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Spatio-temporal dynamics of critical ecosystem services in response to agricultural expansion in Rwanda, East Africa

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A B S T R A C T

Changing natural landscapes to agricultural land, driven by land demand, have been considered an important driver that limits the ability of landscapes to provide ecosystem services. The decline in ecosystem services in the past are mainly due to anthropogenic farming activities that have been undertaken to satisfy human wellbeing in Africa. Quantifying these declining services over time and space is essential to facilitate sustainable management decisions. In this study, the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model was used to quantify and value the ecosystem services in Rwanda from 1990, 2000, and 2010. From the results, while forest cover declined drastically from 61.1% in 1990 and reached 19.9% in 2010, cropland and settlement areas both expanded from 24.7% to 53.4% and from 0.5% to 1.8%, respectively. These variations have resulted in a decrease in total carbon storage from 439.7 Mt to 230.5 Mt in the 20 years, whereas soil export increased from 135 Mt to 712 Mt in 2010. Farmland expansion accelerated the export of nitrogen and phosphorous from 0.9 Mt to 3.1 Mt and 1.0 Mt to 8.4 Mt, respectively. The water yield increased from $2.04 \times 10^9\,m^3$ in 1990 to $2.20 \times 10^9\,m^3$ in 2010. Further tradeoffs analysis reveals that three ecosystem services including water, soil, and nutrient show strong positive correlations with one another, while carbon service appears to have little relationship with the other services. The strategies to manage ecosystem service trade-offs should incorporate farmers' knowledge and scientific research aimed at increasing agricultural production and resource efficiency in Rwanda. To ensure sustainability, demographic pressures should not be neglected.

1. Introduction

Natural ecosystems are very important to society because of the services and goods they provide (Cardinale et al., 2012; CEPF, 2012). Human beings are completely reliant on the services from Earth's ecosystems (MEA, 2005). A sense of balance between exploitation of natural resources for socioeconomic development and conserving ecosystem is key to sustainable development (Falkenmark, 2007). Over the past five decades, humans have altered ecosystems more rapidly and extensively than in any comparable period of time in human history (Keenan et al., 2015; MEA, 2005; Sandker et al., 2015). The transformation of the landscape has contributed to substantial net gains in human well-being and economic development, but it has also transformed and degraded many ecosystem services (Gamfeldt et al., 2013; Kleijn et al., 2011). Previous studies have shown that both natural and anthropogenic land use changes have significantly influenced the provision of crucial ecosystem services, such as food production, carbon sequestration, water flow regulation, and sediment and nutrient retention (Deng et al., 2015; Liu et al., 2014; Stockmann et al., 2015); but Due to the impressive growth of population of Africa, more ecosystem are being traded-off to produce more food. The recent global assessment has revealed that forest area has increased globally, but decreases in poor tropical countries persist (FAO, 2015; Nkonya, 2012).

Agriculture is one of the most significant human-induced land use/land cover change (Gamfeldt et al., 2013; Nkonya, 2012), and they have been the most visible indicator of the human footprint and the most important driver of biodiversity loss (Hooper et al., 2012). Landscape degradation resulting from farming is notable in most African countries due to the pressure of population growth and the need to satisfy socioeconomic requirements of the populace (Beintema and Stads, 2011; Malunda, 2012; REMA, 2011). Rwanda is not an exception to these socioeconomic pressures on ecosystems, owing to high demographic

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pressures such as forced resettlement, and significant conflicts and insecurity as compared to other countries (Kanyamibwa, 1998; REMA, 2015). Demographic statistics showed that Rwanda's population has grown from 2.9 million in 1960 to 12 million in 2015, with population density increasing from 102 to 471 inhabitants per km^2 from 1960 to 2015. With a growth rate of 2.7, the population is expected to reach 14 million by 2025 (NISR, 2012; UNEP, 2011). Like most other countries, agriculture is considered to be the main threat causing ecosystem degradation because of the immense role it plays in Rwanda’s economy, accounting for about 43.0% of the GDP (Diao and Pradesha, 2014; UNEP, 2011). Natural threats such as drought, soil erosion, and flooding are also important drivers. Agriculture provides 90.2% of the country’s food resources, and 80.5% of the country’s labor force is engaged in agriculture. An estimated acreage of arable land in Rwanda is slightly above 1.5 million hectares, 90.4% of which is found on hillsides (Masozera et al., 2008).

Aside from hillside farming, the fragmentation of family farms (i.e. mostly through generational transfers), growing population pressure, and limited alternative employment opportunities have led to the conversion of natural forests and wetlands into cultivated land in the last four decades (MINAGRI, 2009; REMA, 2011). FAO reported that about 40.5% of Rwanda’s land is under threat of erosion. Approximately 37% of the arable lands needs soil maintenance and appropriate practices before cultivation, with only 23.4% of the land not susceptible to erosion (MINAGRI, 2009). Because of the intensive landscape dynamics in Rwanda, local farmers have extended beyond their arable lands to fragile lands such as steep slopes, previously used pasture, woodlots, wetlands etc. (Mukashema, 2007). The intensive cultivation of wetland marsh is causing streamflow changes, reducing water purification, increasing water evaporation, reducing water tables and groundwater recharge, and affecting downstream hydropower production (Nyandwi et al., 2015). Despite the international and local conservation measures (Kleijn et al., 2011), clear impacts on the Rwandan landscape are evident. Moreover, Rwandan communities continue to populate and rely on land resources, resulting in strong trade-offs between resource utilization and ecosystem protection. Hence, understanding how ecosystem dynamics generate and alter the nature of trade-offs is important to making sound management decisions and moving toward ecological sustainability.

