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KEY FUNDAMENTAL ASPECTS FOR MAPPING AND ASSESSING ECOSYSTEM SERVICES: PREDICTABILITY OF ECOSYSTEM SERVICE PROVIDERS AT SCALES FROM LOCAL TO GLOBAL

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Abstract – How an apparent static and ordered landscape condition in social ecological landscapes (SELs), can be made sustainable in terms of maintenance and improvement of the provision of ecosystem services (ESs) in face of unpredictable disturbance and change? Our contribution to the Mapping and Assessment of Ecosystem Services (MAES) working group is to advance some recommendations on how to approach the dynamic analysis of complex adaptive systems to improve ecosystem resilience, habitat connectivity and the delivery of ESs. We show exemplary cases where we utilize the NDVI provided by remote sensing to evaluate land cover transformations and processes and ES provisioning. We focus on NDVI because it allows the supply of information on net primary production, i.e., the energetic foundation of nearly all ecosystems and that provides the basis of most of ESs. The use of spectral entropy, and nonlinear analysis of spatial temporal dynamics to investigate trajectory predictability of SELs provide very useful insight into the dynamics of SELs and can assist in the characterization of the links between land cover patterns with ecological processes to support more reliable assessments and accountings of ESs.

Keywords: Ecosystem Services, Net Primary Production, Time Series, Landscape Connectivity, Non-Linear Analysis, Resilience

Introduction

Even though the persistence of biodiversity and the maintenance of Ecosystem Services (ESs) are largely dependent upon each other, these two aspects are not wholly interchangeable (Williams and Araújo, 2002). Planning for biodiversity and ESs conservation at the same time and in the same place may be difficult because areas important for ESs might not always be important for biodiversity (Balvanera et al., 2001; Chan et al., 2006). Therefore, the implementation of strategies and tools for the conservation of biodiversity (e.g. land reclamation) may differ from those for the maintenance of ESs (e.g. resource management); consequently, planning for ESs might require different perspectives and strategies from that used in conservation policies (Egoh et al., 2007). For this reason, biodiversity conservation plans do not often guarantee the provision of ESs for human use, whereas, strategies geared to sustaining human well-being like good and ES production at landscape level, by fostering the persistence of structures and functions that support ESs, and preserving the natural disturbance regime and the adaptive capacity of the biotic component (Petrosillo et al., 2010) can guarantee also the maintenance of biodiversity in terms of specific-diversity (Chan et al., 2006), The EU 2020 Biodiversity Strategy (Action 5) (Maes et al., 2013) requires EU Member States to map and assess the state

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of ecosystems and their services in their national territory by 2014, assess the economic value of such services, and promote the integration of these values into accounting and reporting systems at EU and national level by 2020. In this respect, national MAES (Mapping and Assessment of Ecosystem Services) working groups should help to provide guidance and tools to support strategic deployment of green infrastructure in the EU urban and rural areas to improve ecosystem resilience and habitat connectivity and to enhance the delivery of ecosystem services at Member State and sub-national level (Maes et al., 2013). Now, it is clear that in SELs ecosystem resilience and habitat connectivity are not unrelated to ES assessment, but they all part of a common picture to be addressed in a systemic way to meet the requirements of the Biodiversity Strategy. However, whereas much has been done on how to make ecosystem service (ES) assessment and accounting operational, it is still quite unclear how to proceed for addressing ecosystem resilience and habitat connectivity that can have some relevant feed-backs on assessment procedures too. In this respect, our contribution to the MAES working group is to advance few suggestions on how to approach the dynamic analysis of complex adaptive systems to gauge and possibly foster ecosystem resilience and habitat connectivity and, meanwhile, improve assessment and even enhance the delivery of ESs.

The urgent need of a spatiotemporal assessment of ESs

Recently, Haines-Young and Potschin (2009) provided a comparison of habitat, systems and place-based ecosystem service assessment approaches (Table 1).
However, it is quite apparent that all assessment approaches in Table 1 are rather «static»; once made tend to be valid almost forever like in the benefit transfer approach, as they do not take into consideration the dynamics of systems. This is a clear limitations that can heavily affect ESs assessment and successive accounting.
As land-use transformation is becoming a main global driver given the worldwide changes to forests, farmlands, waterways, water and air (Millennium Ecosystem Assessment, 2005), the problem we face is how a "static" and "ordered" landscape condition in social-ecological landscapes (SELs), provided by the cross-scale intersections of land use, plans and norms (order) can be made sustainable

Table 1. A comparison of habitat, systems and place-based ecosystem service assessment approaches (adapted from Haines-Young and Potschin 2009).

Approach	Characteristic	Advantages	Disadvantages
Habitat (Biodiversity Pattern) based	Mapping of services made on the basis of spatial patterns in underlying components of biodiversity, e.g. habitat types, biomes	• Clear links with exiting conservation frameworks and approaches • Multi-functional character of 'ecosystems' evident • Can often make use of existing biodiversity or habitat monitoring data	• Unclear how different habitats should be weighted to make some overall assessment of services • Unclear how habitat combinations influence service output
System (Process) based	Mapping services based on the spatial characteristics of biophysical elements on which the service is functionally dependent, e.g. catchment	• Allows overall assessment of service state and trend to be made • Generalisation easier	• Unclear how issues of multi-functionality can be addressed • Systems modelling is complex and present understandings may be limited-especially in the context of predicting spatial pattern
Place-based	Mapping services as bundles across units that have strong social relevance or resonance	• Allows better understanding of local contexts, and therefore priorities and values • Allows issues of trade-offs to be identified and potentially resolved • Allows implications of alternative management of policy options to be tested easily through participatory methods	• Difficult to generalise results • Difficult to model services at local scales because of uncertainties and lack of base-line data

in face of unpredictable disturbance and change (disorder) (Zurlini et al., 2013). In this respect improving the assessment and accounting of ESs is of increasing prominence. Temporal variation is crucial because of life cycles of ES providers and human activities but it is not usually introduced into assessment unless through modelling (e.g., climate forcing variables). Indeed, what we are looking for, i.e. ES provisioning and habitat fragmentation or effective connectivity, can systematically change on the map and what is provided as ES and connected under certain conditions could not be provided and suitable when season, conditions or the set of focal habitats or species are changed.

