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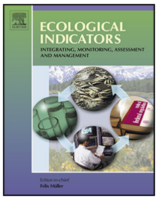

Energy–Landscape Integrated Analysis: A proposal for measuring complexity in internal agroecosystem processes (Barcelona Metropolitan Region, 1860–2000)

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ABSTRACT

Farm systems are facing a global challenge amidst a socio-metabolic transition that places them in a dilemma between increasing land-use intensity to meet the growing demand of food, feed, fibres and fuels, while avoiding a biodiversity loss at the same time. To solve this dilemma a deeper research on how species richness is kept in different land-use patterns is required, according to the quantity and quality of the ecological disturbance that farmers carry out across the landscape. We propose an Energy–Landscape Integrated Analysis model that assesses both the complexity of internal energy loops, and the information held in the whole network of socio-metabolic energy fluxes, so as to correlate this energy-information interplay with the functional landscape structure. The results show that the landscape heterogeneity of Mediterranean land-use mosaics, created by traditional organic mixed-farming, have tended to vanish as a result of a simultaneous reduction in the complexity of the interlinking pattern of energy flows and the quantity of information carried by them. The model could help us to reveal how and why different agroecosystem managements lead to key turning points in the relationship of the energy profile with landscape ecological functioning. No doubt, these results will be very useful for designing more sustainable farm systems worldwide in the future.

1. Introduction

1.1. Sustainable farm systems: the global food-biodiversity dilemma

Farm systems are facing a global challenge amidst a socio-metabolic transition (Muradian et al., 2012; Scheidel and Sorman, 2012; Schaffartzik et al., 2014) that places them in a dilemma between increasing land-use intensity to meet the growing demand of food, feed, fibres and fuels (Godfray et al., 2010; Lambin and Meyfroidt, 2011), while trying to avoid a dangerous biodiversity loss (Tilman, 1999; Cardinale et al., 2012). The industrialization of agriculture through the 'green revolution' spread from the 1960s onwards has been a major driver of this loss (Matson et al., 1997; Tilman et al., 2002). However, it is increasingly acknowledged that well-managed agroecosystems can play a key role in biodiversity maintenance (Bengtsson et al., 2003; Tscharntke et al., 2005). From a land-sharing approach to biological conservation (Perfecto and Vandermeer, 2010; Tscharntke et al., 2012), there is a claim for a wildlife-friendly farming liable to provide complex agroecological matrices. An heterogeneous and well connected land matrix could maintain high species richness in cultural landscapes (Tress et al., 2001; Agnoletti, 2006, 2014; Jackson et al., 2007). Depending on land-use intensities and the type of farming, agricultural systems may either enhance or decrease biodiversity (Altieri, 1999; Swift et al., 2004). In turn, the adaptive capacities to farming disturbances and agroforestry land usages vary across species and biomes (Gabriel et al., 2013; Balmford et al., 2014).

Solving the global food-biodiversity dilemma requires a deeper research to know how species richness is kept or lost in different land-use patterns, according to the level (quantity) and character (spatiotemporal scale and quality) of the ecological disturbances that farmers carry out across the landscape (Fischer et al., 2008;

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Phalan et al., 2011). If human society wants to ensure all sorts of ecosystem services in the future, we need better operative criteria and indicators in order to assess when, where and why the energy throughput driven by farmers increases or decreases the mosaic pattern of cultural landscapes and their capacity to hold biodiversity (Gliessman, 1990; Pierce, 2014). This calls for an integrated research of coupled human-natural systems aimed at revealing complex structures and processes which are not apparent when studied by social or natural scientists separately (Liu et al., 2007; Marull et al., 2015a).

1.2. Aim and scope of this study

A growing consensus in conservation biology points to landscape heterogeneity as being a key mechanism that generates a dynamic biodiversity peak at intermediate levels of ecological disturbance in agroecosystems, thanks to the interplay between spatial diversity, ecosystem complexity and dispersal abilities of colonizing species either coming from less disturbed patches or the survivors in the most disturbed ones (Tilman, 1994; Elmqvist et al., 2003; Roxburgh et al., 2004; Harper et al., 2005; Perfecto and Vandermeer, 2010; Loreau et al., 2010). This opens a research field on how the complexity of energy flows driven by farmers shapes these types of heterogeneous landscapes that can offer a great deal of habitats, food chains and ecological connectivity required by the associated biodiversity of farm systems. The Energy–Landscape Integrated Analysis (ELIA) of agroecosystems proposed in this article aims to contribute to this task by bringing to light the link between the anthropogenic energy carriers flowing among the components of a farm system, the information held within this energy network, and the land-cover diversity of cultural landscapes that arises with the spatial imprint of these farming energy flows.

