 2002) like SELs, so that scale mismatches of different land uses in land tenure and thresholds of potential concern for environmental security can be identified and managed for a key set of ecological response variables. That could be the basis for intentionally planning and managing the adaptability of the SEL, and that is arguably the key to human management of ecosystem service providers.

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