ENVIRONMENTAL SECURITY AS RELATED TO SCALE MISMATCHES OF DISTURBANCE PATTERNS IN A PANARCHY OF SOCIAL-ECOLOGICAL LANDSCAPES

GIOVANNI ZURLINI*, IRENE PETROSILLO,
AND NICOLA ZACCARELLI
Landscape Ecology Laboratory, Department of Biological and Environmental Sciences and Technologies, University of Salento, Lecce, Italy
KURT H. RIITTERS
US Forest Service, Southern Research Station, Research Triangle Park, North Carolina, USA

Abstract. Environmental security, as the opposite of environmental fragility (vulnerability), is multilayered, multi-scale and complex, existing in both the objective realm of biophysics and society, and the subjective realm of individual human perception. For ecological risk assessments (ERAs), the relevant objects of environmental security are social-ecological landscapes (SELs). ERAs, in this case, are less precise than traditional ERAs, but provide results that are more comprehensive and understandable by stakeholders. 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 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). Multi-scale measurements of the composition and spatial configuration of disturbance are the basis for evaluating fragility through multi-scale disturbance profiles, and the identification of scale mismatches revealed by trajectories diverging 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 regional biodiversity. This study clarifies the potential roles

* Corresponding Author: Professor Giovanni Zurlini, Landscape Ecology Laboratory, Department of Biological and Environmental Sciences and Technologies, University of Salento, Ecotekne, Prov.le Lecce-Monteroni, 73100 Lecce, Italy. Phone: +390832298886, Fax: +390832298626, e-mail: giovanni.zurlini@unile.it

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for environmental security of natural areas and permanent cultivations (olive groves and vineyards) in buffering Mediterranean landscape disturbance dynamics and compensating for disturbances across the whole panarchy of Apulia, allowing for potential landscape planning of disturbance.

Keywords: Environmental security; multi-scale disturbance; scale mismatches; social-ecological landscapes

1. Environmental security and ecological risk assessment (ERA)

The major challenge of environmental security concerns the global environmental change, focusing on the interactions between ecosystems and mankind, the effects of global environment change on environment degradation, the effects of increasing social request for resources, and the erosion of ecosystem services and environmental goods. Because land use change by humans is one of the major factors affecting global environmental change (Millennium Ecosystem Assessment, 2003), the question then arises as to how such environmental stresses and the associated risks might vary geographically or evolve over time. Environmental security addresses the risks to, or fragility (vulnerability) of ecosystem goods and services, as well as the subjective perception of those risks (Petrosillo et al., 2006; Zurlini and Müller, in press).

Environmental security, as the opposite of environmental fragility, is multi-layered, multi-scale and complex, existing in both the objective biophysical and social realms, and the subjective realm (Morel and Linkov, 2006). The relevant objects of environmental security are complex, adaptive systems that, in the real geographic world, are social-ecological landscapes (SELs). Those systems are usually designed as made up of two main components: the social, characterized by human intent, and the ecological, arising without intent. However, those two components are often very hard to distinguish because they have been interacting and coevolving historically, and society has always shaped the ecological component of SELs. Therefore, we can address environmental security more appropriately in terms of SEL security.

The subjective perception of security is fundamental at all levels of human organization, from the individual to government entities, and a “threat” is an abstract concept existing in the domains of feelings and cognition. Security is value laden, and related to our normative systems that today recognize concepts like ecosystem functions and services, ecosystem integrity and sustainability as fundamental values for the survival and well-being of mankind.

A fundamental difference between environmental security and ecological risk assessments (ERAs) is that the goal of ERAs is usually restricted to informing risk management decisions in the objective realm, focusing on the relationships between stressors (e.g. a chemical) and ecological effects at different organization levels (EPA, 1998). The animal-toxicity paradigm (Lackey, 1994) is still the most commonly used approach in an ERA, because it is easy to use and to understand, and because a large database exists for many chemicals and biological species. An ERA that estimates likelihoods of specific ecological effects is conceptually equivalent to an assessment of the cancer risk posed by some human health threat (Suter, 1993). This paradigm works best for chemicals (Suter and Loar, 1992) and it assumes that responses of a simple surrogate are adequate to represent responses at the landscape level; it can be precise and reliable, but with a narrow range of inference because of the simple surrogates used.