Complex adaptive systems

The objects of study of the Biodiversity Strategy are complex adaptive systems (Levin, 1998) like SELs where humans are always present and actively changing their properties and processes either directly or indirectly. If we think of an SEL as a mosaic of land uses and land covers in a physiographic unit like a watershed, health would refer to the maintenance of the "usual" state of such system. Indeed, the usual state of affairs in living systems like landscapes or watersheds is one of systems fluctuating around some trend (increasing or decreasing) or stable average; however, sporadically, this condition is interrupted by an abrupt shift to a radically different regime. Disturbance can be deemed as an event causing departure of a living system from the ''usual range'' of conditions typical of its basin of attraction. The apparent paradox that disruption of the existing order (i.e., disorder) and persistence (i.e., order, stability) always coexist in living systems such as watersheds is addressed by the concept of resilience, defined as the amount of disturbance a system can absorb without shifting into an alternative state and losing function and services (Walker and Salt 2006). Such a concept seeks to explain how disorder and order usually work together, allowing living systems to assimilate disturbance, innovation, and change, while at the same time maintaining characteristic structures and processes (Westley et al., 2006). In this respect, health would be referred to the resilience capacity of a system in order to maintain characteristic structures and processes of systems within the same basin of attraction. Fortunately, the complexity of living systems of people and nature emerges not from a random association of a large number of interacting factors but rather from a smaller number of key-controlling processes (Holling, 2001; Gunderson and Holling, 2002). Much of the fundamental nature of systems can often be captured and described by single key state variables, as many features of the system's state tend to shift in concert with a few important key-state variables (Holling, 2001). In watersheds, for example, this is typically ruled by solar radiation and water cycle in terms of amounts and quality.

Which state variables for SELs?

Remote sensing is a primary source of information and it has become a proven tool for scientists to monitor environmental phenomena synoptically and globally, to understand major disturbance events and their historical regimes at regional and global scales (Kerr and Ostrovsky, 2003; Potter et al., 2003; Zurlini et al., 2006a). It has provided valuable indices to describe and quantify natural and human-related land-cover transformations and processes and ES provisioning, such as the Normalized Difference Vegetation Index (NDVI) with all its derived indices. Because of their correlation with the radiation intercepted by vegetation NDVI related indices supply information on net primary production (NPP) (Young and Harris, 2005; Xu et al., 2011) that is the energetic foundation of nearly all terrestrial (as well as marine) ecosystems. In particular, NPP is a fundamental supporting service that represents a measure of the solar energy captured by the system driving the overall functioning of the system itself. NPP represent a key indicator of ecosystem functioning because it governs the flow of many provisioning and regulating services and some cultural services as many ESs are linked to NPP and tend to shift in concert with it (Odum, 1971; Gaston, 2000; Costanza et al., 1998; Costanza et al., 2007; Richmond et al., 2007). Thus NDVI-related indices provide fundamental synoptic information of spatiotemporal provisioning of NPP that, as single key state variable, in turn, provides information on other related ESs.

Furthermore, NDVI-related indices can also supply data on potential species richness in many parts of the world, and may help monitor ESs like carbon sequestration, water cycling and regulation, and soil fertility. NDVI is broadly recognized as a spatially explicit robust indicator to gauge social–ecological processes such as habitat-land use conversion (e.g., urban sprawling) or crop rotation (Guerschman et al., 2003; Potter et al., 2003; Young and Harris, 2005). NDVI is widely used to identify and assess the impact of disturbances such as drought, fire, flood, frost (Potter et al., 2003; Mildrexler et al., 2007), or other human-driven disturbances (Guerschman et al., 2003; Wylie et al., 2008; Zaccarelli et al., 2008a; Zurlini et al., 2013).

Retrospective analyses through time series exploit the information reservoir of our recent past. They can extremely help us understand the past trajectory of the system that is at the basis for tracing future scenarios, to identify the possible driving forces behind changes, mainly due to human activity, and the main consequences of these processes on ESs (Käyhkö and Skånes, 2006; Zaccarelli et al., 2008b; Petrosillo et al., 2009; 2010).

