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Modelling weed management strategies to control erosion in rubber plantations

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ABSTRACT

The role of weeds in soil conservation in agroforestry systems has been largely ignored. We used the Land Use Change Impact Assessment (LUCIA) model to simulate the effects of weed management on erosion in rubber plantations (*Hevea brasiliensis* Muell. Arg). In order to quantify the impact of a dynamic, spatially explicit multi-layer plantation structure on erosion processes in agroforestry systems, we updated LUCIA's erosion module. Its new version simulates soil detachment due to rainfall and runoff, considering the separate effects of the tree canopy and surface cover on soil erosion. The updated LUCIA model was calibrated and validated based on an established rubber plantation experiment in Xishuangbanna, Southwest China, to evaluate the impact of different weeding strategies on soil loss. The model successfully represented the impact of the dynamic multi-layer structure on erosion and was able to predict well the effects of weed management on soil loss and runoff at the test site over 1 year, with a modelling efficiency (*EF*) of 0.5–0.96 and R^2 of 0.64–0.92. Subsequently, we validated the ability of the model to simulate surface cover changes under rubber plantations of different age (up to 40 years). Simulation outputs for 4-, 12- and 18-year-old rubber plantations revealed satisfying to good results. However, the predicted change in surface cover for old rubber plantations (25- and 36-year) failed to meet the field trends. The model predicted the greatest erosion in the year when the rubber canopy started to close. During this period, weed growth was limited by light, while litter input from rubber was insufficient to provide good soil cover. Four weeding strategies ("clean-weeding", "twice-weeding", "once-weeding" and "no-weeding") were designed for scenario simulations. Based on the results of 20-year runs, we concluded that "once-weeding" and "no-weeding" both efficiently minimized soil loss during one rotation length. A high degree of surface and weed cover (over 95% and 60%) under "no-weeding" makes this management strategy with dense undergrowth hardly acceptable by local farmers due to reduced tree accessibility for tapping and increased potential danger through poisonous caterpillars. "Once-weeding", on the other hand, controlled overgrowth of understory vegetation by keeping weed cover below 50%. We therefore suggest "once-weeding" as an improved herbicide management strategy in rubber plantations, to meet ecological system service maintenance and to facilitate adoption in practice.

1. Introduction

Soil erosion is exacerbated by rapid agricultural expansion in steep montane regions of Southeastern Asia, and threatens soil health and crop yields. The effects of erosion and conservation in traditional agricultural land uses, such as maize growing, have been well studied in this region (Pansak et al., 2010; Quang et al., 2014; Tuan et al., 2014). On the contrary, efficient conservation measures remain uncertain for more recently evolved land uses, especially in growth of perennial crops such as rubber plantations. Rubber plantations have rapidly expanded in Southwest China in the past decades. Although this land use type is mostly considered as forest cover by Chinese decision-makers (Zhai et al., 2018), its monoculture cultivation has resulted in biodiversity loss and environmental degradation (Li et al., 2010; Thellmann et al.,

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2017). Compared to that in rainforests, total soil loss per year in rubber plantations has been estimated to increase by 45 times (Wu et al., 2001). In order to reduce potential soil losses, several conservation measures such as terracing and intercropping have been proposed and tested in short-term field experiments (Cha et al., 2005; Sidle et al., 2006). Particularly, minimization of weeding has been proved to be highly efficient in reducing soil loss in established rubber plantations (Liu et al., 2016a) with little effects on latex yields (Abraham and Joseph, 2016).

However, the effects of longer-term weeding conservation remain uncertain due to a lack of long-term experimental data. Rubber is a perennial crop with a rotation length of 20–40 years, so that soil erosion as well as ground cover changes may vary during this time (Liu et al., 2018). Long-term tests of the potential impact and limitations of different weeding strategies are necessary but expensive and laborious. Crop and soil simulation models can provide an efficient tool and reduce associated cost (Matthews et al., 2001). Since the formulation of the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), large efforts have been undertaken to develop advanced soil erosion assessment tools. Process-based models were developed to offset the conceptual limitations of simple empirical models such as USLE, with GUEST (Griffith University Soil Erosion Template; Misra and Rose, 1996), LISEM (Limburg Soil Erosion Model; De Roo and Wesseling, 1996) and WEPP (Water Erosion Prediction Project; Nearing et al., 1989) as prominent examples. These erosion models have proven their validity in plot-based studies with good hydrological (e.g. rainfall, runoff rate) and plant (e.g. ground cover, leaf area index) input (Barros et al., 2014; Cao et al., 2015; Fernandes et al., 2017; Poleto et al., 2014). However, simplification of dynamic plant growth and development routines hampers application of the above-mentioned erosion models for direct simulation of the impact of management on soil conservation. In particular, weed management simulation needs to present farmers' acceptance of weed growth, as well as the relationships between weed growth, tree development and erosion processes. The latter should represent both processes of plant competition for light and resources, and soil conservation. The Land Use Change Impact Assessment (LUCIA) model is a tool for both plot-level management and spatially explicit watershed-level simulations. Its plant growth module is based on the WOrld FOod STudies (WOFOST, Supit, 2003) approach and simulates tree-weed-soil interactions in plantation systems; while infiltration and runoff simulation is built on KINEROS 2 (Woolhiser et al., 1990). LUCIA has been successfully tested in tropical mountainous areas of Thailand and Vietnam (Lippe et al., 2014; Marohn et al., 2013a; Marohn et al., 2013b). LUCIA uses the Rose concept of erosion (Hairsine and Rose, 1992) and considers runoff entrainment-driven soil erosion dominant over rainfall-induced soil detachment (Lippe et al., 2014; Marohn et al., 2013a; Noordwijk et al., 2011). Splash erosion, hereafter called "rainfall detachment", has not yet been considered. In a plantation ecosystem such as a rubber plantation, the tree canopy intercepts raindrops and reduces rainfall amount and intensity, and therefore reduces the erosive power of rain events. On the other hand, accumulation of raindrops increases the kinetic energy of throughfall with rising canopy height. Therefore, the tree canopy should not be simply considered as a component of surface cover contributing only to soil protection. Field studies have proven that rainfall detachment is an important contributor to the total amount of soil detached in plantations (Ghahramani et al., 2011). The average potential splash erosion rate has been observed to be 2.1 times higher in rubber plantations than in open areas (Liu et al., 2015). Thus, it is important to include rainfall detachment in erosion process simulations.