To mitigate ecological degradation, the government of Rwanda intends to reduce, reasonably, the pressure on ecosystems by controlling the degradation progress though the development of various responses, such as constructing terraces and ditches to increase production (Kleijn et al., 2011). More importantly, the it is anticipated that the number of population engaged in agriculture is reduced by encouraging youth to participate in off-farm activities and look for alternative sources of income (REMA, 2011). It has been noted that policies for ecological protection have sometimes failed due to the misunderstandings between stakeholders and decision makers (Clay and Lewis, 1990). Therefore, ecosystem services based on land use change and their tradeoff analysis are highly needed to help national level decision-makers to plan sustainable and rational natural resource utilization (Groot et al., 2007; Long et al., 2012). Understanding how much value and where the ecosystem services are lost or gained can provide the basis for decision-makers to resolve conflicts between natural resources and socioeconomic development (Ingram et al., 2012). It will help to find some optimized or harmonized management strategies that sustain the environment and increase resilience (Bagstad et al., 2013).

Aiming at quantifying ecosystem services, a spatially explicit integrated modelling tool namely Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) has been developed and widely employed (Tallis and Polasky, 2009). The InVEST models use maps and tabular data of land use and its management and consider environmental information, such as soil, topography, and climate, to generate spatially explicit estimations of ecosystem services. It can provide useful information for managers and policy-makers to weigh the trade-offs in ecosystem services, biodiversity conservation, and other land-use objectives (Bagstad et al., 2013; Tallis and Polasky, 2009). The model has been successfully employed in many regions around the world (Tallis et al., 2012; Tallis and Polasky, 2009), and been proved to be a powerful tool for mapping, and valuing multiple ecosystem services. In Africa, its applications have emerged in only a couple of years. Mansoor et al. (2013) employed it to quantify and map multiple ecosystem services changes in West Africa. In the Eastern Arc mountains of Tanzania, it was used to analyse threatened ecosystem services and propose measures for ecosystem services trade-off under different scenarios (Fisher et al., 2012). Recently, the model has also been tested in another east African country, Uganda to restore the degraded forest landscape in order to achieve the greatest benefits, as well as to visualize related trade-offs to meet multiple objectives which generated relevant and profound information for decision-makers (Gourevitch et al., 2016). Even though the InVEST model has been used in different regions in Africa, such studies are still needed for local areas to help local government design appropriate policies for ecological sustainability (Richard Sharp et al., 2015; Tallis and Polasky, 2009).

This study aimed to quantify the impacts of land use on the changes of critical ecosystem services from 1990 to 2010. Specifically, we investigated: (1) the spatio-temporal changes of land use types as influenced by agricultural land expansion from 1990 to 2010 in Rwanda, (2) the corresponding spatiotemporal changes of critical ecosystem services including carbon storage, water yield, and sediment and nutrient retention services, and (3) the trade-off relationships among these critical ecosystem services and the different land uses. Evidence from our study can be used by policymakers to discover new practice opportunities for improving ecosystem management though minimizing land degradation and sustaining related ecosystem services.

2. Materials and methods

2.1. Description of study area

Rwanda is located in East Africa (Fig. 1) ranging between 1°4′S and 2°51′S and 28°45′E and 31°15E. The total surface area is 26,338 km^2, with 1672 km^2 occupied by water. Rwanda has a mountainous and sloping landscape with an altitude varying between 900 m and 4507 m, which increases from east to west. The country is characterized by a sub-equatorial climate with four seasons of which two rainy seasons from January to April and from October to mid-December alternate with two dry seasons. Temperature is relatively stable and ranges between 15 °C and 25 °C depending on the altitude. The highlands receive more rainfall (> 2000 mm annually) than the lowlands, and the rainfall in the northwest part of the country is more abundant than the east where the annual rainfall drops below 1000 mm. The arable land areas were about 1.4 million hectares which is around 52.5% of the total land, while actual cultivated land exceeded 1.6 million ha. Culture, population dynamics, and government policies are the main drivers of land use in Rwanda (FAO, 2014; Verdoodt and Ranst, 2003).

We divided the whole country into 9 sub-basins (Fig. 1) referring to the 2012 National Water Resources Master Plan (NWRMP) (MINIRENA, 2013) for better identification of water-related ecosystem services. These sub-basins include the Congo River Kivu North (CKIV), Congo Rusizi River (CRUS), Nile Upper Nyabarongo River (NNYU), Nile Mukungwa River (NMUK), Nile Lower Nyabarongo River (NNYL), Nile Akanyaru River (NAKN), Nile Upper Akagera River (NAKU), Nile Lower Akagera River (NAKL), and Nile Muvumba River (NMUV).

2.2. Data sources

2.2.1. Land use/cover data

Land use/cover data for 1990, 2000, and 2010 were obtained from the Regional Centre for Mapping of Resources for Development (Appendix I) (http://apps.rcmrd.org/), and land use maps were