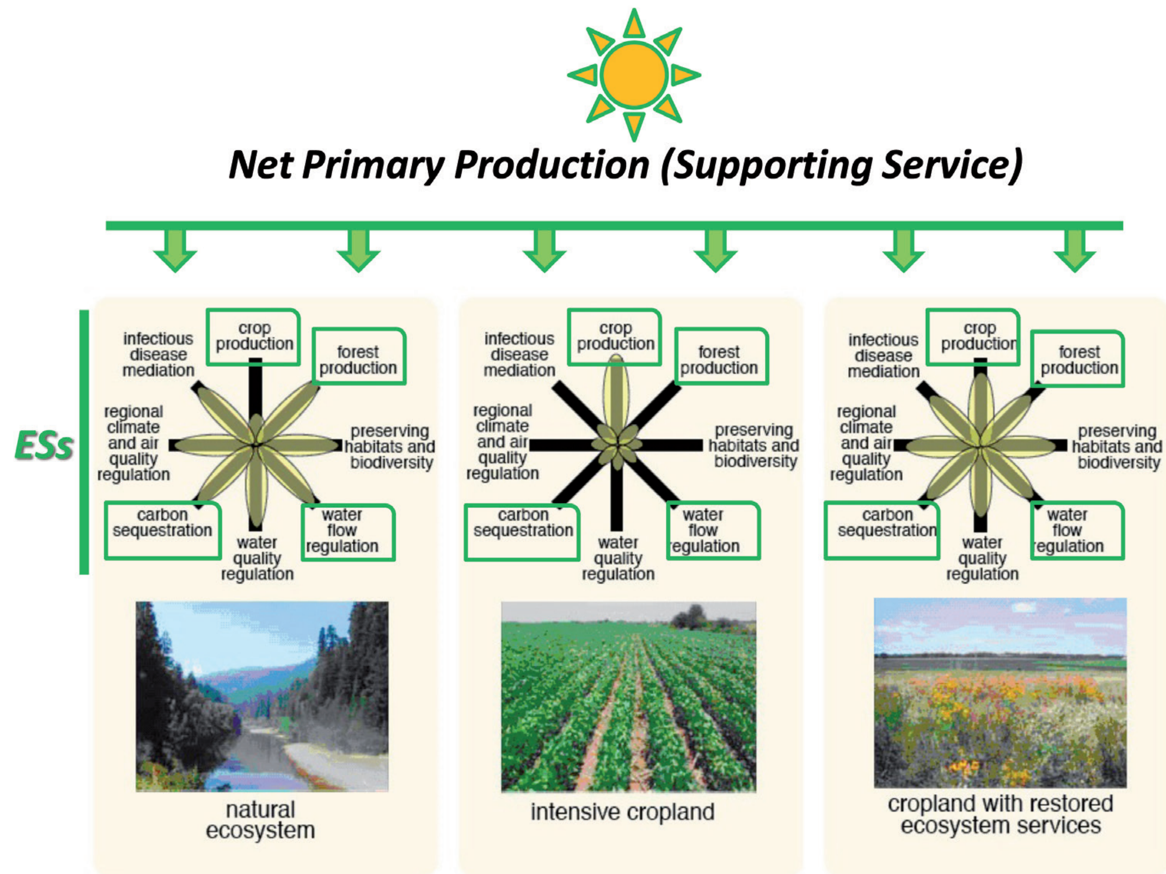

Figure 1. The Ecosystem Services supply chain showing the relationship between the supporting ecosystem service like net primary production (NPP) and the other fundamental ESs in different types of ecosystems (adapted from Foley et al. 2005).

However, the overall provision of services does not so much depend on the features of the individual lands use/land cover (LULC) patches, but rather on the spatial interactions of the mosaic elements generated from natural and human-managed patches, and by human elements, such as footpaths and roads (Termorshuizen and Opdam, 2009), causing synergies and trade-offs between services across multiple scales.

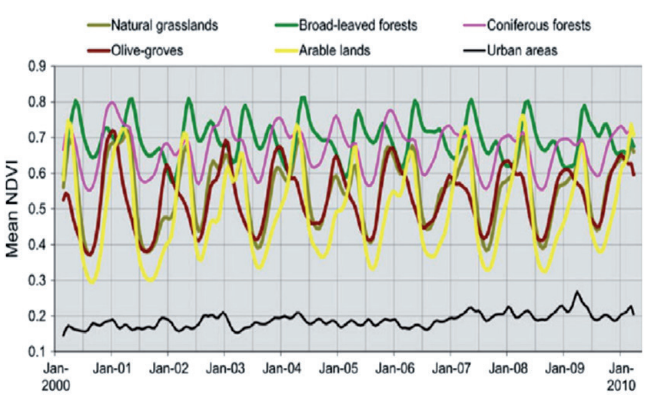

Figure 2. Mean Normalized Difference Vegetation Index (NDVI) time trajectories computed on 148 16-days NDVI maximum value composite images acquired by the two MODIS platform TERRA and AQUA with a spatial resolution of 250 meters (MOD13Q1 v.005 and MYD13Q1 v.005).

Time series are an essential reservoir of past SEL information as they keep track of the disturbances that occurred so they must be deeply investigated since can reveal a great deal about the magnitude of disturbance and the timing of return to the usual functionality of systems (Zurlini et al., 2013).
An example of NDVI time series (2000 – 2010) for primary LULC categories of the Apulia region (south Italy) (Figure 2) demonstrates the differences in the inter-annual periodicities of NDVI related to both human controls (arable lands and olive groves) and natural balancing feedback loops (natural grasslands, broad-leaved forests, coniferous forests), whereas urban areas show a disordered behavior.

SEL connectivity

A variety of ESs depend on the movement of organisms and materials across landscapes (Tscharntke et al., 2005; Kremen et al., 2007) and, therefore, are likely influenced by landscape connectivity that is the degree to which a landscape facilitates movement (Taylor et al., 1993). We use the term to include both biotic connectivity (movement of organisms) and abiotic connectivity (movement of water, nutrients, soil; Fischer and Lindenmayer, 2007), each of which influences the provision of different ESs. The need for maintaining ecological fluxes in the landscape and, particularly, the natural dispersal routes for wildlife species' movements, call for a more integrated management of ecosystems in which connectivity considerations should be necessarily incorporated (Hortal and Saura, 2007).

A proper mapping of the distribution and spatial configuration of hot-spot for ecosystem services in the landscape (e.g. Chustet al., 2004; Weiers et al., 2004) is first required in order to adequately address the structural pattern-dependent aspects of connectivity (Tischendorf and Fahrig, 2000).

Just because we are not so good in predicting the future and what could be a suitable network sustaining ES provisioning, material, organism and gene exchange, we have to rely on past time series (at suitable scales) to define on a map the trajectory of every landscape segment to see whether it is predictable or not, that is, if it is persistent or not.

The "normalized spectral entropy" (Hsn) is an entropy-related index able to describe the degree of order and predictability (i.e., regularity) within an ecological time-series based on its power spectrum (Zaccarelli et al., 2013). This index has been suggested as a holistic indicator for system level properties able to characterize heterogeneity in time and pointing to the system's self-organization strength (Li, 2000). Thus,1-Hs_n can be calculated to emphasize the degree of regularity or predictability of the series.

Spectral entropy (Hs_n) of NDVI time series (Zaccarelli et al., 2013) can practically serve for mapping predictability of SELs (Figure 3) (Zurlini et al., 2013). It is based on the trajectories for each pixel and calculated from 10 year long time series of 16-day maximum NDVI composite images acquired by the two MODIS platform for the Apulia region (south Italy) (Figure 2). Figure 3 shows the "predictability" map of invariant structures as provided by NDVI (NPP). In particular it illustrates distinctive spatial patterns at 250 m resolution with greener zones meaning higher predictability (1 - Hs_n), i.e. more regular time series, while reddish areas are more unpredictable. Low spectral entropy refers to locations with less complex temporal pattern, i.e. with more stable cyclical developments. Clear coherent regions of predictability and unpredictability emerge as well as gradients of transition between the two. Large predictability geographic regions arise in the map (e.g., olive groves near Brindisi, or large farmlands near Foggia) whereas unpredictability regions tend to be associated with heterogeneous cultivation areas (Zurlini et al., 2013).

