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Soil aggregate breakdown and carbon release along a chronosequence of recovering landslide scars in a subtropical watershed

J. Schomakers[a], H. Mayer[b], J.Y. Lee[c], T.Y. Lee[d], S.H. Jien[e], A. Mentler[a], T. Hein[f,i], J.C. Huang[c], Z.Y. Hseu[g], L.W. Cheng[h], C.K. Yu[h], F. Zehetner[a,*]

[a] Department of Forest and Soil Sciences, Institute of Soil Research, University of Natural Resources and Life Sciences, Vienna, Austria
[b] Department of Material Sciences and Process Engineering, Institute of Physics and Material Sciences, University of Natural Resources and Life Sciences, Vienna, Austria
[c] Department of Geography, National Taiwan University, Taipei, Taiwan
[d] Department of Geography, National Taiwan Normal University, Taipei, Taiwan
[e] Department of Soil and Water Conservation, National Pingtung University of Science and Technology, Neipu, Taiwan
[f] Department of Water – Atmosphere - Environment, Institute of Hydrobiology and Aquatic Ecosystem Management, University of Natural Resources and Life Sciences, Vienna, Austria
[g] Department of Agricultural Chemistry, National Taiwan University, Taipei, Taiwan
[h] Department of Atmospheric Sciences, National Taiwan University, Taipei, Taiwan
[i] WasserCluster Lunz, Lunz am See, Austria

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ABSTRACT

Typhoons episodically trigger landslides and export large quantities of particulate and dissolved organic carbon (POC and DOC) to the ocean from high-standing islands of the western North Pacific. On landslide scars, new soils are forming and organic carbon (OC) re-accumulates; however, these young soils may remain vulnerable to recurrent erosion. Here, we examined soil aggregate breakdown and concomitant release of OC from soils on recovering landslide scars in Taiwan. We calculated the kinetic energies of falling raindrops during two past typhoon events that hit Taiwan, i.e. Morakot (2009) and Fanapi (2010), at 137 kJ m^{-2} and 21 kJ m^{-2}, respectively. Soils from a chronosequence of recovering landslide scars (6 to 41 yrs) in the Central Mountain Range of Taiwan were subjected to ultrasonic vibrations simulating those typhoon energies. The younger soils of the chronosequence (< 12 yrs) displayed little aggregate stability. Our results show that it may take several decades before soil aggregate stability significantly improves to withstand energy inputs corresponding to more frequent, moderate typhoons such as Fanapi; however, even the soils from an undisturbed reference site showed almost complete aggregate breakdown when subjected to the simulated energy of a rare but severe typhoon such as Morakot. With increasing recovery age and vegetation change towards forest cover, OC was increasingly accumulated in the soil aggregates and efficiently protected against disruption by lower simulated typhoon energy; however, upon increased aggregate breakdown induced by high simulated typhoon energy, significantly more DOC and POC was released. In light of increasing frequency of typhoon events with global climate change, active reforestation can stabilize soil structure and thus enhance protection against recurrent erosion of the newly forming soils.

1. Introduction

The expected future increases in frequency and magnitude of typhoon events in East and South East Asia (Liang et al., 2017; Mei and Xie, 2016; Tu et al., 2009) will likely increase soil erosion and the release of terrestrial carbon (C), and enhance its land-to-ocean transfer through small mountainous rivers (Hilton, 2017; Lee et al., 2017). Typhoons are one of the most extreme rainstorms in the western North Pacific, and Taiwan, located between the Philippine Sea plate and the Eurasian continent, is characterized by a steep topography. The average typhoon invasion rate in Taiwan was 3.3 yr^{-1} (1970–1999), but increased to 5.7 yr^{-1} (2000–2006), thus almost doubling (Tu et al., 2009). This has raised the potential threat of magnified soil erosion, which causes intensified carbon cycling (Jacinthe et al., 2004). Intensive precipitation during typhoons may trigger mass wasting processes such as landslides on forested hillslopes, providing a significant new supply of biomass and soil organic carbon (SOC) to stream channels (Hilton, 2017; Lee et al., 2015; West et al., 2011). The abundant

* Corresponding author.
E-mail address: franz.zehetner@boku.ac.at (F. Zehetner).