There is a growing awareness that a much greater ecological realism must be achieved by ERAs for attaining more informed management decisions (cf. Suter, 1995). Thus, for instance, ERAs should make better use of ecological information such as landscape features to generate spatially explicit estimates of exposure to environmental stressors, e.g. invasive species and physical disturbance (Kapustka, 2005). However, even holistic ERAs seldom address the integrated evidence of the entire complex hierarchical pattern and composition of real social-ecological landscapes, in terms of scaling properties of land use and pertinent anthropogenic disturbances (Zurlini et al., 2004).

The actual object of holistic ERAs should be a real-world social-ecological landscape. ERAs should contribute to the objective evaluation of environmental security and provide less precise results but more comprehensive and understandable by stakeholders (Shrader-Frechette, 1998). This would help people to focus on landscape systems instead of surrogates or proxies, and to recognize that SEL systems are open, hierarchically structured, and self-organizing, with historical trajectories, memory and learning capabilities, and with different processes dominating at different scales (Kay, 2000; Gunderson and Holling, 2002).

In summary, the development of new integrated system-specific evaluation and prediction models for environmental security at multiple scales, framed in terms of both subjective and objective observable quantities in the geographical real world domain, is necessary to formulate and evaluate ideas relevant to environmental security in SELs. Towards this goal, we exercise an evaluation framework with real landscape disturbances and demonstrate its interpretive power by examining actual disturbance maps relative to land use for a panarchy of SELs in Apulia, an administrative region in southern Italy. We exemplify concepts and methods with reference to the recent works of Zurlini et al. (2006;

in press) in the framework of potential environmental security evaluation with a view towards understanding how disturbances might impact biodiversity and ecosystem services through land use and habitat modification. Even though we exercise the framework based only on the objective dynamics of land use and land cover, we believe this framework can represent a common basis for assessing security of SELs both objectively and subjectively, at all levels of human organization, by replacing the traditional interpretation of results in ecological terms with an alternate interpretation in terms of environmental security.

2. Panarchy of social-ecological landscapes

SELs are organized in a panarchy of nested levels of organization, which draws on the notion of hierarchies of influences between embedded scales (Gunderson and Holling, 2002). A panarchy is a nested hierarchy of systems where each system follows an adaptive cycle and interacts with other levels through top-down or bottom-up connections. One of the essential features of the panarchy is that it turns hierarchies into dynamic structures. Individual levels have non-linear multi-stable properties while can be stabilized or destabilized through critical connections between levels.

Understanding environmental security 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 that take into account the scales and patterns of human land use as ecosystem disturbances (e.g. Figure 1). 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. Figure 2). Social-ecological systems may have different dynamics when compared to the ecological component alone because the social domain contains the element of human intent. Thus, management actions can deliberately avoid or seek the crossing of actual and perceived thresholds (Walker et al., 2006). It is not clear whether a common framework of system dynamics could be used to examine and explain both social and ecological systems. 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 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". Land use decisions affect both ecological and social structures and processes, and vice versa.

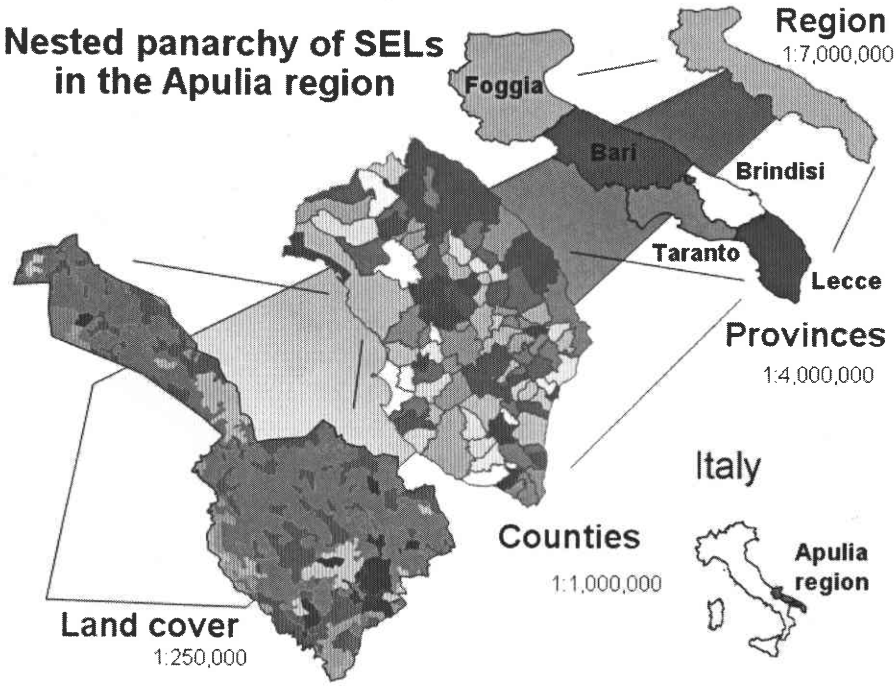

Figure 1. An example of a panarchy of nested SELs for Apulia, an administrative region in southern Italy. Three main levels of governance hierarchy can be identified (one region, five provinces and 258 counties) embodying different social, economic, and cultural constraints. The entire region and each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

