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Impact of herbicide application on soil erosion and induced carbon loss in a rubber plantation of Southwest China

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ABSTRACT

Rubber plantations are strongly increasing in Xishuangbanna, Southwest China. Herbicide applications controlling the undergrowth may increase erosion potential and carbon export by decreasing plant and litter cover. Quantitative evaluation of the erodibility of rubber systems and the impact of herbicides has not been studied. This study aimed at assessing the impact of herbicide application on soil loss and the induced carbon export in a rubber plantation. Runoff, sediment yield, and total organic carbon (TOC) content in sediments were measured under natural rainfall for one year in a 12-year old rubber plantation subjected to three different herbicide treatments: i) standard application twice per year practiced by the majority of farmers (Hs); (ii) no application to maintain a high understory plant cover (H−); and (iii) bimonthly application (adopted by some farmers) in order to largely avoid understory plant cover (H+). The infiltration rate under different treatments was measured with a rainfall simulator. Monthly measurements of fine root density using soil coring, surface cover, and understory plant cover making photography were carried out. The highest soil and TOC in sediment losses (425 g m^{-2}, 15 g C m^{-2} respectively) were observed under H+ treatment, while under H− treatment they were strongly reduced (50 g m^{-2} and 2 g C m^{-2} respectively). Compared to Hs, H+ increased soil and sediment TOC loss by 34 and 52%, while H− reduced soil and TOC loss, both by 82%. Notably, H− presented high conservation efficiency, reducing sediment yields by 86% for highly erosive rainfall events. The cover and management (*C*) factor and support practice factor (*P*) are essential components of the common Universal Soil Loss Equation (USLE) model. We combined the *C* and *P* factors into a single value (*CP*) and, for the first time, derived estimations of annual *CP* values for a rubber plantation (0.005–0.04) using our data. The dynamic change of the *CP* factor of plantations during the rainy season was quantified by relating relative soil loss to changes in understory plant cover (PC), which can be expressed as $CP = 0.04e^{-0.028PC}$ ($R^2 = 0.88$, $P < 0.0001$). Understory plant cover as affected by herbicide application was thus a key factor controlling the soil loss of established rubber systems. This suggests options to improve the soil conservation and biodiversity through reduced herbicide management.

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1. Introduction

High soil erosion threatens long-term soil fertility and consequentially sustainable land use (Battany and Grismer, 2000). Water erosion, as one of the most pervasive soil degradation processes, affects an area of approximately 1100 million hectares annually worldwide (Lal, 2008). Water erosion comprises splash effects caused by raindrops, runoff generation, and soil particle transportation and sedimentation (Mohammad and Adam, 2010). Vegetation may reduce the soil erosion rate significantly (Chen et al., 2004; Greene et al., 1994) by intercepting raindrops, with parts of the rain forming the stem flow while another portion eventually evaporates from the leaf canopy. Stem flow, which indirectly leads rain water onto the soil surface, reduces its kinetic energy for soil particle detachment and thereby the erosion potential (Greene et al., 1994; Nunes et al., 2011). Plant roots penetrate the soil and leave macro-pores that increase soil porosity and infiltration capacity, thereby decreasing surface runoff and erosion (Amezketa, 1999). Additionally, plant roots can improve soil aggregate stability by enmeshing fine particles into stable macro-aggregates using root secretions/exudates, leading to better resistance to the impact of raindrops.

Land use strongly affects runoff production and sediment yield (Mohammad and Adam, 2010). Natural vegetation especially was found to be most effective in reducing erosion (Chen et al., 2004),

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while land use change in tropical highlands in Southeast Asia greatly increased soil degradation (Valentin et al., 2008). Recently, rubber plantations have expanded by 1,000,000 ha to encompass areas that were not conventionally planted in countries such as China, Laos, and Thailand (Fox and Castella, 2013). The para rubber tree (*Hevea brasiliensis*) was introduced to Xishuangbanna, South China, during the last decades. From 1992 to 2010, the area covered by rubber plantations increased by almost 340,000 ha (a gain of 400%) (Xu et al., 2014). This large-scale land conversion from rainforests to rubber plantations resulted in biodiversity loss and environmental degradation (Li et al., 2010). In particular, most rubber in Xishuangbanna has been planted on steep slopes (more than 25°) with high erosive potential. Wu et al. (2001) reported that higher soil water repellency by increased soil compaction in rubber plantations could potentially increase runoff by a factor of three and thereby increase soil loss by a factor of 45.

Rubber plantation management (land terracing, removal of understory vegetation, etc.) may further influence the soil erosion potential of this monocrop system. Terraces can alleviate soil loss in rubber plantations (Cha et al., 2005), while poorly designed and managed terraces may be ineffective in controlling surface erosion and even contribute to land sliding (Sidle et al., 2006). Intercropping can greatly improve soil conservation and is normally adopted in young plantations (Rodrigo et al., 2005; Ulahannaan et al., 2014). Herbicide application is a common treatment to reduce understory vegetation after plantation establishment in order to facilitate access to rubber tree trunks for tapping. By eliminating protective understory plant cover and rooting systems, this management practice is most likely a key activity affecting sediment yield and runoff production in rubber plantations that has not yet been studied in this area.

