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Quantifying sheet erosion in agricultural highlands of Sri Lanka by tracking grain-size distributions

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ABSTRACT

The reduction of productivity in arable lands of the tropical highlands through intensified soil erosion is a major reason for food scarcity in many developing countries. Identifying soil erosion hot spots in highland agricultural croplands and monitoring the effectiveness of soil conservation are crucial for improving land management practices. This paper develops a low cost and efficient method to quantify the rate of soil loss caused by splash and sheet erosion, *in-situ* at the plot scale. This method assumes that textural differences between the topsoil and the underlying soil within the plot are due to erosion of the top layer. Grain size analyses conducted in agricultural soils of the Upper Uma Oya Catchment (UUOC) of Sri Lanka provided data to quantify splash or sheet erosion and deposition. Net soil loss from the plot was calculated based on rates of area weighted soil loss and deposition. The net splash and sheet erosion rate in the plot was 20 t ha^{-1} yr^{-1}, which is comparable with previous soil erosion results obtained in the area (25 t ha^{-1} yr^{-1}) at similar temporal and spatial scale and under the same agricultural use. This study suggests that approximately half of the total erosion in the UUOC area results from splash and sheet erosion, whereas the rest is driven by concentrated flow through rill and gully erosion. This method is potentially transferable to other croplands as a robust approach for rapid measurement of splash and sheet erosion.

1. Introduction

Soil erosion is recognized as one of the world's most serious environmental problems affecting steep lands in tropics since it significantly reduces the area of croplands available for food production (Pimentel, 2006). It is a natural process that occurs on lands under agriculture or natural vegetation, but its magnitude can be enormously increased in the agricultural lands depending on the land management practices. The lands under agriculture are much more vulnerable to soil erosion because the removal of the vegetation cover and repeated preparation by tillage exposes the surface to erosion. It directly reduces land productivity by reducing water availability, soil depth, soil organic content and essential plant nutrients. Further, soil erosion has many other secondary effects such as siltation in reservoirs, thereby reducing the generation of hydro-electricity, limiting water supplies for irrigation and impairing the quality of drinking water (Pimentel and Burgess, 2013). It has been estimated that the reservoirs of the world are losing their storage capacity at a rate of 1% per year due to siltation (Mahmood, 1987). Worldwide, soil erosion on croplands averages about 30 t ha^{-1} yr^{-1} ranging from 0.5 to 400 t ha^{-1} yr^{-1} (Pimentel et al., 1995). It has been estimated that about 10 million ha of lands are lost each year due to the intensified soil erosion under agriculture, thus reducing the croplands available (Pimentel and Burgess, 2013). At the global scale, rate of soil loss under the croplands is 10–40 times faster than the natural rates of soil replenishment (Pimentel and Burgess, 2013). This loss has been gravely noted in many areas of the developing world, especially in the humid tropics, where minimum attention is paid on land management. For an example, the average rate of soil loss due to erosion in India has been reported as 16.4 t ha^{-1} yr^{-1} (Pandey and Chaudhari, 2010). In the Sierra Region of Ecuador, about 60% of the cropland has been abandoned from agriculture because of erosion and unsuitable land management (Southgate and Whitaker, 1992). In the Central Highlands of Sri Lanka, soil loss in lands under shifting cultivation and tobacco has been reported as high as 70 t ha^{-1} yr^{-1} (Gunatilake and Vieth, 2000), which is about 100 times faster than the natural replacement rate (Hewawasam et al., 2003). Therefore, conservation of soil in the

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croplands and monitoring its success by quantifying soil loss rates are very decisive.

The Central Highlands of Sri Lanka is an economically sensitive terrain, as it is the center for generating hydropower that supplies about 40–50% of the total power consumption in the country and, yet has arable lands for seasonal crops and tea (Fig. 1). This terrain was forested until the early nineteenth century, when the land was cleared at a regional scale, to make way for coffee and tea plantations (Wickramagamage, 1998). Subsequently, with the decline of tea production, some of the abandoned lands, characterized by steep slopes were converted to seasonal crops. Moreover, due to the inadequacy of arable lands, farmers have further extended their croplands into steeply sloped areas (Erabadupitiya, 2006). These areas are presently under seasonal crops without proper land management practices (Abegunawaradana and Gunathilaka, 1992; Samarakoon, 2004). As a result of rapid land use changes in the last two centuries, soil erosion has accelerated by several orders of magnitude over the natural replenishment rates (Hewawasam et al., 2003) and it has adversely affected the hydropower generation (Hewawasam, 2010), crop yield (Ananda et al., 2001) and surface water quality (Amarasekara et al., 2009).