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supply and shorter residence time of eroded material in watersheds in Oceania results in disproportionally high discharge of terrestrial material, including particulate (Hilton et al., 2011; Kao et al., 2005; Lyons et al., 2002) and dissolved OC (Carey et al., 2005; Lee et al., 2017; Lloret et al., 2013). This C transfer is globally significant (Lyons et al., 2002; Schlünz and Schneider, 2000b) and can result in drawdown of atmospheric carbon dioxide (CO_2) if the eroded particulate OC escapes degradation during river transfer and sedimentary deposition (Hilton, 2017). The Oceanic region shares similar climatic and geomorphic features with Taiwan (Milliman and Farnsworth, 2011). Results from the island of Taiwan are thus of wider importance.

Typhoon-induced erosion drives the export of POC and DOC from the terrestrial biosphere and its delivery to rivers (Hilton, 2017). This can lead to higher OC concentrations in sediments than in the source bulk soil (Hu and Kuhn, 2016; Wei et al., 2017), due to preferential transport and deposition during erosion events (Doetterl et al., 2016). During translocation by erosion and runoff, soil aggregates, which protect OC, may get broken up by raindrop impact and mechanical slaking, exposing SOC to mineralization (Wei et al., 2014). In a sequence of rainfall events with repeated erosion, transport and deposition, exposure and mineralization of eroded SOC are also likely to be more pronounced (Kuhn and Bryan, 2004).

The breakdown of macro-aggregates affects the magnitude of C mineralization during soil transport and depends predominately on the kinetic energy of raindrop impact (Doetterl et al., 2016). Hence, knowledge of the relationship between rainfall intensity and kinetic energy and its variations in time and space is important for erosion prediction (Van Dijk et al., 2002). Soil erosion in the tropics is concentrated spatially (over bare soils) and temporally (before vegetation is fully established), and existing vegetation is essential in mitigating soil erosion (Labrière et al., 2015). Aggregate stability can be a key indicator of the resistance of tropical soils to erosion (Bryan et al., 1989; Chappell et al., 1999) and a key factor controlling sediment sources within tropical forest terrain (de Roo, 1993).

This study investigated the effect of simulated typhoon rainfall energies on soil aggregate destruction. Soils from a chronosequence of recovering landslide scars were subjected to defined ultrasonic energy treatments in order to test (1) how fast soil structure gets stabilized and (2) how efficiently OC is protected within soil aggregates on recovering landslide scars.

2. Materials and methods

2.1. Study area and site selection

The study area is located in Tsengwen watershed, central-south Taiwan, where erosion and landslides are recurrent (Fig. 1). Tsengwen watershed has a mean annual precipitation of 2800 mm, with 90% of its rainfall occurring in the wet season from May to September (Water Resource Agency, 2008). The mean annual temperature is 18.3–22.5 °C. According to the 2012 land-use survey (NLSC, Taiwan), 77% of the catchment area was forest, while other land-use categories included betel nut plantation (4.3%), bare land (3.6%), grassland (3%), tea plantation (1.5%), fruit trees (1%), and dry farming (1.1%). The lithology is homogenous, consisting of sandstone and shale (Chen et al., 2013) with a rock strength of 6.2–33.8 MPa (Western Foothills). The basin-average erosion rate is 4.8 mm yr^{-1} (Dadson et al., 2003) and the average slope is ~50% for the zero-order channels; elevations range from 108 m above sea level (a.s.l.) near the Tsengwen dam to 2610 m a.s.l. at the upstream boundary, which is Mount Ali. Favored by torrential rainfall and steep topography, the average landslide erosion rate in Tsengwen watershed is 13.15 ± 1.47 mm yr^{-1} (Chen et al., 2013), which affected an area of 2.68 ± 0.7 $km^2 yr^{-1}$ between 2005 and 2013 (unpublished data, Taiwan Forestry Bureau, Council of Agriculture, Executive Yuan).

