Higher runoff and soil detachment in rubber tree plantations compared to annual cultivation is mitigated by ground cover in steep mountainous Thailand

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Abstract

Due to high rainfall erosivity and rapid land-use changes, South-East Asia is one of the hot spots of soil degradation worldwide. In recent decades, several studies showed that the expansion of rubber tree (RT) plantations into previously forested areas has caused a major increase in soil erosion. However, the effects of cropland conversion to RT plantations on surface runoff and soil detachment are still unclear. Here we show that mature RT plantations considerably increase runoff and soil detachment compared to annual crops or young RT plantations with intercrop, mostly due to the absence of understorey.

Monitoring 1 m^2 microplots over four years in mountainous Northern Thailand, we found that runoff and detachment increased with time since the onset of the rainy season and with rainfall height, but more so in mature RT plantations than in young RT plantations and

maize. This led to much higher annual soil detachment in mature RT plantations (5.7 kg/m^2 on average) than in maize and young RT plantations with intercrop (0.36 kg/m^2). We identified two main factors explaining this difference: first, rubber tree leaf litter, although abundant, seemed ineffective in reducing runoff at the end of the rainy season. Secondly, the cover by low-growing plants in mature rubber tree plantation was usually sparse and provided little protection. In particular we showed that increasing the cover by low-growing plants from quasi-null cover to >31 % cover decreased runoff coefficient by 32 %.

Our results demonstrate that afforestation by RT, at least under current management practices and on steep slopes, is overall detrimental to soil conservation but that its effects could be mitigated by the adoption of less intense weeding practices.

1. Introduction

In 2012, the UN Rio+20 conference on sustainable development acknowledged the importance of soil protection and sustainable land management (United Nations, 2012). Following this recognition, the Sustainable Development Goals (SDG) pledged to "protect, restore and promote sustainable use of terrestrial ecosystems [...] and halt and reverse land degradation and halt biodiversity loss" (SDG 15). Maintaining soil functionality and resilience is a major element of several sustainable development global challenges: food and water security, climate change mitigation, ecosystem service provision, biodiversity protection, and energy sustainability (Koch *et al.*, 2013; McBratney, Field & Koch, 2014).

Southeast Asia is doubly exposed to land degradation, due to extreme meteorological conditions and to rapid land-use changes (Van Lynden & Oldeman, 1997; Borrelli *et al.*, 2017; Panagos *et al.*, 2017). Oldeman (1991) classified all South-East Asia as having medium to high land degradation rates due to water erosion, especially due to adverse meteorological conditions. For example, the Global Rainfall Erosivity Database classifies the area as one of the regions with the highest rainfall erosivity (> 7 400 MJ/ha/*year*, Panagos *et al.* (2017)), and some models predict that climate change will cause a continued increase in rainfall erosivity (Plangoen & Udmale, 2017). Besides, in 2012, the GLASOD (Global Assessment of Human-Induced Soil Degradation, Oldeman *et al.* (1991)) estimated that 18% of Asian lands had been degraded by humans (ISRIC, 2012). More recently, Borrelli *et al.* (2017) predicted a 5% yearly increase of soil erosion rates in most of South East Asia due to very high rates of land-use change. In the area, deforestation (among the highest rates in the world, Zhao *et al.* 2006; Sodhi *et al.*, 2010) and the intensification of agriculture exacerbated environmental degradation, especially in mountainous areas with steep slopes. In the uplands of Northern Thailand, where subsistence agriculture was previously dominant, government incentives started in the 1970s to encourage the transition to more intensive and market-oriented agriculture (Fox & Vogler, 2005). The intensification and the expansion of cash crops into previously forested areas led to intense environmental degradation (Wangpakapattanawong, Tiansawat & Sharp, 2016), increasing surface runoff and sedimentation (Mohammad & Adam, 2010) as well as soil organic carbon losses (Häring *et al*. 2014). Maize and cassava cultivation systems were found to be particularly prone to erosion (Valentin *et al.*, 2008). Thus, more recently, national and international organisations and programmes such as UNCCD and REDD+ encouraged the replacement of annual cash crops by perennial cash crops, such as teak or rubber tree (RT). The objective was to increase farmers' income and to expand tree cover in mountainous areas. The replanting of trees in degraded areas was expected to restore favourable soil conditions and water resources. Yet the effect of perennial monoculture expansion is far from consensual. While natural forest regrowth decreases overland flow and soil erosion, the replacement of annual crops by teak plantations in Laos led to a sharp increase of soil detachment and overland flow (Lacombe *et al.*, 2016; Ribolzi *et al.*, 2017; Patin *et al.*, 2018). Other ecosystem services, such as carbon storage or support for biodiversity are also lower in tree plantations compared to natural forests (Hall *et al.*, 2012). Most studies investigating the impacts of RT plantations on soil compared the plantations to forests or other tree plantations (Noguchi *et al.*, 2003; Li *et al.*, 2012; Liu *et al.*, 2015; Nurulita *et al.*, 2016). Yet, many plantations are planted on previously arable lands (Holt *et al.*, 2016): an adequate estimation of RT impact on soil erosivity should thus include annual as well as perennial crops.