2. Theory

2.1. Towards an Energy–Landscape Integrated Analysis

Living systems are capable of using metabolic energy carriers in order to maintain or even increase their organization (Schrödinger, 1944), when they attain a far-from-thermodynamic equilibrium set up with the organized information that allows transferring energy while maintaining their complexity, reproducing themselves, and evolving (Ho, 1998; Gladyshev, 1999; Ulanowicz, 2003). Applying this approach to agroecosystems requires analysing (1) the energy throughput and closure degree of socio-metabolic cycles; (2) the information carried by the spatially differentiated shape of these energy fluxes flowing across the land-matrix; and (3) the land-cover diversity of the landscape to which the species are adapted (Ho and Ulanowicz, 2005). Like any other ecosystem, in agroecosystems the energy dissipated in space also leads to the emergence of self-organized structures that experience historical successions ruled by adaptive selection (Morowitz, 2002). Thanks to the internal biophysical cycles that link organisms one another, these agroecosystems can enhance their own complexity, increase temporal energy storage and decrease entropy. This set of emergent properties translates into integrated spatial heterogeneity and biodiversity of landscapes (Ho, 2013; Ulanowicz, 1986). Their sustainability is directly related to the information-complexity interplay, and inversely related to energy dissipation (Prigogine, 1996; Ulanowicz, 1997).

In this vein, agroecosystems are seen as the historically changing outcome of the interplay between sociometabolic flows (Haberl, 2001), the land-use patterns set up by farmers, and ecological functioning (Farina, 2000; Wrbka et al., 2004). Despite the long-lasting work done on energy analysis of farm systems, which revealed a substantial decline in energy returns of agro-industrial management brought about by the massive consumption of cheap fossil fuels (Odum, 1984, 2007; Giampietro and Pimentel, 1991; Giampietro et al., 2011, 2013), the role played by sociometabolic energy throughput as a driving force of contemporary Land Cover and Land-Use Change (LCLUC) is not yet well understood (Peterseil et al., 2004). ELIA intends to link these two lines of research, the agroecological accounting of energy flows (Guzmán and González de Molina, 2015; Tello et al., 2016) and the study of LCLUC from a landscape ecology standpoint (Marull et al., 2015a). This requires specifying and measuring the pattern of energy flows and the information held in agroecosystems.

2.2. Cultural landscapes as socio-metabolic imprint

Traditional organic farm systems with a solar-based metabolism, like the ones existing in Europe before the massive spread of the green revolution from the 1960s onwards, tended to organize their land usages according to different gradients of intensity, keeping an integrated management of the landscape because their whole subsistence depended on this. In order to offset the energy lost in the inefficient human exploitation of animal bioconversion—on which they had to depend to obtain the internal farm services of traction and manure (Guzmán and González de Molina, 2009)—, traditional organic farming kept livestock breeding carefully integrated with cropland, pasture and forest spaces (Krausmann, 2004). While the organic farm management strategy of closing cycles within an agroecosystem led to landscape mosaics, the socio-ecological transition to agro-industrial farm systems that rely on external flows of inputs coming from underground fossil fuels has enabled society to overcome the age-old energy dependency on bioconverters (Krausmann et al., 2003; Schaffartzik et al., 2014). As a result, integrated land-use management at a local or regional scale was no longer necessary—and overcoming this former necessity also led to losing its agroecological virtue (Cussó et al., 2006a, 2006b). The environmental damage caused worldwide by this lack of integrated management between energy flows and land usages urges societies to recover the former 'landscape efficiency' (the socioeconomic satisfaction of human needs while maintaining the healthiest landscape ecological patterns and processes) at present (Marull et al., 2010). Since the lack of an integrated management of energy flows and land-uses at different scales is part of the current global ecological crisis, its recovery becomes crucial for a more sustainable foodscape.

This line of research involves a wider and more complex approach to agroecosystems' energy efficiency. It requires not only accounting for a single input-output ratio between the final product and the external energy consumed, but looking at the harnessing of energy flows that loop within the system as well. The cyclical nature of these flows is important in order to grasp the emergent complexity and the information held within the agroecosystem, given that they involve an internal maximization of less-dissipative energy carriers—in the same vein as Ho and Ulanowicz (2005) explain the 'loopy' character of any living system. The temporal energy storage that these loops allow becomes a foundation for all sustainable systems (Ho, 2013). Hence, the usual methodology of energy flow analysis of social metabolism needs to be adapted and enlarged in order to give account of the cyclical character of agroecosystems' processes (Giampietro, 2004; Giampietro et al., 2011, 2013; Guzmán and González de Molina, 2015).