This study aims to expand the runoff entrainment-driven (stream power) erosion approach with simulation of a multi-layer plantation structure by incorporating rainfall detachment into the erosion module of the LUCIA model. We then i) tested whether the updated LUCIA model could simulate erosion in a dynamic multi-layer system, specifically in rubber plantations, ii) tested how weed management, in particular the frequency of herbicide application, affects erosion during one rotation cycle (20–40 years) of rubber and iii) suggest an improved weeding strategy for rubber plantations, based on the model results, to efficiently control erosion.

2. Materials and methods

2.1. Model description

We simulated biophysical processes in rubber plantations at the plot scale using LUCIA model, which describes interactions between trees, weeds and soil in plant growth, water balance, erosion and soil organic matter modules. This study focused on including splash simulation into the erosion module. Where necessary, inputs provided by other modules are explained, while related equations are detailed in supplementary Table S1.

The erosion simulation in LUCIA follows the basic assumption that runoff-driven soil erosion, hereafter called 'runoff entrainment' (Hairsine and Rose, 1992), dominates over rainfall detachment. Runoff is simulated by water balance module as the remainder of daily rainfall minus interception and the water that infiltrates unsaturated soil (Supplementary, table S1). Runoff entrainment (c_{en} in kg m^{-3}) is calculated based on the maximum sediment concentration at transport capacity (c_{max} in kg m^{-3}), soil erodibility (β in the range of (0,1), dimensionless) to account for the resistance of flow detachment by the cohesive soil matrix, and cover efficiency (α, dimensionless) to exponentially reduce soil detachment with increasing surface cover (SF in the range of (0,1), dimensionless):

$$c_{en} = c_{\max}{}^{\beta} \bullet \exp(-\alpha \bullet SF) \tag{1}$$

where $c_{\max}$ is the transport capacity, the theoretical maximum of sediment concentration (kg m^{-3}) limited by stream power, runoff flow depth and average sediment settling velocities (Misra and Rose, 1996). The coefficient β ($0 < \beta \leq 1$) to account for the resistance of flow entrainment by the cohesive soil matrix (Misra and Rose, 1996). The influence of surface cover in reducing the force of sediment entrainment is accounted for the second part of Eq. (1) (Rose, 1993); more details can be found in the work of Lippe et al. (2014).

Surface cover (SF, dimensionless) is simulated as a function of dynamic leaf area index of rubber ($LAIRubber$, dimensionless), leaf area index of weed ($LAIWeed$, dimensionless), Lit_{eff} (ha Mg^{-1}) the effectiveness of plant litter covering the soil surface, and Lit_{surf} (Mg ha^{-1}) the surface litter amount (Marohn et al., 2013a)

$$SF = (1 - exp^{-\delta \bullet LAIRubber}) + [1 - \exp(-0.7 \bullet LAIWeed)] + (Lit_{eff} \bullet Lit_{surf}) \tag{2}$$

Three parts of Eq. (2) represent canopy cover (Gash et al., 1995), weed cover and litter cover (Marohn et al., 2013a), respectively. δ (dimensionless) is the coefficient of leaf distribution and light inclination, ranging from 0.6 to 0.8 for trees. $LAIRubber$ and $LAIWeed$ are the simulated rubber leaf area index and weed leaf area index by plant module (Supplementary, Table S1). Lit_{eff} is an input from plant module, and Lit_{surf} is simulated in the soil organic matter module of LUCIA (Marohn et al., 2013b).

2.2. LUCIA update: Erosion simulation under multi-layer plant cover

In order to simulate the influence of multi-layer plant cover on erosion, we firstly redefined surface cover as litter and weed cover, excluding the tree canopy cover. Therefore, surface cover calculation changed from eq. (2) to:

$$SF = [1 - \exp(-0.7 \bullet LAIWeed)] + (Lit_{eff} \bullet Lit_{surf}) \tag{3}$$

The influence of the tree canopy on soil erosion was simulated by calculating amount and intensity of free rainfall and canopy