Erosion processes must be measured and analysed at different scales. At the largest scale, variations in rivers flows, sediment loads and sediment redeposition can provide information about regional erosion processes. At the catchment scale, processes include water partitioning into overland and underground flow; the detachment and redeposition of sediments downslope; and runoff connectivity and redistribution by topographical features such as gullies or terraces. The catchment scale is particularly appropriate for tackling long-term issues, for instance regarding the impacts of land-use changes on erosion processes (Valentin *et al.*, 2008).

In this four-year study located in Northern Thailand, we investigated the combined effects of rainfall, soil surface conditions, ground cover and land use (maize, young RT plantations with intercrop, and mature RT plantations) on surface runoff and soil detachment. We used 1 m^2 erosion microplots (Janeau *et al.*, 2003) which is a relevant scale for investigating very local, fine-scale processes of soil particle detachment and water infiltration (e.g. Lacombe *et al.,* 2018) and their relation to local soil surface characteristics. It provides key information about the erosion potential of a particular field or land use. We characterised soil surface by quantifying the proportions of crusts, free gravels and aggregates as well as soil cover by weeds and crops (Casenave & Valentin, 1992). The dynamics of soil cover by low-growing plants were quantified using weekly standardised pictures. We hypothesised that the main factors affecting runoff and detachment would be the presence of a high canopy associated with discontinuous ground cover; and thus that mature RT plantations (high trees and sparse understorey) would cause higher runoff and detachment than young RT plantations (with intercrop) and maize, unless ground cover by living plants was high. We aimed (i) to quantify runoff and soil detachment on an annual and monthly basis (2015 experiment) in the different land uses; (ii) to quantify the different runoff and soil detachment responses of the different land uses to rainfall (2016 experiment) and (iii) to quantify the effect of ground cover by low-growing plants on runoff in mature RT plantations (2017-2018 experiment).

2. Material and methods

2.1. Study sites

Study sites were located in Huai Lang, Chiang Rai province, northern Thailand (100◦27’E, 20◦00’N). Soils belonged to Alfisols with clay to clay-loam texture. A detailed soil description is provided in Table S1. The local climate is typical of tropical mountainous regions. It is characterised by the succession of a dry season (December to April) and a rainy season (May to November), which accounts for most of the annual rainfall. The meteorological station installed for the study showed that total annual rainfall was approximately 1 600 mm/year with a high inter-annual variability of 200 mm/year. Mean annual temperature was 24.2 °C with a low inter-annual variability of 0.4 °C but a high amplitude between maximum and minimum daily values, 43.5 °C and 4.8 °C respectively. The total annual potential evapotranspiration was approximately 900 mm with an inter-annual variability of 30 mm. All studied plots were deforested more than 20 years ago. In 2000, they were all already intensely cultivated with open-field crops and the first RT plantations were planted in 2003.