We hypothesize that the characteristic scales of particular phenomena like anthropogenic changes should entrain and constrain ecological processes, and be related to the scales of human interactions with the biophysical environment. 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 natural and human resources in SELs, and their consequences on environmental security.

3. Disturbance of what and to what

A fundamental difficulty with social-ecological systems is that their complexity makes it difficult to forecast the future with any sense of reliability. One way of dealing with this problem is to look retrospectively at the observed trends of effects caused by past exposure to stressors and, on this basis, to create future scenarios, taking into account the anticipated changes of the driving forces at work and of their consequent disturbances. The future system trajectories can at least be compared to each other to assess whether management scenarios have more or less effect on trajectories, that is, whether proposed actions will move the system in expected directions at expected rates.

We use land cover change as a measure of disturbance and historical stress. 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. New land cover types can be juxtaposed and shifted within increasingly fragmented remnant native land cover types, and changes in the structure of the landscape can disturb nutrient transport and transformation (Peterjohn and Correll, 1984), species persistence and biodiversity (Fahrig and Merriam, 1994; With and Crist, 1995), and invasive species (With, 2004).

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 the upper or lower percentile of 5% 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 even tiny and relatively frequent vegetation changes which are mainly assignable to fast human-driven processes. This perspective is different from classical land cover mapping that would ignore, for instance, crop rotation because agricultural fields can be fallow one year and planted the next, and still be labeled as "agricultural fields." 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. In the context of environmental security, 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 practices like, for instance, fire could spread disturbance agents in the landscape to other neighboring land uses like natural areas or permanent cultivations.

Thus, 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 neighbor areas, as it may occur because of disturbance agents like, for instance, fire, pests, disease, alien species, urbanization. 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, grazing, 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.

4. Disturbance patterns at multiple scales

Patterns can be measured in many ways, but many authors have suggested focusing on a few key measures (Li and Reynolds, 1994; Riitters et al., 1995). Li and Reynolds (1995) suggest that the two most fundamental measures of pattern 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*

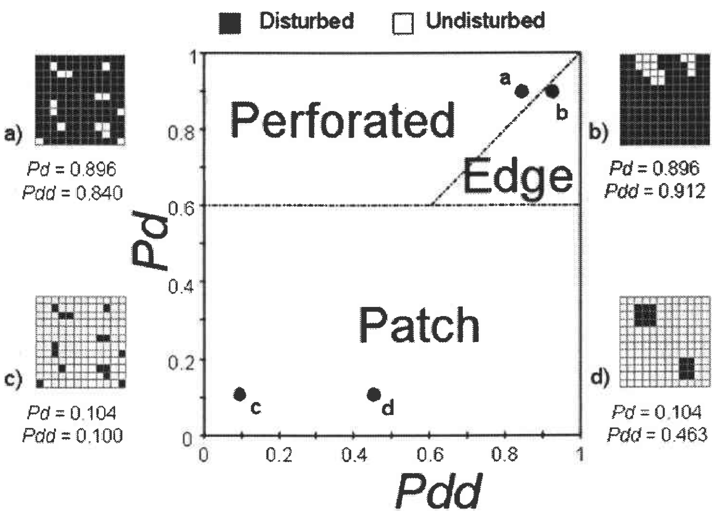

Figure 2. The graphical model used to identify disturbance categories from local measurements of *Pd* and *Pdd* in a fixed-area window. *Pd* is the proportion of disturbed and *Pdd* is disturbance connectivity (modified after Riitters et al., 2000). Four simple examples of binary landscapes (a, b, c, 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.)

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 broad land use type classification spanning the whole SEL mosaic except for urban regions. We considered four classes roughly coincident to the second level of the European CORINE classification (Heymann et al., 1994) 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). In contrast to our earlier work (Zurlini et al. 2006), we include land use composition of the SEL by developing at multiple scales the mean accumulation disturbance profiles of each land use from each location.

