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Evaluation of ecosystem responses to land-use change using soil quality and primary productivity in a semi-arid area, Israel

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ABSTRACT

Land-use change (LUC) from natural to human-dominated land is a critical aspect of global change and ecosystem response. To improve our understanding of LUC, this study focused on: (1) developing a general theoretical framework for quantifying and evaluating the attributes of ecosystem response as a consequence of LUC; and (2) testing the validity of this framework using recent LUC in the desert fringe of the northern Negev Desert. Our framework is based on the premise that changes in soil and vegetation states are the most important and universal facets of ecosystems' response to LUC. The framework depicts LUC as trajectories of indicators that signify soil and vegetation states, such as the soil quality index (SQI) and aboveground net primary productivity (ANPP), respectively, in a phase plane. The trajectories are characterized by both magnitude and the direction of the change that enable us to address and compare the general trends of the LUC. Our study explored the validity of the proposed framework for the following LUC cases: (1) grazing to natural ecosystem; (2) natural to grazing ecosystem; (3) rain-fed agricultural to natural ecosystem; and (4) rain-fed agricultural to grazing ecosystem. The SQI was quantified by 14 physical, biological, and chemical attributes that were merged into one index, while the ANPP was derived from biomass sampling. All transitions show strong relationships between SQI and ANPP ($0.70 < R^2 < 0.85$; $p < 0.05$). Transitions from grazing to natural ecosystems are characterized by an increase in both SQI and ANPP variables; while all transitions that change from agricultural systems to less intensively managed systems, such as grazing or a natural system, show no change or a decrease in both SQI and ANPP. We infer that all the trajectories' trends are a result of changes in the biodiversity dimensions during LUC. Analysis of the results revealed four properties of a theoretical framework that can be used for the developing science of LUC and ecosystem responses. Our framework enables: (1) a comparison between different types of LUC; (2) a study of transitions among self-organized and managed ecosystems; (3) the identification of short- and long-term effects; and (4) the integration of biodiversity and ecosystem function. We suggest that the four properties of the framework can provide the foundation for the development of an LUC science. However, the validity and the generality of the framework should be tested over a wide range of LUCs of terrestrial systems in the world.

1. Introduction

1.1. Land use changes: Conceptual framework

The term land use encompasses a wide range of human activities on the land surface, such as grazing, agriculture, and urban use (DeFries et al., 2004). Land-use activities, whether converting natural landscapes to human use or changing management practices on human-dominated lands, have transformed a large proportion of the planet's land surface (Foley et al., 2005). Worldwide observations have confirmed that a large portion of the terrestrial surface has been changed from natural ecosystems to human-dominated ecosystems, mainly to grazing and agro-ecosystems (e.g. Goldewijk, 2001; DeFries et al., 2004; Foley et al., 2005; Zhou et al., 2006; de Chazal and Rounsevell, 2009). The transitions in land-use activities are largely due to demographic and economic causes and are expected to increase over time. Different parts of the world are at different transition stages, depending on their history, social and economic conditions, and ecological context. The type of land-use change (LUC) significantly affects key aspects of

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ecosystem responses, in terms of ecosystem structures, functions, and dynamics, and creates new complex interactions among soil, nutrients, and vegetation that determine the ecosystem health (Adeel et al., 2005). These responses vary not only according to the state of LUC, but also with the biophysical and ecological setting (DeFries et al., 2004; Foley et al., 2005) due to the modifications of biodiversity, productivity, and soil quality (Matson et al., 1997; Tscharntke et al., 2005).

Historically, LUCs of natural environments to rangelands and, later, to croplands are known from the beginning of human settlement as a consequence of the domestication of plants and animals, and of land cultivation, and this type of ecosystem transformation became the most common on earth (Goudie, 2009). During the last 300 years, the global area of agricultural land has increased from 256 Mha in 1700 to 1471 Mha in 1990, and it currently occupies between 24% and 38% of the Earth's land surface (Goldewijk, 2001; Swinton et al., 2007). In addition, the global amount of pasture land has also increased from 524 Mha in 1700 to 3451 Mha in 1990, and it occupies around 25% of the global land surface (Asner et al., 2004).