2.2. Location of erosion microplots

In March 2015, microplots were installed in a maize field (M), a young rubber tree plantation with maize intercrop (YR) and a mature RT plantation either within the RT rows (OR_s, where canopy is usually dense and rainfall interception is high) or between the rows (OR_i, with usually sparser canopy and lower interception). The owner of this mature plantation reported no herbicide application. Three replicates were installed for each situation. M and YR were located on different soil types than OR (Table 1, Table S1). To control for this potential bias, in 2016, during the dry season, the microplots were moved to fields with similar land uses and the soil types were switched compared to 2015. These new locations were also located closer to the automatic meteorological station presented hereafter, allowing the use of high-resolution rainfall kinetic energy data provided by the station. The baseline weed management in this new plantation was two applications of glyphosate each year. In 2017 and 2018, we redistributed the microplots in the two RT plantations studied in 2015 (OR_1) and 2016 (OR_2), thus in both soil types. All microplots were located between tree rows. In each plantation, half the microplots were treated with herbicides twice a year ($OR_{1,h}$ and $OR_{2,h}$), while herbicides were excluded from the other half ($OR_{1,nh}$ and $OR_{2,nh}$). The effect of the treatment was not investigated *per se* but rather through its effect on weeds, and more generally on cover by low-growing plants.

At the start of the experiment, all young RT were approximately 4 years old and mature trees approximately 13 years old. Information on RT girth and plantation management is provided in Table 1.

Table 1 Plot characteristics in maize fields (M), young RT plantations with intercrop (YR), and mature RT plantations inter (OR_i) and within (OR_s) tree rows. Soil belonged to two soil series: Moklek (Ml) and Wang Saphung (Ws). Soil series and textures were obtained from Jumpa (2012). Gly = glyphosate, Gra = gramoxone, Atr = Atrazine. Tree girth was averaged over at least 25 trees, numbers preceded by "~" indicate too few measurements to provide a very precise estimation.

Year	Land use	Soil series	USDA soil texture	Tree girth (cm)	Tree planting grid (m)	Baseline herbicide application
2015	M	Ml	Clay	/	/	Gly (April), Gra (May)
	YR	Ml	Clay	~ 20	3 x 6.5	Gly (April)
	OR_i	Ws	Clay	48.9 +/- 6.1	3.5 x 7	None
	OR_s	Ws	Clay		3.5 x 7	None
2016	M	Ws	Loam	/	/	Gly + Atr (May), Gra (July)
	YR	Ws	Clay-loam to loam	20.0 +/- 5.2	3 x 6.5	Gly (April)
	OR_i	Ml	Clay to clay-loam	~ 54	3.5 x 7	Gly (July, October)
	OR_s	Ml	Clay to clay-loam		3.5 x 7	Gly (July, October)
2017-2018	OR_1	Ws	Clay	56.1 +/- 5.8	3.5 x 7	None*
	OR_2	Ml	Clay to clay-loam	58.8 +/- 10.4	3.5 x 7	Gly* (July, October)

* Baseline application. It was modified in half the plots in 2017 and 2018, resulting in half the plots receiving no herbicides and the other

2.3. Meteorological monitoring

An automatic weather station (Campbell BWS200) has been installed since March 2015 in the middle of a small flat grassland located at an elevation of 535 m AMSL. Meteorological parameters were measured on a one-minute basis: temperature and air relative humidity with CS215 Sensor; and rainfall with a tipping bucket rain gauge adjusted to tip once for each 0.2 mm of rain (Campbell ARG100).

The starting and ending time of an individual rain event was determined by a delay of at least 20 min between two bucket tips. For each rain event, we calculated the EI_{30} and R indices established by Renard *et al*. (1997) to describe rainfall aggressiveness, as established within the Revised Universal Soil Loss Equation (Table S2). We also used two manual cumulative rain gauges located in open areas close to M and YR fields (for the 2015 experiment) and to OR_1 (2015 and 2017-2018 experiments).

2.4. Runoff and soil detachment monitoring

Erosion microplots were 1 m^2 metallic frames, driven into the soil to a 10 cm depth to avoid any influence of hypodermic lateral flow. They have been widely used in studies of soil detachment in South-East Asia (Janeau *et al.*, 2003; Pierret *et al.*, 2007; Podwojewski *et al.*, 2008; Patin *et al.*, 2018). Their installation was realised carefully to avoid any disturbance of the soil surface into the frame or preferential infiltration along the sides of the frame. This allowed us to start monitoring just after installation, from mid-May 2015 onwards.

