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Ecological and economic indicators for measuring erosion control services provided by ecosystems

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ABSTRACT

The physical process of soil erosion leads to a range of impacts – both onsite and offsite – such as land degradation, nutrient depletion and sedimentation, which in turn affect different economic sectors that are reliant on productive capacity of land and aquatic resources. This erosion process is highly moderated by undisturbed natural ecosystems through physical and geochemical means. However, methods to quantify these linkages are scarce. The purpose of this article is to demonstrate an analytical framework for physical measurements and economic valuation of erosion control services provided by forested ecosystems. The article is divided into two parts: the first part deals with physical measurements of *onsite* and *offsite* erosion control services, and in the second part various economic valuation methods for different beneficiary groups are discussed. Ecosystem services are divided according to three beneficiary groups: (1) private benefits to farmers, (2) benefits to businesses, and (3) societal benefits. The article concludes with implications, challenges and future directions.

1. Introduction

Soil erosion is known to have direct impacts on soil productivity (Lal, 1998). A simulated erosion impact study showed that grain yields are reduced as much as by 10 to 38.5% due to erosion (Larney and Janzen, 2012). Similar results are reported in other empirical studies from around the world (Kagabo et al., 2013; Gao et al., 2015). A large number of studies also reported on the mechanisms through which this erosion is avoided and mediated. Using long-term data Gao et al. (2011) demonstrated that soil properties and nutrient balance is significantly affected by the presence of vegetation cover. Similarly, experimental studies on agroforestry systems showed that maintaining tree cover in agricultural landscapes reduced erosion risk and improved soil productivity (Atangana et al., 2014; Thevathasan and Gordon, 2004). This change in soil productivity directly translates into economic benefits generated by different production systems (Alam et al., 2014).

Despite the widespread recognition that improved landscape management reduces soil degradation, the quantitative relationship between erosion, vegetation cover and economic impacts is little-known. Past attempts typically looked into implications of soil erosion from an agricultural productivity perspective, but there is little information on how to measure erosion control as an ecosystem service provided by ecosystems, such as forests (but see Zheng, 2006; Zhou et al., 2008). Limitations also exist in economic approaches. While there is a rich body of literature on economic valuation of multiple ecosystem services provided by landscapes (Bateman et al., 2011), little work was done to attribute economic values to ecosystems that mediate erosion and land degradation.

The purpose of this article is to provide an analytical framework and indicators to bridge this research gap. Ecosystems are often converted to profitable land use systems, without accounting for the role that those ecosystems play in numerous ways to benefit the society. This article bridges the key linkages between ecosystems, erosion and the economy. First, with an illustrative example the article describes the physical erosion process and how it is mediated by an ecosystem, leading to provisioning of erosion control as an ecosystem service. In the economic analysis section potential methods for measuring economic value of erosion control services from the perspectives of three beneficiary groups – farmers, businesses and the society – are discussed. The article concludes with limitations, challenges and future directions.

2. A physical process leading to an ecosystem service

Soil erosion is a physical process – a process that has been taking place for millions of years – by which soil particles are moved from a source to a sink by natural forces such as water and wind. However, evidence suggests that human induced erosion is a relatively recent phenomena (Dotterweich, 2013; Enters et al., 2008).

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While it takes thousands of years for the topsoil to form, erosion can disintegrate all the organic matter and nutrients on the top soil in merely a few years, dramatically reducing soil productivity. The other aftermath of erosion is deposition of soil particles in downstream wetlands – a process called sedimentation – that increases the probability of flood occurrences by raising water beds. It also reduces water storage capacity and related economic activities such as hydroelectricity, navigation and transportation of goods.

Anthropogenic interventions can both accelerate and slow down this natural process. On the one hand, soil disturbances through logging operations and intensive agricultural practices are known to have large impacts (Ehigiator and Anyata, 2011; Mansikkaniemi, 2013), and on the other hand, conservation practices such as tree plantation on degraded soil and improved agricultural practices are effective in moderating erosion (Rocha et al., 2012). Studies have shown a strong correlation between ecosystems management and erosion. Trees and other vegetation cover reduce wind energy and hence windborne erosion (Leenders et al., 2014). Similarly, interception of rain and better drainage reduce waterborne erosion (Fattet et al., 2011). However, the magnitude and capacity of ecosystems to reduce erosion largely depend on many factors such as amount of precipitation, wind velocity, soil properties, slope, vegetation characteristics and agricultural management practices. Soil erosion models, such as the Universal Soil Loss Equation (USLE), in fact, work based on many of those factors.

Both *onsite* (e.g. in ecosystems) and *offsite* (e.g. in agricultural fields) reduction of erosion and sedimentation generates essential benefits to humans – known as “ecosystem services”. Erosion control measures can significantly reduce erosion, water runoffs and nutrient leaching (Rocha et al., 2012), and the costs of those measures and benefits realized from such conservation practices have been discussed in a number of past works. Paterson et al (1993) demonstrated a positive benefit-to-cost ratio of sediment control in urban areas in North Carolina. Pimentel et al (1995) estimated that every dollar spent on erosion control and soil conservation can benefit the society by a factor of five.