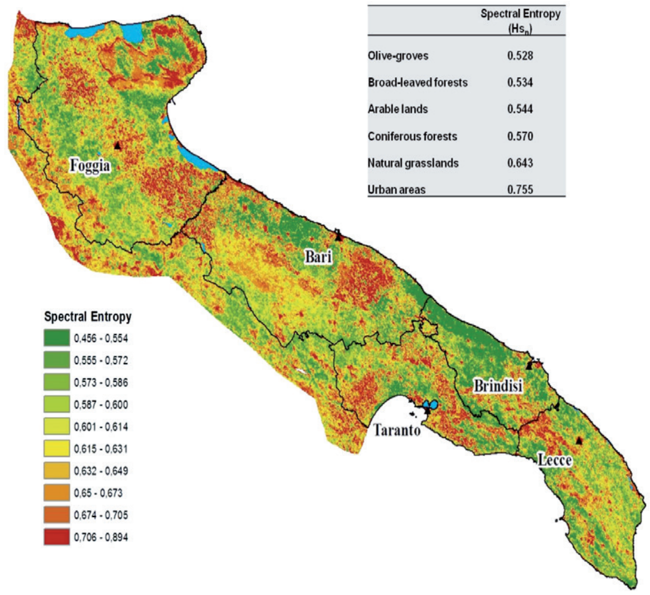

Figure 3. "Predictability" map of invariant structures in the Apulia region based on time series in Figure 2 (adapted from Zurlini et al., 2013).

Once one gets a "predictability" map of invariant structures, then one can think of applying different modelling tools to derive, under uncertainty, what possibly could be an effective corridor network and a suitable fragmentation for the future (Figure 4, connectivity arrows).

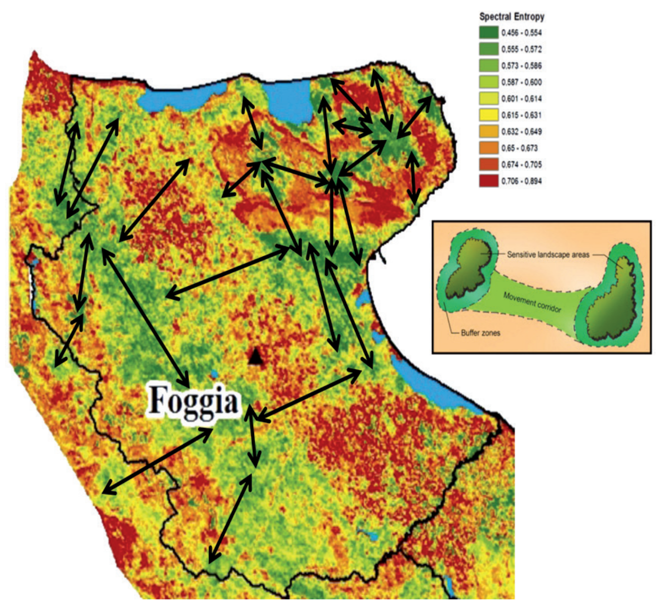

Figure 4. Example of connectivity network based on a predictability map of the area of Foggia and Gargano in the Apulia region. Arrows search to connect the most predictable areas indicating which areas could be transformed in more predictable by a proper change of their management or type of land cover to foster the overall network.

So one could discover that along with "classical" green and blue ways other elements in the landscape could be crucial based on their predictability for the maintenance of the overall connectivity in the face of climate change. Then, one could try to transform them in "persistent" through planning and management efforts (Zurlini et al., 2013). The same principle should be applied to fragmentation /connectivity for marine systems (Treml et al., 2008). Indeed, for many marine species, population connectivity is determined largely by ocean currents transporting larvae and juveniles between distant patches of suitable habitat. So, connectivity relies on the persistence of ocean currents suggesting areas that might be prioritized for marine conservation efforts and that are working like "stepping stones" in the maintenance of the overall network. On the other hand, one might identify "new" candidate stepping stone areas in case of predicted changes in the oceanic current pattern due to climate change.

Nonlinear analysis of spatial-temporal dynamics of ESs

Natural or human dominated processes can have a distinct recurrent behaviour, e.g. periodicities (as seasonal or Milankovich cycles), but also irregular cyclicities (as El Niño Southern Oscillation). Moreover, the recurrence of states is a fundamental property of deterministic dynamical systems and is typical for nonlinear or chaotic systems (Marwan et al., 2007). In analyzing SELs for simulating their behavior into the future, biophysical laws that govern aspects of nature can reveal a set of regularities (Holling, 2001). Those regularities occur even though complex adaptive systems are typically characterized by strong nonlinearities, tipping points and dramatic regime shifts (Scheffer and Carpenter, 2003). Insofar as natural patterns are found in all dynamical systems, the degree to which those systems exhibit recurrent patterns speaks volumes regarding their underlying dynamics and balancing feed-back loops. Resilience is deemed as the amount of disturbance a system can absorb without shifting into an alternative state and losing function and services (Carpenter et al., 2001; Walker et al., 2006). Adaptability captures the capacity of any SEL to learn, combine experience and knowledge, adjust its responses to changing external drivers and internal processes, and continue developing within the current stability domain or basin of attraction (Berkes et al., 2003). The probability that such state will persist is a measure of its resilience (Peterson, 2002), even though measures of past (retrospective) resilience can provide very useful insights into the dynamics of systems (Zurlini et al., 2006b)