65 L buckets, located downward each microplot, allowed to collect the part of the rainfall which runs over the soil surface (overland flow), as well as the transported soil particles detached by splash erosion or by the velocity of the overland flow. The total volume of the overland flow was calculated from the measurement of water height in the collecting bucket. The concentration of soil particles was measured on a 300 mL aliquot, which was filtered and dry-weighted at the Land Development Department laboratory in Chiang Mai, Thailand. The maximum frequency of overland flow sampling was once a day. The events occurring within this period were pooled as indicated in Table S2. For these cumulated rain events we calculated:

- Cumulated rainfall height, cumulated kinetic energy and maximum EI_{30} as described in Table S2;
- Runoff coefficient, ratio between runoff volume collected for 1 m^2 (L/m^2 and hence

mm) divided by rainfall height (mm);

- Soil detachment (g/m^2) as the product of sediment concentration in the collected samples (g/L) by runoff volume (L/m^2).

The adjustments in the protocol, made to fit with the specific objective of the experiment in each year, are described in Table S3. In particular, as we found large differences in 2015 between rainfall measured at the automatic weather station and at manual rain gauges, in 2016 we moved the plots closer to the station to be able to use rainfall kinetic energy and EI_{30} calculated with the records of the automatic weather station. Besides, while in 2015 the objective was to measure precisely soil detachment on a monthly or annual basis, in the following years we focused on event-scale analyses with a slightly different methodology for soil detachment measurements (Table S3).

2.5. Soil surface conditions

We visually estimated the proportion of each soil surface type for each microplot from two direct observations a year using the method proposed by Casenave and Valentin (1992) (Janeau *et al.*, 2003; Chaplot *et al.*, 2005; Podwojewski *et al.*, 2008; Patin *et al.*, 2012, 2018). The assessment, both accurate and reproducible when applied by the same expert (Malam Issa *et al.*, 2011), identified:

- Free aggregates (Fag) not anchored to the soil surface, and readily detached by gently brushing the soil surface;

- Crusts resulting from the slaking of aggregates and the sealing of soil surface pores, including erosion crusts (ERO), gravel crusts (G) and structural crusts (ST);

- Litter and plant fragments lying directly on the soil surface.

In 2016, the same expert also analysed a series of detailed pictures (instead of direct observation) to estimate the same parameters at the end of the rainy season.

In 2017 and 2018, in addition to soil surface type estimations, we took weekly standardised pictures of soil cover for each microplot, which corresponded to approximately 1 200 pictures in total. All images were corrected for perspective deformation using the GIMP software. We conducted precise segmentation using Fiji (Fiji Is Just Image J) plugin Weka Segmentation on 350 soil cover images from both rubber tree plantations and other land uses, to account for different soil and light conditions. The images were annotated at a pixel level and each pixel was associated to one label (living plants, litter and bare soil). Annotating images at a pixel level is time consuming, and takes between 5 to 15 minutes per image. We thus used a computer vision approach to annotate the remaining images. We used the 350 labelled images to learn a segmentation network, and then used the learned model to automatically predict the label of each pixel (Figure S1 and supplementary methods). The segmented images were finally analysed to measure the proportion of soil surface covered by living plants. The litter cover was poorly distinguished from bare soil and was not used in the analysis. We then calculated the proportion of plant cover at the date of each runoff measurement by interpolation. Separate interpolations were fitted for five periods between each herbicide spraying (January-June 2017, June-August 2017, August 2017-June 2018, June-September 2018, and September-December 2018).

2.6. Data processing

We completed all data analyses using the R software (R Core Team, 2018).

Corrections of biased data

In mature rubber tree plantations, some rain events with very high intensity or rainfall height could not be correctly recorded, for two main reasons. Firstly, the maximum possible runoff volume recorded corresponded to the volume of the buckets, i.e. approximately 50 L. Some exceptional events (e.g. with rainfall height > 100mm) created runoff larger than this volume, but the records had an artificial threshold of 50 L/m^2. Besides, some very intense events created concentrated runoff coming from an upslope section of unknown area, which entered over the frame of the microplots and led to overestimation of detachment and runoff. We considered that runoff and detachment were likely biased if the runoff volume reached the volume threshold (>50 L), or if the runoff coefficient was higher than 2 (runoff coefficient slightly higher than one is possible if there is some concentrated throughfall from the canopy). These "biased" measurements represented between 0.5% and 3.5% of the total number of runoff and detachment data, depending on the year. To correct these measurements, we re-estimated them based on mixed models with square-root transformed runoff (or detachment) as the response. For runoff, the explanatory variables were meteorological variables (rainfall height, API (Antecedent Precipitation Index), cumulated kinetic energy, and maximum EI_{30}) and their interaction with the year and plot.