The [*Pd, Pdd*] phase space (Figure 2) and the use of a convergence point (CP; an asymptotic point for a window exactly equal to the entire study region) to represent SELs (Zurlini et al., 2006), can be very useful to provide the appropriate dynamic representation of different SELs in the panarchy, as traced by their recent disturbance history. 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 scales 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" as characterized by the 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 (Figure 3). A small window with high *Pd* combined with a large window with low *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 at all spatial scales.

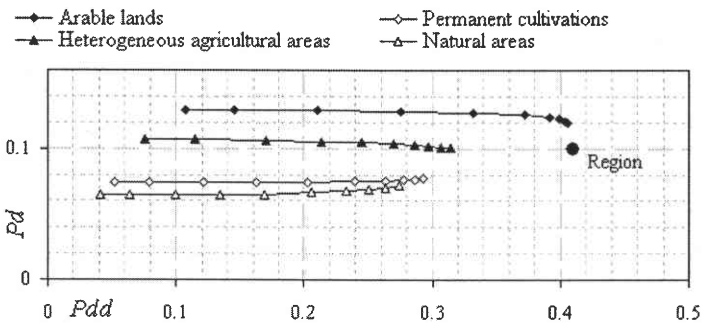

Figure 3. Trends of disturbance profiles at multiple scales (10 window sizes in increasing order from left to right), and relative convergence point (black dot) for four broad land use classes at the regional hierarchical level (see text).

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, Figure 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, Figure 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 (CP) are shown in Figure 4.

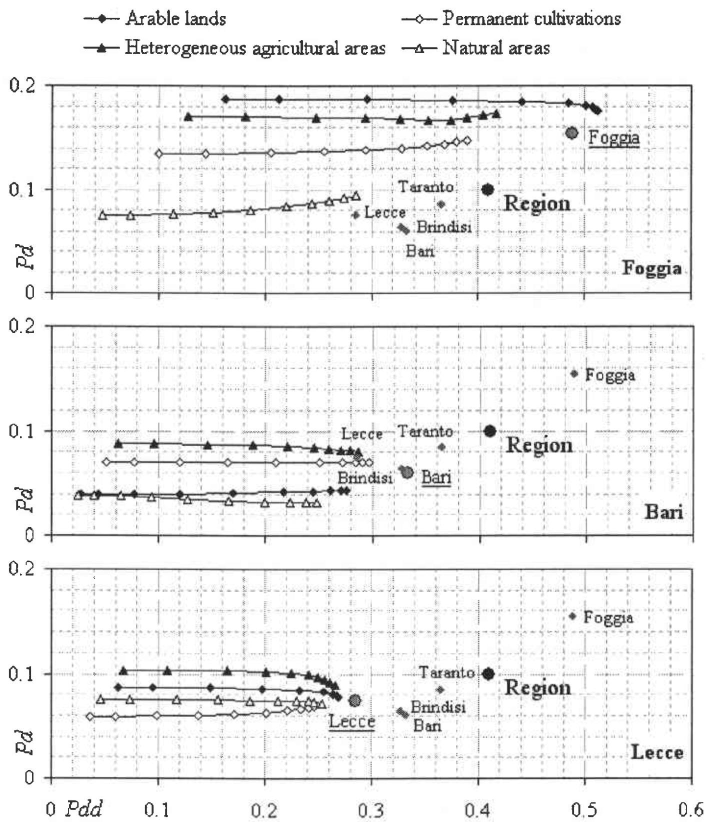

Figure 4. Trends of disturbance profiles at multiple scales (10 window sizes in increasing order from left to right) of the four land uses for three different provinces of Apulia are presented to show their reciprocal source–sink role. Convergence points for the five provinces and for the Apulia region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

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, 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 (Figures 3 and 4). Conversely, dissimilar trends imply differences in spatial profiles of disturbance with consequent scale mismatches of disturbance (Figures 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 (Figure 1).

The differences of *Pdd* values between window points tell an interesting story 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 (Figure 3), meaning that fields have been merged and enlarged to enhance farming efficiency, resulting in almost homogeneously farmed landscapes (e.g. Foggia, Figure 4).

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

5. Discussion: environmental security at multiple scales

Because disturbances are inflicted at multiple scales, various species 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).

All land use disturbance trajectories in Apulia panarchy are located near the lower left corner in the [*Pd, Pdd*] pattern space (Figures 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 (Figures 3 and 4).