The quantitative evaluation of vegetation type and management of soil erosion is an important factor considered in various soil loss prediction models. The most widely used empirical model, the Universal Soil Loss Equation (USLE) first proposed by Wischmeier and Smith (1978), introduced a cover and management (*C*) factor to calculate the impact of vegetation on soil loss compared to bare soils. This empirical model considers five major factors affecting sediment yield: rainfall (*R*), soil properties (*K*), topographic characteristics (*L*, *S*), cover and management (*C*), and support practice (*P*), where the *C* factor is the ratio of the soil loss from a vegetated area compared to the soil loss from an identical continuously tilled fallow area (Kinnell, 2010). This concept has been widely adopted in other erosion and hydrological models including empirical and physically based models like RUSLE (Revised Universal Soil Loss Equation), ANSWERS (Areal Non-point Source Watershed Environment Response Simulation), WEPP (Water Erosion Prediction Project), and SEMMED (Soil Erosion Model for Mediterranean regions) (Jong et al., 1999). Major efforts have been made to estimate the *C* value for annual crops (Grabriels et al., 2003; Schönbrodt et al., 2010; Wischmeier and Smith, 1978). However, there have been few studies on *C* value estimations for woodland systems or plantations (Özhan et al., 2005, Kitahara et al., 2000). When applied to a forest system, *C* and *P* factors were in some cases combined together as the *CP* factor. Nine subfactors of *CP* were identified by Dissmeyer and Foster (1980) to better predict erosion on forest land. Soil cover and fine roots are two subfactors that are likely to be affected by herbicide management and that further influence erosion in rubber plantations. Identifying the impact on the *CP* factor of the rubber system can help in understanding the cause and effect relationships between management practices and erosion.

Carbon loss through water erosion is another concern that can cause soil degradation and affect carbon dynamics and greenhouse gas emissions (Wang et al., 2014). Land use conversion from forests to rubber resulted in losses of soil carbon stocks of 37 Mg C ha^{-1}, which were attributed to soil disturbances during site preparation, terrace construction, and sparse vegetation cover (De Blecourt et al., 2013). Topsoil carbon stocks declined exponentially over the years since rubber plantations were converted from forest and then reached a steady state after around 20 years (De Blecourt et al., 2013). However, the lack of data on carbon loss through erosion makes it difficult to determine whether soil carbon losses in established rubber plantations are mainly caused by erosion or soil organic matter decomposition and how management influences the soil carbon stock. Häring et al. (2013) demonstrated that uncertainties in the soil erosion rate were considered to have the greatest impact on the misrepresentation of soil organic carbon (SOC) dynamics on steep slopes in tropical ecosystems.

The absence of existing estimations of a *CP* value for rubber systems makes it difficult to apply models like USLE or RUSLE for soil loss in rubber plantations and to further evaluate their impact on ecosystem functions. Studying the impact of understory vegetation control (herbicide application) on soil as well as carbon loss and estimating its contribution to anti-erosive effectiveness in rubber plantations can justify effective forest management options and improve soil loss model predictions in plantation (woodland) systems. Therefore, we conducted a natural runoff experiment with different herbicide treatments in a 12-year old rubber plantation in 2014. Thus, the main objectives of this study were 1) to evaluate soil erosion and carbon loss under different herbicide application frequencies; 2) to identify the major factors (understory plant cover, surface cover, and fine root density) that are affected by herbicide treatments and therefore influence soil erosion processes; and 3) to estimate the combined factor (*CP*) of cover and management (*C*) and support practice (*P*) in the USLE model for rubber plantations.

2. Materials and methods

2.1. Study site

The study site (22°17′ N, 100°65′ W, 764 m asl) is located in the Nabanhe River Watershed National Nature Reserve (NRWNNR) in Xishuangbanna, Yunnan Province, Southwest China. The elevation decreases from northwest to southeast with the highest elevation of 2304 m and the lowest point at 539 m. The annual precipitation is 1100–1600 mm and the mean annual temperature is 18–22 °C. The region has a typical monsoon climate characterized by a distinct rainy season from May to October and a dry season from November to April. Sixty to 90% of the precipitation is distributed during the rainy season. The soil in the study site is a silt clay loam, Acrisol (Table 1). High contents of silt and low permeability have made the soil more erodible, while a relatively high organic matter content can alleviate the erodibility.

Rubber has been introduced to NRWNNR since the 1970s and expanded to cover 28.6 km^2 in 2013. Over 85% of established plantations already have a closed canopy and a rotation time that is generally about 25 years. Hence, a representative established rubber plantation of 12 years (12Y) with a canopy radius of 2.6 m was selected for the current study. The tree density in the selected plantation was 600 trees per hectare, which is within the range of the usual density of 450–600 trees per hectare in the area (Yang, 2011). Rubber trees are planted in rows on terraces located on a 29° slope with a tree space of 1–2 m and distance between two adjacent planting terraces of 5–5.5 m. The terraces were built 12 years ago before the tree plantation. The most common practice among local farmers is the application of herbicide twice a year in the mid-rainy season and mid-dry season, respectively, using 10 kg ha^{-1} of 10% glyphosate.

2.2. Experimental layout

In order to assess the impact of different management options on runoff and erosion, three herbicide treatments were implemented in 2014: (i) herbicide application practiced by the majority of farmers, namely two times per year in mid-February 2014 and late July 2014, respectively, using 10 kg ha^{-1} of 10% glyphosate (Hs); (ii) no herbicide application to maintain a high understory plant cover (H−); and

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