For soil detachment, available only in 2015 and 2016, the explanatory variables were runoff volume, API, cumulated kinetic energy, and maximum EI_{30} and their interactions with year. The models also included the microplot as a random effect. We fitted the models for all non-biased data and conducted stepwise model selection based on AIC. The final models had an R^2 of 67% (69 % when including random effects) for runoff volume and 83% (85% when including random effects) for soil detachment. The missing runoff and detachment measurements were then predicted from these models (function *predict*) and integrated into all following analyses.

Data analyses

We investigated the variation of monthly runoff coefficients using mixed linear models (R package LME4, Bates *et al.*, 2014) with month and land use as fixed effects and microplot identity as the random effect to take into account the repeated measurements within each microplot. We conducted pairwise comparisons using the EMMEANS package (Lenth, 2018) and we corrected p-values for multiple testing using the Tukey method. To investigate the relations between runoff and soil detachment and meteorological variables, we discarded "small" events with rainfall height under 2 mm. Fixed effects were rainfall characteristics (e.g. rainfall height) or date, and random effects were the microplots. Surface runoff and soil detachment were non-normal and with heterogeneous variance. We thus performed model-specific box-cox transformations:

$$y' = \begin{cases} \dfrac{y^{\lambda} - 1}{\lambda} \; if \; \lambda \neq 0 \\ \ln(y) \; if \; \lambda = 0 \end{cases}$$

With *y* the runoff or soil detachment, y^{j} the transformed variable, and λ the optimised box-cox parameter (function *boxCox*, R package CAR, FOX, WEISBERG & PRICE, 2011). We then performed stepwise model selection based on AIC (function *step*, R package LMERTEST). Because maximum EI_{30} was highly correlated with rainfall height, we present only results for rainfall height, which is the most common rainfall variable used in erosion models. The date was coded as day number since January 1st.

To test the relationship between soil surface characteristics and runoff in the different land uses during the different stages of the rainy season, we first calculated early (until August 14th) and late (from August 15th) semi-annual runoff coefficients. We then conducted mixed model analyses of the semi-annual runoff coefficient with soil crusting per microplot in each stage of the rainy season. We also tested the effect of ground cover by low-growing plants on runoff volume (square-root-transformed for ensuring normalisation of the residuals) of individual rain events during the rainy season 2017 and 2018 (May-November) in a mixed model with rainfall height (square-root transformed), soil cover and plantation (OR_1 or OR_2) as fixed effects. In both cases, microplots were included as random effects.

3. Results

3.1. Meteorological conditions

Annual rainfall varied from 1 270 mm in 2015 (measured from March onwards) to 1 836 mm in 2017. It was intermediate in 2016 (1 539 mm) and 2018 (1 447 mm). The rainy season was clearly bimodal in 2015 and 2018, with rainfall peaks in April-May and August, but less so in 2016 and 2017, with a large rainfall peak in August and a smaller one in May-June (Figure 1a). The monthly erosivity factor R (10^2 kJ mm/m^2/h, corresponding to the monthly sum of EI_{30} divided by 100, Renard *et al.*, 1997) peaked in April and August 2015 and June and August 2016, July and August 2017 and August and October 2018 (Figure 1b). Rainfall events larger than 25 mm were particularly numerous in 2017 (Table 2).

Figure 1. Seasonal variations of a. Rainfall height (mm) and b. Rainfall erosivity between 2015 and 2018. Note that monthly records started in March 2015.

Table 2 Cumulative rainfall height separated by rain event size from 2015 to 2018 in maize fields (M), young RT plantations with intercrop (YR), and mature RT plantations inter (OR_i) and within (OR_s) tree rows. In 2015, 2017 and 2018 results are presented separately for M/YR and OR_i/OR_s (2015) and OR_1/OR_2 (2017-2018) because of rainfall spatial variability. OR_1 and OR_2 correspond, respectively, to the plantations studied in 2015 and 2016; *h* and *nh* indices indicate treatment (with or without herbicide application). Rainfall in 2015 was measured only from March onwards; for the following years it is measured from January 1st. For runoff and detachment data, each line shows the data for one individual microplot.