A considerable amount of field data on erosion from the Central Highlands of Sri Lanka has been gathered at plot scale and reported for different land use. In these studies, soil loss rates have been measured at on-site sediment traps or at field runoff plots. However, some of the rates have been predicted from the universal soil loss equation (USLE) adjusted with parameters more suitable to Sri Lankan conditions. Soil loss rates in areas of tea plantations in the Central Highlands have been reported for three different land management practices: (1) seedling plots, without any soil conservation, soil loss equals 75 t ha^{-1} yr^{-1}; (2) unprotected seedling tea lands where soil losses range between 46 t ha^{-1} yr^{-1} and 18.5 t ha^{-1} yr^{-1}; (3) managed plots, where soil loss is low at 2 t ha^{-1} yr^{-1} (El-Swaify and Krishnarajah, 1983). Hasselo and Sikurajapathy (1965) identified that soil erosion patterns are seasonal, with very high erosion during the replanting period, amounting to rates as high as 72 t ha^{-1} yr^{-1}. Manipura (1972) elaborated on the importance of having a cover crop against surface run-off during replanting. His experiments showed a very low soil loss across mulched plots of 0.8 t ha^{-1} yr^{-1} and higher values of 52 t ha^{-1} yr^{-1} for unmulched plots, both under same monsoon rain. For the lands under seasonal crops in the Central Highlands of Sri Lanka, high rates of soil erosion have been reported. Experiments that were carried out at plot scale revealed that the soil loss under tobacco, capsicum and carrot equal 70 t ha^{-1} yr^{-1}, 38 t ha^{-1} yr^{-1} and 18 t ha^{-1} yr^{-1}, respectively (Krishnarajah, 1982). Samarakoon and Abegunawaradana (1995) also reported high rates of soil loss for potato crop in steep slopes of the Central Highlands estimated at 24 t ha^{-1} yr^{-1} on average. A team of agricultural engineers and soil scientists of the Ministry of Forestry and Environment, reviewed the most accurate estimates of soil loss based on field studies and presented soil erosion rates for different land use types (Ministry of Forestry and Environment, 1995, as cited by Gunatilake and Vieth, 2000). Accordingly, the average soil loss reported for vegetable plots (referred as "market gardens") in the Central Highlands is 25 t ha^{-1} yr^{-1}. Similarly, a large number of plot studies elsewhere in the tropical regions showed high rates of soil loss under croplands since these lands are very susceptible to soil erosion after removal of natural vegetation, especially under harsh climates (Dadson et al., 2003; Correchel et al., 2006; Verbist et al., 2010). Labri'ere et al. (2015) quantitatively reviewed a large data set of soil loss measurements at the plot scale from 21 countries in the humid tropics and showed that soil erosion is very intense on steep slopes where soils have been exposed and were kept bare for various reasons. Accordingly, soil loss rates vary significantly depending on the land use type: from 0.2 t ha^{-1} yr^{-1} for well vegetated croplands with soil conservation measures to 25 t ha^{-1} yr^{-1} for croplands without proper management. The implementation of vegetation and soil related conservation practices in tropical region can reduce erosion even by up to 99%. Therefore, conservation of soil by applying suitable conservation methods and testing of their effectiveness is imperative for croplands in the humid tropics for their long-term sustainability. However the application and monitoring of soil conservation measures depend on availability of simple, rapid and robust assessment tools that can be readily employed to quantify soil erosion rate together with understanding of erosion mechanisms.

In the Central Highlands of Sri Lanka, the focus of research over the last few decades, has been on catchment scale studies, after impoundment of large hydropower reservoirs under the Accelerated Mahaweli Project, commenced in 1977. Measuring of siltation rates in reservoirs (NEDECO, 1984) and, gauging of rivers for suspended loads (NEDECO, 1984; Wallingford, 1995; Hewawasam et al., 2003; Illangasinghe and Hewawasam, 2015) have been used to calculate spatially averaged erosion rates in the contributing catchments. Whilst catchment-scale spatially-averaged erosion rate studies may be more suitable than plot-scale studies to predict the siltation rates in reservoirs, these studies cannot resolve the local effects of erosion. Sediment loads as monitored by river load gauging, may not accurately reflect erosion rates within the catchment, as it effectively averages out, and masks other processes operating at the meso- and micro-scales. To provide an example, spatially average erosion rate estimated by river load gauging in a catchment of the tropical island of Sumatra has exceeded soil loss measured in erosion plots by a factor 3–10. In this catchment, 60% of the total sediment load, is from an area of <20% of the total catchment, indicating that severe erosion is localized within the catchment ("soil erosion hot spots") (Verbist et al., 2010). Therefore, catchment-scale studies may not resolve, or identify, the sites directly affected by high rates of soil erosion, where immediate attention for conservation is needed. Thus, the main advantages of plot scale studies are the identification of erosion hot spots, providing the means to assess the impact of specific cultivation methods, determine the effects of soil-crop combinations on erosion rates and, the framework to test different conservation methods at the field scale (Correchel et al., 2006). Geochemical tools can be applied at plot scale to measure erosion rates with high accuracy. For example, radionuclides of ^{137}Cs can be used to determine erosion rates at a decennial temporal scale (Collinsa et al., 2001; Correchel et al., 2006; Foucher et al., 2014), which can be used for soil conservation and land management practices. However, these methods have a high experimental cost and are difficult to be applied frequently for a rapid assessment of soil erosion rate in the scope of a regular monitoring programme. This study focuses on the development and validation of a simple method that quantifies soil erosion at the plot scale in agricultural lands, through an experimental study in the Central Highlands of Sri Lanka (Fig. 1). The key assumption supporting this study is that fine particles on the soil surface are selectively removed by overland flow and that the armor layer is increasingly enriched in coarser soil particles. This paper documents the methodology behind this conceptual framework, including field and laboratory procedures, and then provides, an experimental study resulting in the determination of soil erosion rates. Finally, the inferred soil erosion rates are compared with rates that have reported by independent erosion assessments based on soil loss measurements, river load gauging, ^{137}Cs fallout radionuclide measurements and ^{10}Be cosmogenic nuclide measurements.