Measuring both the *onsite* and *offsite* erosion control services is necessary considering that they are often the results of the same physical processes and therefore are interrelated. Table 1 provides a brief description of erosion and sedimentation related ecosystem services provided by ecosystems.

3. Physical measurements

This section describes an analytical framework for physical measurements of erosion control services both *onsite* – erosion that is prevented within the forest, and *offsite* – erosion that is prevented outside the ecosystem boundary such as in an agricultural landscape.

3.1. Onsite erosion control

Among the models and techniques, the USLE is a widely known one that predicts annual soil erosion based on six parameters: *R,* rainfall-runoff erosivity factor; *K,* soil erodability factor; *L,* slope length factor; *S,* slope steepness factor; *C,* land cover management factor; and *P,* support practice factor.

$$E = R.K.L.S.C.P \tag{1}$$

Although it was developed to measure soil loss primarily in agriculture under different cropping and management practices, it has been equally applied in non-agricultural landscapes, sometimes in combination with GIS-based analysis for spatial modeling purposes (Kim and Julien, 2006).

If applied in a forested landscape, this equation can predict soil erosion under current land cover and land management conditions in a three-step process. Let *E (on, m)* be the marginal physical value of forest’s erosion control services. First, measure *onsite* (*on)* erosion in a *without-forest* (*wo*) scenario (equation 2); then measure it in a *with-forest* scenario (equation 3); and finally, divide the difference by the area of forest (*A(f)*) (equation (4):

$$E(on, wo) = f(R_{wo}.\ K_{wo}.\ L_{wo}.\ S_{wo}.\ C_{wo}.\ P_{wo}) \tag{2}$$

$$E(on, w) = f(R_{w}.\ K_{w}.\ L_{w}.\ S_{w}.\ C_{w}.\ P_{w}) \tag{3}$$

$$E(on, m) = \frac{E(on, wo) - E(on, w)}{A(f)} \tag{4}$$

For instance, if erosion *without-* and *with-forest* are 50 tons/year (equation 2) and 25 tons/year, (equation 3) respectively in a 1.5 ha forest land, then the marginal erosion control service is 16.6 tons/ha/year (equation 4). In these equations, the *C* factor is the most computationally complex parameter, and is also the most important one. For the same area of interest if all other factors (slope, climatic conditions etc.) remain unchanged, the variable that changes is *C* (and to some extent *K*). It is therefore important that these parameters are measured accurately in current and alternative land management scenarios.

Note that *without-forest* here refers to a counter-factual scenario in which the land is considered barren, devoid of any vegetation. However, soil erosion can also depend on current forest management practices. By comparing erosion rates in two alternative land management scenarios it is possible to measure the role of forests in soil retention. In this case the erosion difference is measured between two alternative land use regimes through an undisturbed forest condition *versus* an alternative forest management regime such as intensive logging, intensive agriculture practices or forest disturbance such as fire, roads network and infrastructure development. A similar approach was applied by Elliot et al (1999) who ran simulations of soil erosion using WEPP model to predict soil erosion under different forest management and disturbance regimes as summarized in Table 2.

3.2. Offsite erosion control

To measure *offsite* erosion control there is one condition and one assumption. Ecosystem services are, by definition, benefits generated by ecosystems to beneficiaries. Thus, if there is no beneficiary (e.g., no agricultural land to be protected), there is no services generated. Therefore, existence of beneficiaries is a pre-condition for ecosystem services assessments. The assumption, on the other hand, is that erosion control service decays with distance. That is: (i) there is a distance-limit within which erosion service can be realized, and (ii) the rate of service provision decreases with distance from ecosystems. The decay function needs to be empirically determined taking into consideration of the topography, soil characteristics, climatic conditions and soil cover among other factors (Kosmas et al., 2000; Ochoa et al., 2016).

Let’s delimit a buffer around the forest (the dashed circle in Figure 1, acknowledging that in reality the buffer will not be a circle due to irregularities of the shape of forest patches) and measure the

Table 1
Various *onsite* and *offsite* erosion control services provided by ecosystems

Processes	Ecosystem services	Description
Erosion	*Onsite* erosion control	Keeps soils onsite leading to prevention of soil degradation (Fu et al., 2011)
	Offsite erosion control	Keeps soil *offsite* (e.g. agricultural lands) (De Baets et al., 2011)
Sedimentation	*Onsite* sediment retention	Leads to nutrient retention that prevents water pollution (Valiela et al., 2013)
	Offsite sedimentation control	Prevents sedimentations in waterbodies, rivers and irrigation channels (Yin et al., 2014)