For this study, we applied a chronosequence approach to quantify C recovery on landslide scars (Schomakers et al., 2017). We used landslide mapping from remote sensing (aerial photographs before 2000 and satellite images thereafter) to identify landslide scars of different recovery ages, that were comparable with respect to their parent material, slope and climate zones, and that showed minimal human management. The sites were investigated in the field before making a final selection.

2.2. Description of the sites and soil sampling

We identified 4 landslide scars ranging in age from 6 to 41 yr post-disturbance (Table 1 and Fig. 1). Additionally, we selected a reference site adjacent to the oldest landslide scar, for which the aerial photos did not show any disturbance in the past 55 yrs and the oldest trees had an age of > 100 yrs based on growth parameters. The younger sites (6- and 11-yr-old) were overgrown predominantly by *Miscanthus* (*M.*) *floridulus* which is an herbaceous perennial originating from East Asia and a commonly found pioneer plant on infertile collapsed lands in Taiwan (Chou et al., 2009). The older sites were under bamboo (*Bambusoideae*), i.e. *Phyllostachys* (*P.*) *makinoi* (26-yr-old site) and *P. pubescens* (41-yr-old site) were the respective dominant vegetation. The reference site was a *Cryptomeria* (*C.*) *japonica* stand. The younger *M. floridulus* site (6 yrs old) accumulated 2.9 ± 0.6 Mg C ha^{-1} in the soil, reflecting the limited C input by its sparse vegetative cover. Soil OC accumulation strongly increased after a dense vegetative cover had established, reaching 17.3 ± 1.7 Mg ha^{-1} at the 11-yr-old site. After bamboo invasion, SOC stocks continued to increase, reaching 45.8 ± 8.5 Mg C ha^{-1} after 26 yrs and 75.6 ± 5.0 Mg ha^{-1} after 41 yr post-landslide disturbance; however, the SOC stocks of the reference site (117.9 ± 18.1 Mg C ha^{-1}) had not been reached, then (Schomakers et al., 2017). The sites ranged in slope from 19 to 32° (mean ± SE = 29 ± 3°), in size from 1730 to 50,440 m^2 (mean ± SE = 17,677 ± 9826 m^2) and in elevation from 990 to 1560 m a.s.l. (mean ± SE = 1288 ± 103 m a.s.l.). The samples were collected between December 2014 and March 2015. Topsoil samples (0–10 cm) were taken from 5 randomly selected subsites on the former scarp areas of the 4 landslide scars and on the reference site (Table 1). Detailed information about the sites, the selection process and sampling design, including photographs, can be found in (Schomakers et al., 2017).

2.3. Simulated typhoon events

We studied two past typhoon events, Fanapi and Morakot (s. Supplementary materials, Table A1), which differed in magnitude and return frequency. Morakot was a category 2 hurricane on the Saffir-Simpson Hurricane Scale, which hit Taiwan in August 2009 with winds of approx. 150 km h^{-1}. When it made landfall, its translation speed slowed from 20 km h^{-1} to 10 km h^{-1} and it continued to move on at about 5 km h^{-1} (Chien and Kuo, 2011). It brought record-breaking torrential rainfall to southern Taiwan, about 3000 mm in four days. Typhoon Morakot produced a large debris volume from landslides (49.86 ± 6.36 Mm^3) in Tsengwen watershed accounting for 88% of the total landslide volume in the watershed (Chen et al., 2013).

Fanapi was the first typhoon to hit Taiwan after Morakot. Fanapi was also a category 2 hurricane on the Saffir-Simpson Hurricane Scale with sustained winds of 160 km per hour (Central Weather Bureau) when it made landfall on Taiwan in September 2010. Fanapi approached the Eastern city of Hualien at a speed of about 22 km h^{-1} but slowed to 14 km h^{-1} during landfall (Wang et al., 2013); it had a maximum 2-day accumulated rainfall of 1127 mm (Lin et al., 2014).

We calculated the total kinetic energies of falling raindrops during these two typhoon events using rainfall and wind speed data (s. Supplementary materials) to be 134 kJ m^{-2} for typhoon Morakot and 21 kJ m^{-2} for Fanapi. To simulate these energy inputs within a laboratory setting, we used a custom-built ultrasonic fatigue testing apparatus capable of deploying very low energies with high accuracy