A recurrence is a time the trajectory returns to a location it

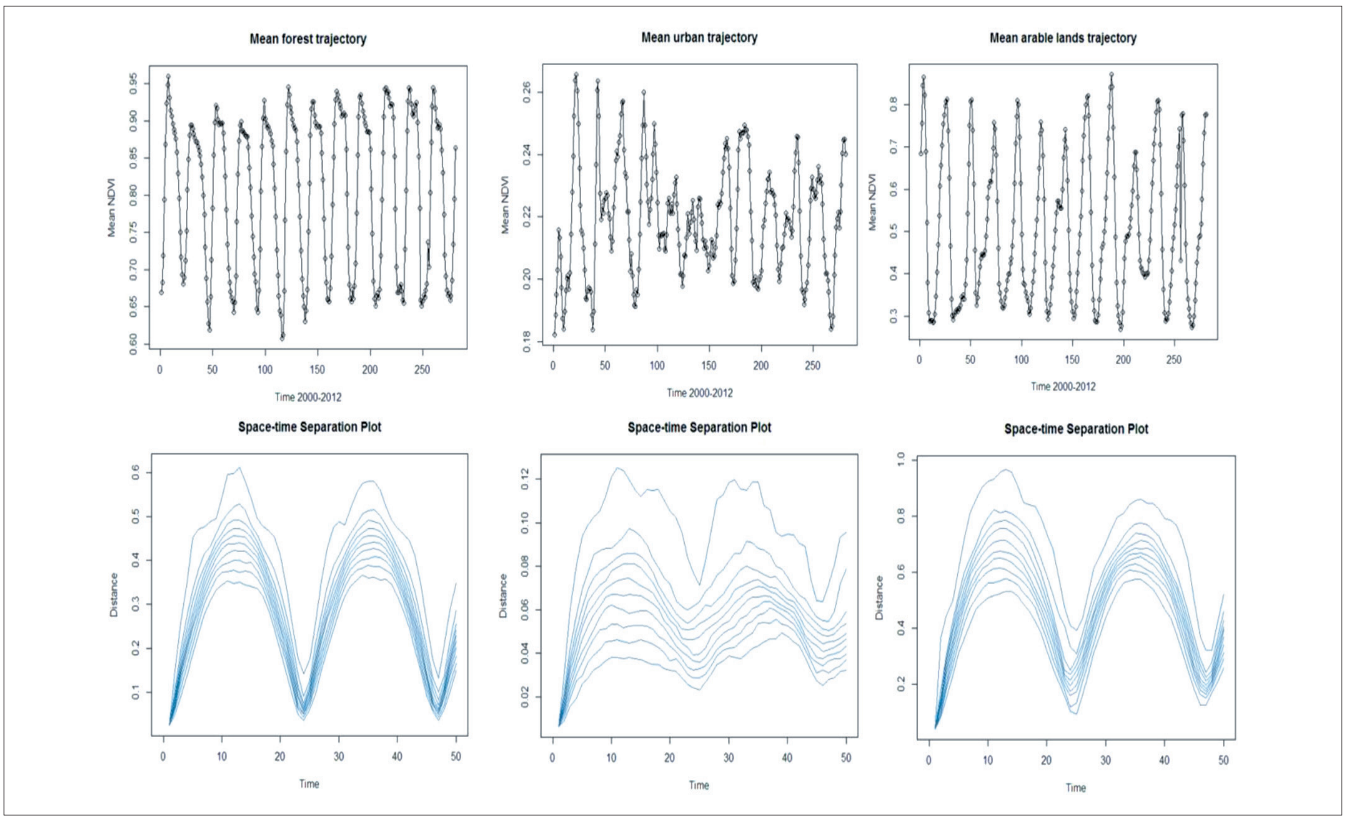

Figure 5. Time series of Normalized Difference Vegetation Index (2000-2012) and space-time separation plots for the Apulia region.

has visited before. The recurrence plot (RP) depicts the collection of pairs of times at which the trajectory is at the same place; it is a visualization (or a graph) of a square matrix, in which the matrix elements correspond to those times at which a state of a dynamical system recurs (columns and rows correspond then to a certain pair of times) (Marwan et al., 2007).

Time series for Forest, Urban, and Arable lands LULC classes are given in Figure 5 along with space-time separation plots. There is a strong time correlation of the series for Forest and Arable lands and around a lag of 10 the spatial component tends to saturate the distribution of values (Figure 5, below).

Let us consider the RPs of three prototypical systems (Figure 6, top), namely of a periodic motion on a circle (Fig. A), of a chaotic system (Fig. B), and of uniformly distributed, independent noise (Fig. C) (Marwan et al., 2007). In all systems recurrences can be observed, but the patterns of the plots are rather different. The periodic motion is reflected by long and non-interrupted diagonals. The vertical distance between these lines corresponds to the period of the oscillation.