Previews studies show the important role of ecosystem response to LUC due to modulation of the biosphere by changes in biogeochemical, biodiversity, hydrological, and climatic responses (e.g. DeFries et al., 2004). However, more theoretical and empirical work is needed in order to manage these human-controlled biospheres (Foley et al., 2005). Land use change models that incorporate ecosystem processes, dynamics, and responses can help to advance our understanding of the ecosystem-level consequences of LUC and their sustainable management. In this study, we aim at: (1) developing a theoretical framework for evaluating the changes of ecosystem response to LUC; and (2) demonstrating the validity of the framework using LUCs in the northern Negev Desert as a case study. We propose that the transitions between natural, grazed, and agricultural ecosystems, which include the human activities of land cultivation and replacement of the natural vegetation and animals by domesticated organisms (Tscharntke et al., 2005; Swinton et al., 2007) are the prevailing LUC on earth, and can be presented by a simple state and transition conceptual scheme. This scheme can be quantified in relation to changes in soil and vegetation states or other core states, such as biodiversity, hydrological, and climate (Fig. 1). The scheme includes three ecosystems: (1) Natural – defined as self-organized systems without human management (Levin, 1998) or livestock grazing (Perevolotsky, 1999). In our framework, abandoned agricultural and grazing systems that are self-organized by plant and animals' re-colonization from the available natural species pool are natural ecosystems; (2) Grazing – defined as terrestrial ecosystems with high densities of domestic livestock herbivores introduced by humans. The abundant domestic herbivores determine plant community dynamics and ecosystem processes (Manley et al., 1995; Greenwood and McKenzie, 2001; Lin et al., 2010); (3) Agricultural – defined as an ecosystem under intensive cultivation aiming at the production of crops. These agricultural management reduce the species diversity and the complexity of species assemblages, energy flow, and nutrient fluxes in the system (Clergue et al., 2009).

1.2. Ecosystem responses to land use changes

We further propose that reciprocal LUCs between the above three states are possible and create six types of transitions (Fig. 1): (1) Transition from natural to grazing ecosystem. This transition occurs mainly in natural grasslands, shrublands, and savannas since domesticated grazing livestock are typically adapted to these biomes. The transition is maintained by managing the stocking rates and foraging strategies of the domestic animals (Dean and Macdonald, 1994; Manley et al., 1995). (2) Transition from natural to agro-ecosystems. This transition is continuously sustained by human management that includes the clearing of native vegetation and its replacement by domesticated plant and animal species whose ecological traits are controlled by humans (Swift et al., 2004; Clergue et al., 2009; Smith et al., 2012). (3) Transition from agro-ecosystems to natural ecosystems. This transition occurs as a result of the abandonment of agricultural fields where natural processes of self-organization facilitate the natural regeneration of ecosystem structure, function, and processes and are preserved by natural succession and disturbance regimes (MacDonald et al., 2000). (4) Transition from grazing to agro-ecosystems. This transition takes place when socio-economic conditions inhibiting access to input factors, such as water and fertilizers, are removed. The human management includes the input of energy and nutrients to the system (Metzger et al., 2006; Goldstein et al., 2012). (5) Transition of agro-ecosystem to grazing ecosystems. This transition takes place when socio-economic conditions are poor or when the environmental conditions are not profitable for agricultural production, and it persists under continuous management by humans that includes the abandonment of agricultural land and the introduction of domestic livestock. (6) Transformation of grazing to natural ecosystems. This transition takes place when conservation efforts to restore the natural environment take place in order to prevent degradation and desertification processes. For example, this transition can be created by excluding livestock from the grazing system for allowing the recovery of the natural vegetation (Perevolotsky, 1995, 1999). This transition encourages natural processes of self-organization that facilitate the regeneration of the natural ecosystem structure, function and processes.

Changes in soil and vegetation states are important facets of ecosystem response to LUC (DeFries et al., 2004; Foley et al., 2005). Therefore, we propose that a trajectory of variables that represent soil and vegetation states, along with their relations, can be used as a common currency to describe substantial changes of terrestrial ecosystem components due to LUC, to address general trends, and to analyze effects on ecosystem structure (e.g., soil quality) and functions (e.g., primary production) (Fig. 2). We suggest a conceptual framework for the trajectories in the soil and vegetation states phase plane resulting from LUC: (1) Trajectories that signify similar (equal contribution of the two variables) relationships between the two states. These trajectories are marked by the diagonal line that indicates either a common increase or a decrease in both variables. We assume that the contribution of each variable changes between the trajectories due to different effects of soil and vegetation relations. These relations are the most prevailing trajectories since, in natural, grazed, and agricultural ecosystems; the capacity of the soil to produce plant biomass (productivity function) is an essential function. This capacity is determined by the soil state. Under high soil quality, within a natural or managed ecosystem, the ability to sustain plant and animal productivity is high (Karlen et al., 1997). However, when soil is degraded and soil quality is low, the ability to support primary productivity is low; (2) Trajectories that signify changes in either the soil or vegetation state but not simultaneously in both. These trajectories are marked by the horizontal and vertical lines in the phase plane and indicate either an increase or a decrease in only one state variable. We propose that an increase or a decrease in the vegetation or in the soil state, for example, occurs when the environmental factors (landscape quality factors) are not uniform as temperature, topography, and hydrology, or is due to ecological processes, such as herbivores. This framework can present diverse trajectories due to different relations between vegetation and soil states. The trajectories that emphasize equal contributions or signify changes in soil or vegetation states only represent under extreme conditions and all other relations can exist in reality. The magnitude and the direction of the trajectories enable us to address and compare general trends of change in ecosystem attributes and responses as a result of LUC.