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

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ABSTRACT

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

1. Introduction

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

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

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

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

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

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

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

2. Data and methods

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

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

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