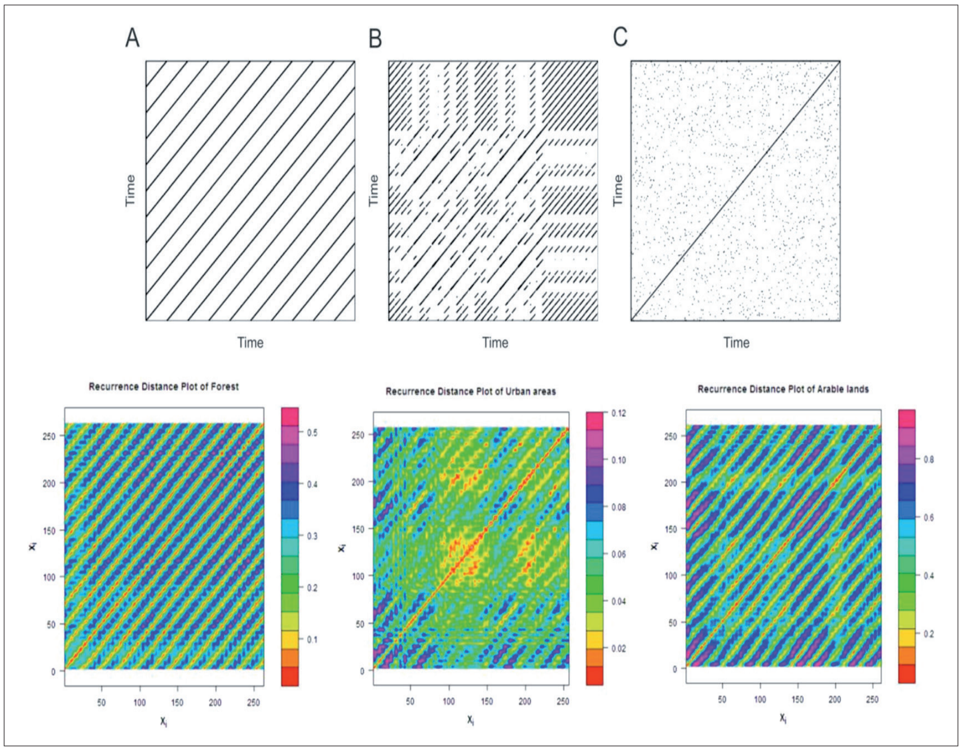

Figure 6. Recurrence plots of three prototypical systems (top) (A) a periodic motion with one frequency (very predictable), (B) of a chaotic system (unpredictable), and (C) of uniformly distributed noise (from Marwan et al., 2007) and Recurrence plots (bottom) of Forest, Urban areas, and Arable lands for the Apulia region (2000-2012).

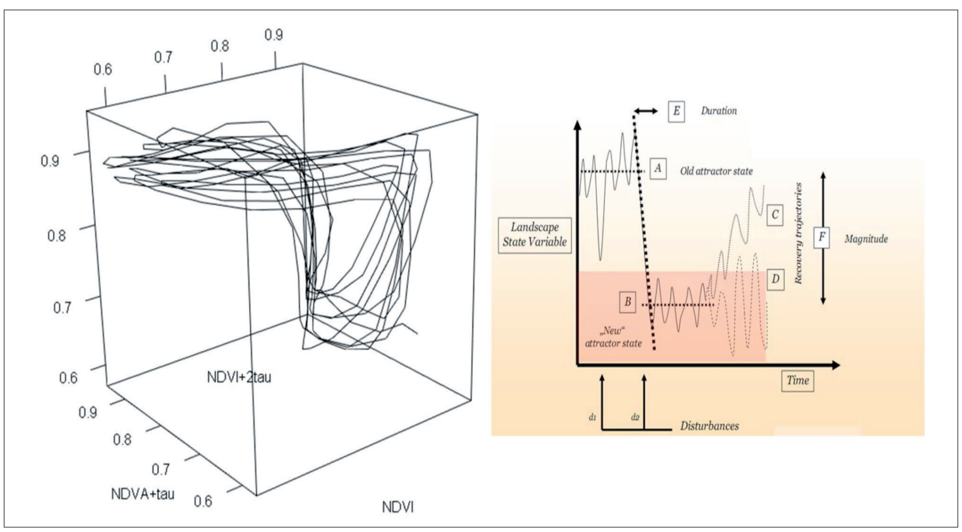

Figure 7. Left: Three-dimensional reconstruction of Normalized Difference Vegetation Index signal in phase space for the land cover class of Forest (2000-2012) by the method of time delays, with phase space trajectories visiting approximately the same area all the times.

The RPs of NDVI for the Apulia region (Figure 6, below) show that space trajectories can visit roughly the same area in the phase space all the times, i.e., ES dynamics for Forest are fairly spatiotemporally predictable, thus the probability that such state will persist is rather high (resilience is high). Arable lands are less predictable despite the action of self-correcting balancing feedback loops (e.g., drought-irrigation, soil impoverishment-fertilization). Urban areas, on the contrary, show a chaotic behavior (Figure 6, below).

Nonlinear analysis of spatial-temporal dynamics of SELs helps gauge the capacity of any SEL to activate balancing feed-back loops to adjust its responses to drivers. Adaptability (Walker and Salt, 2006) is a fundamental component of resilience and captures the capacity of any SEL to learn, combine experience and knowledge, and activate balancing feed-back loops to adjust its responses to changing external drivers and internal processes, and continue developing within the current stability domain or basin of attraction (Berkes et al., 2003) (e.g., Forest in Figure 7); whereas resilience is the probability that such state will persist (Peterson, 2002). Moreover, looking at phase space trajectories of time series can help to look at possible impeding regime shifts. The three-dimensional reconstruction of NDVI signal in phase space for Forest (2000-2012) (Figure 7, left) shows that phase space trajectories have been visiting for twelve years approximately the same area all the times showing a high adaptability.

Conclusions

We should be aware that not all ESs bear the same importance, some of them are crucial for the functioning of the entire SELs, determining much of their dynamics; so they are real key-state variables to focus on. Addressing only single ESs without looking at the underpinning supporting services is a very partial approach making hard if not impossible to derive the overall supply picture. Supporting services like NPP (through NDVI), as provided by remote sensing techniques in a dynamic and spatially explicit way, underpin most of ESs allowing a proper systemic approach to study all the resulting provisioning cascade of ESs that can shift in concert with NPP, which results the real engine of the overall system functioning. This helps gauge synergies, trade-offs, and synchronies and asynchronies of ESs and relative time lags. Therefore, ES assessments must be conducted based on the dynamical features of SELs otherwise all ES estimates would turn very inaccurate and unreliable strongly affecting subsequent accountings and payments for ESs and their practical application and acceptance in the real world. We have shown here some examples of how to address this issue that can reveal synergies and trade-offs in space and time otherwise neglected by a static assessment approach like the classic benefit transfer averaging most of the dynamics.

As a result, even the overall provision of ESs does vary with time where different ESs can have a different spatiotemporal role and importance (see e.g., Figure 2). However, it does not so much depend on the features and dynamics of the individual LULC patches, but rather on the spatial and temporal interactions of the mosaic elements generated from natural and human-managed patches causing synergies and trade-offs between services across multiple spatial and temporal scales. In this respect, key-state variables are fundamental for modelling the overall provision of ESs as they are behind of any SEL functioning. Further research activity must be encouraged in this direction of SEL complexity in order to investigate the main linkages among related supporting services behind overall ES delivery.

