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Hotspots of human-induced biomass productivity decline and their social–ecological types toward supporting national policy and local studies on combating land degradation

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ABSTRACT

Identification and social–ecological characterization of areas that experience high levels of persistent productivity decline are essential for planning appropriate management measures. Although land degradation is mainly induced by human actions, the phenomenon is concurrently influenced by global climate changes that need to be taken into account in land degradation assessments. This study aims to delineate the geographic hotspots of human-induced land degradation in the country and classify the social–ecological characterizations of each specific degradation hotspot type. The research entailed a long-term time-series (1982–2006) of Normalized Difference Vegetation Index to specify the extents of areas with significant biomass decline or increase in Vietnam. Annual rainfall and temperature time-series were then used to separate areas of human-induced biomass productivity decline from those driven by climate dynamics. Next, spatial cluster analyses identified social–ecological types of degradation for guiding further investigations at regional and local scales. The results show that about 19% of the national land mass experienced persistent declines in biomass productivity over the last 25 years. Most of the degraded areas are found in the Southeast and Mekong River Delta (17,984 km^2), Northwest Mountains (14,336 km^2), and Central Highlands (13,504 km^2). We identified six and five social–ecological types of degradation hotspots in agricultural and forested zones, respectively. Constraints in soil nutrient availability and nutrient retention capability are widely spreading in all degradation hotspot types. These hotspot types are different from each other in social and ecological conditions, suggesting that region-specific strategies are needed for the formulation of land degradation combating policy.

1. Introduction

Land is understood as a terrestrial ecosystem that includes not only soil resources, but also vegetation, water, other biota, landscape setting, climate attributes, and ecological processes (Scherr and Yadav, 1996; MEA, 2005; Vlek et al., 2008) that operate within the system, ensuring its functions and services. From internationally authoritative concepts of United Nations Convention to Combat Desertification (UNCCD, 2004) and Millennium Ecosystem Assessment (MEA, 2005), *land degradation is defined as the persistent reduction or loss of land ecosystem services, notably the primary production service* (Safriel, 2007; Vogt et al., 2011). First, this definition focuses on the ecological services of the land: land degradation makes sense to our society only in the context of human benefits derived from land ecosystems uses (Safriel, 2007). Negative changes in soil fertility (e.g., soil erosion, deteriorations of physical, chemical, and biological soil properties) are concerned in the changes resulting in reductions of supporting (e.g., primary production), provisioning (e.g., biological products including foods) and regulating (e.g., carbon sequestration) services of the land. In addition, the definition emphasizes the pivotal role of primary production among a wide range of land ecosystem services. The crucial reason for this emphasis is that primary production generates products of biological origin, in which much of other ecosystem services depend on (Safriel, 2007). Primary production is the basis of food productions, regulates water, energy, and nutrient flows in land ecosystems, sequestrates carbon dioxide from the atmosphere and generally provides habitats for diverse lives (MEA, 2005).

From the view of above-mentioned definition of land degradation, the phenomenon can involve not only soil degradation, but also the degradation of vegetation functions and services either within a land-use/cover type (e.g., forest degradation and yield-degraded crop land), or a conversion of natural productive land cover type to a less productive one (e.g. deforestation). In fact, soil and vegetation degradations

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have close inter-linkages as they are the two pivotal components of land ecosystems (MEA, 2005; Safriel, 2007).

Land degradation has been considered as a major global environmental issue. Eswaran et al. (2001) estimated that about 13.6 million km^2 of global land are moderately or severely degraded. In the tropical countries, where livelihoods are usually agriculture-based, land degradation is a serious problem for food security and development of society (FAO, 2010; Vlek et al., 2010).

Vietnam is a typical case of land degradation. About 93,000 km^2 of land (28% of the national land mass) was affected by degradation, of which 20,000 km^2 is seriously degraded (UNCCD, 2006). Land degradation in Vietnam is driven by both natural and anthropogenic phenomena (Cooke and Toda, 2008). The land has gradually lost its biological productivity due to soil erosion, landslide, lateralization, and acidification. In addition the fast development of economy, modernization–urbanization, and high growth in population have created a high pressure on land for agricultural production (Muller and Zeller, 2002). Those factors act as drivers of land-use change (e.g., deforestation, forest degradation, and shortening of fallow periods in shifting cultivation in the uplands; and more intensified agriculture in the lowlands) that can have a direct impact on soil's and land ecosystem's functions and services, including the biomass productivity of the land. To combat land degradation on the national level, policy makers often need information about areas of severe degradation in order to prioritize national budgets and plan strategic interventions (Vogt et al., 2011; Le et al., 2012). First, the main requirement at this *large scale* is a view of areas *where* degradation magnitude and extent are relatively high, i.e., *geographic degradation hotspot*, for prioritizing the investments on the restoration or reclamation of degraded land, and focal field-based studies. With the geographic hotspot approach, the expected output is the map of degradation hotspots that can be seen as the first version of land degradation map to guide the obtaining of the more comprehensive and accurate one in the next steps. Although the National Action Programme to Combat Desertification for the Period 2006–2010 and Orientation to 2020 has recently prioritized four regions that urgently need anti-degradation measures (i.e. the Northwest, the Central Coast, the Central Highlands and the Mekong River Delta) (NAP, 2006), the report was based on national experts' opinions and did not show explicitly the areas for policy interventions. Second, efforts to mitigate land degradation at the social level also require identification of the *potential causes* of degradation in different regions, which are important for formulating cause-targeted management strategies.