For an environmental security interpretation of the [*Pd, Pdd*] space, we have to look not only at the disturbance accumulation profiles at multiple scales (context) of land use and 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 to neighbor areas.

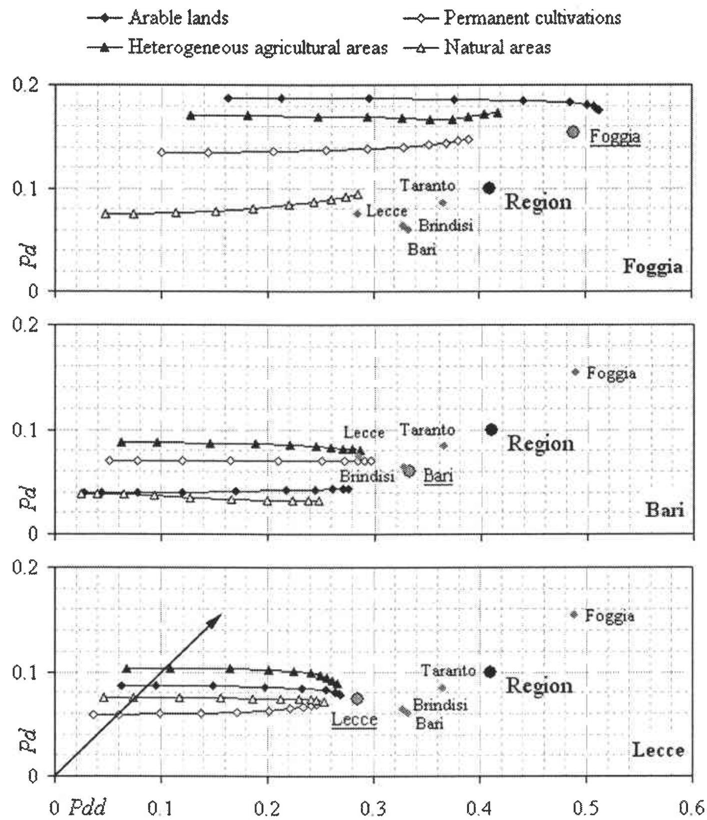

Figure 5. Fragility estimates for the five different provinces spanning Apulia as indicated by convergence points, and comparison of disturbance accumulation profiles at multiple scales (10 window sizes in increasing order from left to right) of the same land use within the same province. The CP for the entire Apulia region is shown for comparison. The arrow indicates the direction of fragility (see text).

As to the first side, the [*Pd, Pdd*] pattern space has already been interpreted in terms of fragility (Zurlini et al., 2006), where fragility is highest for scale domains where disturbance is most likely and clumped for trajectories of location clusters, independently of single location membership to a definite land use. We can identify a gradient of fragility, with fragility increasing with both *Pd* and *Pdd* from the lower left corner to the upper right corner in Figure 2.

The same interpretive framework can be used to compare portions of the SEL such as two provinces in the [*Pd, Pdd*] space (Figure 4), as to their CP, given by its overall *Pd* and *Pdd* values, without taking into account single disturbance patterns of the four land uses. In this way, provinces can be ranked according to relative fragility, and the province of Foggia turns out to be the most fragile (Figure 4). We can also compare the fragility of each single land use at multiple scales among different provinces by looking at its disturbance profiles (Figure 5). 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.

However, we cannot use the [*Pd, Pdd*] space to interpret and compare disturbance profiles of single land uses within the region or a province, because further factors integral to each specific land use other than disturbance patterns determine its fragility like, for instance, habitat sensitivity (Zurlini et al., 1999), ecosystem service and natural capital values (Costanza et al., 1997).

Natural areas and permanent cultivations are usually thought to have higher natural capital value, and higher potential for regulating landscape dynamics and compensating for disturbances in the SELs of Apulia. Consequently, in an environmental security framework, natural areas and permanent cultivations must be considered intrinsically more fragile (sink) than arable lands which generally act as potential source that could affect neighboring land uses (Figures 3, 4, and 5).

6. Conclusions

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 (Figure 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. Both land uses act as buffering mechanisms for land use disturbance, thus providing essential indirect ecosystem services, with consequences likely for regional biodiversity management which requires ecological knowledge of both natural areas and their surroundings.

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. The reading of [*Pd, Pdd*] space in terms of fragility gradients (or its reverse, environmental security), where fragility 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 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).

However, we acknowledge that agricultural land use intensification might not only mean a decrease in habitat occupancy with consequent higher extinct-tion, 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).

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, which is arguably the key to human management of environmental security

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