Landscape connectivity too is not a static but rather a very dynamical feature of complex adaptive systems like SELs, and as such must be treated. So, connectivity relies primarily on the temporal persistence of certain landscape and seascape features that are to be considered the pillars for building up reliable ecological networks (e.g., Figure 4). Furthermore, as critical transition in SELs can dramatically change the flow and provisioning of ESs, landscape connectivity can be a very useful indicator of impeding regime shifts and so it can be used as early-warning signal of such transitions (Scheffer et al., 2009; Dakos et al., 2010) as provided, for example, by regularly cross-scale analysis of land cover connectivity (Zurlini et al., in press).

We have shown a promising way to monitor phase space trajectories of time series to derive indications on current and past adaptability based on nonlinear analysis of spatial-temporal dynamics of SELs, and also to look at possible impeding regime shifts (Figure 7).

In a nutshell, we have to learn from what we are doing but, most of all, from what we have already done.

References

Balvanera P., Daily G.C., Ehrlich P.R., Ricketts T.H., Bailey S.A., Kark S., Kremen C., Pereira H., 2001. Conserving biodiversity and ecosystem services. Science 291, 2047.

Berkes F., Colding J., Folke C., (eds), 2003. Navigating social–ecological systems: building resilience for complexity and change. Cambridge University Press, Cambridge.

Carpenter S.R, Walker B.H., Anderies J.M., Abel N., 2001. From metaphor to measurement: resilience of what to what? Ecosystems 4, 765-781.

Chan K.M.A., Shaw M.R., Cameron D.R., Underwood E.C., Daily G.C., 2006. Conservation planning for ecosystem services. PLoS Biology 4, 2138-2152.

Chust G., Ducrot D., Pretus J.L., 2004. Land cover mapping with patch-derived landscape indices. Landscape Urban Planning 69 (4), 437-449.

Costanza R., d'Arge R., de Groot R.S., Farber S., Grasso M., Hannon B., Limburg K., Naeem S., O'Neill R.V., Paruelo J., Raskin R.G., Sutton P., van den Belt M., 1997. The value of the world's cosystem services and natural capital. Nature 387, 253-260.

Costanza R., Fisher B., Mulder K., Liu S., Christopher T., 2007. Biodiversity and ecosystem services: a multi-scale empirical study of the relationship between species richness and net primary production. Ecological Economics 61, 478-491.

Dakos V., van Nes E.H., Donangelo R., Fort H., Scheffer M., 2010. Spatial correlation as leading indicator of catastrophic shifts. Theoretical Ecology 3, 163-174.

Egoh B., Rouget M., Reyers B., Knight A.T., Cowling R.M., van Jaarsveld A.S., Welz A., 2007. Integrating ecosystem services into conservation assessments: a review. Ecological Economics 63, 714-721.

Fischer J., Lindenmayer D.B., 2007. Landscape modification and habitat fragmentation: asynthesis. Global Ecology and Biogeography 16, 265-80.

Foley J.A, Defries R., Asner G.P., Barford C., Bonan G., Carpenter S.R., Chapin F.S., Coe M.T., Daily G.C., Gibbs H.K., Helkowski J.H., Holloway T., Howard E. A, Kucharik C.J., Monfreda C., Patz J.A, Prentice I.C., Ramankutty N., Snyder P.K., 2005. Global consequences of land use. Science 309, 570-574.

Gaston K.J., 2000. Global patterns in biodiversity. Nature 405, 220-227.

Guerschman J.P., Paruelo J.M., Burke I.C., 2003. Land use impacts on the normalized difference vegetation index in temperate Argentina. Ecological Applications 13 (3), 616-628.

Gunderson L.H., Holling C.S. (eds), 2002. Panarchy: understanding transformations in human and natural systems. Island Press, Washington, DC.

Haines Young R.H., Potschin M.B, 2009. Methodologies for defining and assessing ecosystem services. Final Report, JNCC, Project Code C08-0170-0062, 69 pp.

Holling C.S., 2001. Understanding the complexity of economic, ecological, and social systems. Ecosystems 4, 390-405.

Hortal L.P., Saura S., 2007. Impact of spatial scale on the identification of critical habitat patches for the maintenance of landscape connectivity. Landscape Urban Planning 83, 176-186.

Käyhkö N., Skånes H., 2006. Change trajectories and key biotopes-assessing landscape dynamics and sustainability. Landscape and Urban Planning 75, 300–321.

Kerr J.T., Ostrovsky M., 2003. From space to species: ecological applications for remote sensing. Trends in Ecology & Evolution 18, 299-305.

Kremen C., Williams N.M., Aizen M.A., Gemmill-Herren B., Le Buhn G., Minckley R., Packer L., Potts S.G., Roulston T., Steffan Dewenter I., Vazquez D.P., Winfree R., Adams L., Crone E.E., Greenleaf S.S., Keitt T.H., Klein A.M., Regetz J., Ricketts T.H., 2007. Pollination and other ecosystem services produced by mobile organisms: a conceptual framework for the effects of land-use change. Ecology Letters 10, 299-314.

Levin S., 1998. Ecosystems and the Biosphere as Complex Adaptive Systems. Ecosystems 1, 431-436.

Li B.-L., 2000. Fractal geometry applications in description and analysis of patch patterns and patch dynamics. Ecological Modelling 132, 33-50.

Maes J., Teller A., Erhard M., Liquete C., Braat L., Berry P., Egoh B., Puydarrieux P., Fiorina C., Santos F., Paracchini M.L., Keune H., Wittmer H., Hauck J., Fiala I., Verburg P.H., Condé S., Schägner J.P., San Miguel J., Estreguil C., Ostermann O., Barredo J.I., Pereira H.M., Stott A., Laporte V., Meiner A., Olah B., Royo Gelabert E., Spyropoulou R., Petersen J.E., Maguire C., Zal N., Achilleos E., Rubin A., Ledoux L., Brown C., Raes C., Jacobs S., Vandewalle M., Connor D., Bidoglio G., 2013. Mapping and Assessment of Ecosystems and their Services. An analytical framework for ecosystem assessments under action 5 of the EU biodiversity strategy to 2020. Publications office of the European Union, Luxembourg.