Large-scale land degradation assessments based directly on the temporal states of soil parameters is constrained by the lack of soil data for long-term quantitative comparisons (Safriel, 2007). With current technologies, it would be very costly to track the dynamics of soil properties directly over longer time spans at a national or regional scale to develop time-series of soil properties that could detect *persistent changes* in soil status (compared to a baseline). On a continental or national scale, these long-term comparisons are basically impossible (Vlek et al., 2008, 2010). Early global land degradation assessments evaluated soil parameters, and were based on qualitative, subjective assessments by experts (Oldeman et al., 1991).

As an alternative, recent large-scale land degradation assessments have been based on quantitative evaluation of changes in vegetation greenness or net primary productivity (NPP), which has been explicitly postulated in the UNCCD's definition. This approach has become feasible with the availability of satellite-driven time-series of vegetation data spanning the past three decades and covering the whole globe. The Normalized Difference Vegetation Index (NDVI), a relative measure of vegetation health and photosynthetic process, is increasingly used for evaluating vegetation productivity decline or improvement. The relationship between the NDVI and vegetation productivity is well-established theoretically and empirically (Pettorelli et al., 2005). Previous studies (Zhao and Running, 2010; Fensholt et al., 2012) have found that NDVI is strongly correlated with NPP and is often used to estimate NPP at global, national and regional scales, and served as an indicator of NPP to monitor temporal changes in vegetation. The parameter is suitable for geographic hotspot assessment for prioritizing resource allocation in either land management policies or more detailed studies at finer scale (Vogt et al., 2011). Above-ground net primary production (represented by NDVI) has been shown to increase with increasing annual precipitation (Huxman et al., 2004), and indeed, correlation studies between climate factors (rainfall and temperature) and NDVI have been used to distinguish between human-induced and climate-induced biomass productivity decline, where any NDVI trends not explained by rainfall and temperature dynamics are ascribed to human actions (Herrmann et al., 2005; Wessels et al., 2007; Vlek et al., 2010; Le et al., 2012; Li et al., 2012). The Advanced Very High Resolution Radiometer (AVHRR) of the National Oceanic and Atmospheric Administration (NOAA) satellite is a unique instrument that enables the assessment of global or regional vegetation dynamics over a long duration (i.e., more than two decades), which can be combined with other time-series (e.g., climate, soil, land use, and population) to allow spatially explicit interpretation of the causes and processes of degradation.

Recent reviews suggest that NDVI-based methods for detecting land degradation need to be continuously verified in different geographic regions (Vogt et al., 2011). Thus far, in Vietnam, spatio-temporal trend analysis has not been used for assessing long-term changes in biomass productivity of the land on a national scale. Further, the causes of degradation have not been systematically identified on a national scale and in a spatially explicit manner.

This study aims to (i) delineate the geographic hotspots of human-induced biomass productivity decline in Vietnam over the last two decades, and (ii) identify different types of hotspots with respect to different social and ecological causes of biomass productivity degradation. The findings may provide a nationwide pattern that could guide follow-up studies conducted on finer scales in terms of what focus to adopt.

2. Methods and data sources

2.1. Study area

Vietnam is characterized by a complex physical geography, with three-quarters of the land territory dominated by hills and mountains. The total land area of Vietnam is about 331,051 km^2, of which agricultural and forest land comprises 251,273 km^2 (75.9% of the total area). The area used for residential, industrial and transportation purposes is 34,692 km^2 (10.5% of the total), and the remaining area (45,086 km^2 or 13.6% of the total) is bare and unused (i.e. unused flat land, unused mountainous land and rocky mountain). The land area for agricultural production is about 96,000 km^2 (29% of the total) (GSO, 2010). The national population in 2009 was about 86 million, an increase of 26 million compared to 1985 (about 60 million) (GSO, 2010). The rapid population growth has created a high degree of pressure on land for food production as well as forest cover for nature services. From 1930 to 2000, the farming area per person was dramatically reduced from 2548 m^2 to 675 m^2 (Bo et al., 2003b). The national forest coverage decreased from 43% in 1943 (mainly multistory and dense tropical forests) to 28% in 1990 (De Koninck, 1999), then rose up to 37% by massive reforestation programs (UNCCD, 2006). Today, most replanted forests are mono-species stands with rapidly growing species and simple structure.

2.2. Proxy of long-term biomass productivity decline at the national level

Given the large scale (large spatial coverage and large pixel size) and long-term perspectives of our assessment, we used the *long-term trend of inter-annual mean NDVI*, driven from AVHRR satellite images, over the period 1982–2006, as a proxy for persistent decline or improvement in NPP of the land, thereby reflecting past land degradation. The approach