Marwan N., Romano M.C., Thiel M., Kurths J., 2007. Recurrence Plots for the Analysis of Complex Systems. Physics Reports 438, 237-329.

Mildrexler D.J., Zhao M., Heinsch F.A., Running S.W., 2007. A new satellite-based methodology for continential-scale disturbance detection. Ecological Applications 17, 235-50.

Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-Being: Current State and Trends. Island Press, Washington, DC.

Odum H.T., 1971. Environment, Power, and Society. John Wiley & Sons, New York.

Peterson G.D., 2002. Estimating resilience across landscapes. Conservation Ecology 6(1), 17 (online). http://www.consecol.org/vol6/iss1/art17/

Petrosillo I., Semeraro T., Zurlini G., 2010. Detecting the ‘conservation effect’ on the maintenance of natural capital flow in different natural parks. Ecological Economics 69, 1115-1123.

Petrosillo I., Zaccarelli N., Semeraro T., Zurlini G., 2009. The effectiveness of different conservation policies on the security of natural capital. Landscape and Urban Planning 89, 49-56.

Potter C., Tan P.N., Steinbach M., Klooster S., Kumar V., Myneni R., Genovese V., 2003. Major disturbance events in terrestrial ecosystems detected using global satellite datasets. Global Change Biology 9, 1005–1021.

Richmond A., Kaufmann R.K., Mynen R.B., 2007. Valuing ecosystem services: A shadow price for net primary production. Ecological Economics 64, 454- 462.

Scheffer M., Carpenter S.R., 2003. Catastrophic regime shifts in ecosystems: linking theory to observation. Trends in Ecology & Evolution 18(12), 648-656.

Scheffer M., Bascompte J., Brock W.A., Brovkin V., Carpenter S.R., Dakos V., Held H., van Nes E.H., Rietkerk M., Sugihara G., 2009. Early-warning signals for critical transitions. Nature 461, 53-59.

Taylor P., Fahrig L., Henein K., Merriam G.,1993. Connectivity is a vital element of landscape structure. Oikos 68, 571-3.

Termorshuizen J.W., Opdam P., 2009. Landscape services as a bridge between landscape ecology and sustainable development. Landscape Ecology 24, 1037-1052.

Tischendorf L., Fahrig L., 2000. On the us age and measurement of landscape connectivity. Oikos 90 (1), 7-19.

Treml E.A., Halpin P.N., Urban D.L., Pratson L.F., 2008. Modeling population connectivity by ocean currents, a graph-theoretic approach for marine conservation. Landscape Ecology 23, 19-36.

Tscharntke T., Klein A.M., Kruess A., Thies C., 2005. Landscape perspectives on agricultural intensification and biodiversity-ecosystem service management. Ecology Letters 8, 857-74.

Walker B.H., Salt D., 2006. Resilience thinking: sustaining ecosystems and people in a changing world. Island Press, Washington, DC.

Weiers S., Bock M., Wissen M., Rossner G., 2004. Mapping and indicator approaches for the assessment of habitats at different scales using remote sensing and GIS methods. Landscape and Urban Planning 67 (1-4), 43-65.

Westley F., Zimmerman B., Patton M., 2006. Getting to maybe. Random House of Canada, Toronto.

White P.S., Jentsch A., 2001.The search for generality in studies of disturbance and ecosystem dynamics. Progress in Botany 62, 399-450.

Williams P.H., Araújo M.B., 2002. Apples, oranges, and probabilities: integrating multiple factors into biodiversity conservation with consistency. Environmental Modelling and Assessment 7, 139-151.

Wylie B.K., Zhang L., Bliss N., Ji L., Tieszen L.L., Jolly W.M., 2008. Integrating modelling and remote sensing to identify ecosystem performance anomalies in the boreal forest, Yukon River Basin, Alaska. International Journal of Digital Earth 1,196-220.

Xu L., Samanta A., Costa M.H., Ganguly S., Nemani R., Myneni R.B., 2011. Widespread decline in greenness of Amazonian vegetation due to the 2010 drought. Geophysical Research Letters 38, L07402.

Young S.S., Harris R., 2005. Changing patterns of global-scale vegetation photosynthesis, 1982-1999. International Journal of Remote Sensing 26, 4537-45.

Zaccarelli N., Petrosillo I., Zurlini G., 2008b. Retrospective Analysis. In: Encyclopedia of Ecology, Vol 4 System Ecology. Sven Erik Jørgensen and Brian D. Fath (Eds.), pp.3020-3029. Publisher: Oxford: Elsevier.

Zaccarelli N., Petrosillo I., Zurlini G., Riitters K.H., 2008a. Source/sink patterns of disturbance and cross-scale effects in a panarchy of social–ecological landscapes. Ecology and Society 13(1), 26 (online) http://www.ecologyandsociety.org/vol13/iss1/art26/

Zaccarelli N., Li B-L., Petrosillo I., Zurlini G., 2013. Order and disorder in ecological time-series: introducing normalized spectral entropy. Ecological Indicators 28, 22-30.

Zurlini G., Riitters K.H., Zaccarelli N., Petrosillo I., Jones K.B., Rossi L., 2006a. Disturbance patterns in a social–ecological system at multiple scales. Ecological Complexity 3,119-128.

Zurlini G., Zaccarelli N., Petrosillo I., 2006b. Indicating retrospective resilience of multi-scale patterns of real habitats in a landscape. Ecological Indicators 6,184-204.

Zurlini G., Petrosillo I., Jones K.B., Zaccarelli, N., 2013. Highlighting order and disorder in social–ecological landscapes to foster adaptive capacity and sustainability.

Landscape Ecology 28, 1161-1173.

Zurlini G., Jones K.B., Riitters K.H., Li B-L., Petrosillo I., 2014. Cross-scale connectivity of land-use patterns as early-warning signal of regime shifts. Ecological Indicators, in press.