		Rainfall (mm) & **(number of events)**				**Runoff** (L/m^2)				**Soil detachment** (g/m^2)			
Year	**Land use**	**<25mm**	**25-50mm**	**>50mm**	***Total***	**<25mm**	**25-50mm**	**>50mm**	***Total***	**<25mm**	**25-50mm**	**>50mm**	***Total***
2015	M	552 (80)	472 (14)	214 (3)	*1238 (97)*	5	24	13	*42*	1	47	87	*136*
						10	60	26	*95*	5	735	143	*883*
						18	65	40	*123*	11	250	173	*434*
	YR					28	57	38	*122*	60	249	157	*466*
						25	55	20	*101*	105	149	51	*305*
						12	32	13	*58*	9	89	9	*107*
	OR_s	583 (81)	490 (13)	221 (3)	*1295 (97)*	75	170	65	*309*	625	2973	492	*4090*
						79	165	81	*325*	409	3137	1799	*5344*
						58	115	62	*234*	268	1846	1236	*3350*
	OR_i					64	251	62	*376*	186	2230	367	*2784*
						97	283	43	*423*	709	4819	365	*5894*
						64	266	24	*354*	181	2348	569	*3098*
2016	M	634 (79)	499 (14)	406 (6)	*1539 (99)*	18	19	28	*65*	17	79	267	*364*
						20	24	31	*75*	48	125	189	*362*
						38	42	36	*116*	92	134	137	*363*
	YR					24	31	41	*97*	41	86	202	*330*
						26	33	40	*99*	50	103	102	*255*
						26	30	27	*83*	57	125	81	*263*
	OR_i					122	163	233	*518*	606	1029	4841	*6476*
						199	201	216	*616*	1711	1811	4365	*7887*
						165	168	210	*543*	1487	1625	4812	*7923*
	OR_s					135	152	209	*496*	975	1746	5900	*8621*
						101	119	178	*398*	743	1311	3743	*5798*
						139	167	203	*508*	1024	1858	4920	*7803*
2017	$OR_{1,h}$	336 (35)	751 (23)	898 (11)	*1985 (69)*	58	285	322	*664*				
						56	257	219	*532*				
						57	260	273	*590*				
	$OR_{1,nh}$					52	237	226	*515*				
						35	179	137	*351*				
						58	261	208	*528*				
	$OR_{2,h}$	391 (38)	781 (22)	702 (9)	*1874 (69)*	164	450	398	*1013*				
						156	455	344	*955*				
						105	347	271	*724*				
	$OR_{2,nh}$					85	290	188	*564*				
						155	414	373	*943*				
						95	371	291	*757*				
2018	$OR_{1,h}$	541 (56)	681 (19)	409 (5)	*1631 (80)*	77	208	101	*385*				
						81	230	104	*414*				
						68	217	112	*397*				
	$OR_{1,nh}$					35	127	43	*204*				
						47	127	42	*215*				
						52	158	61	*271*				
	$OR_{2,h}$	493 (56)	637 (19)	297 (6)	*1427 (81)*	171	318	162	*651*				
						95	301	137	*533*				
						74	206	105	*385*				
	$OR_{2,nh}$					62	192	97	*351*				
						78	242	130	*450*				
						86	186	108	*381*				

3.2. Effect of land use and rainfall on runoff and soil detachment (2015-2016)

Yearly runoff and soil detachment for each microplot are summarised in Table 2.

In M (and YR respectively), annual runoff coefficient was 7.7% (median for the three M microplots; resp. 8.1% in YR) in 2015 and 6.1% in M (resp. 7.8% in YR) in 2016. Monthly runoff coefficients in 2015 in M and YR were the lowest in M microplots in June (2.7 %) and peaked at 22% in M microplots in October (Figure 2a), when monthly rainfall height was low but rainfall erosivity density still high (Figure 1). In 2016, monthly runoff coefficients remained stable throughout the rainy season, around 6% (Figure 2b). Median annual soil detachment was 0.43 kg/m^2 in M (resp. 0.31 kg/m^2 in YR) in 2015 and 0.36 kg/m^2 (resp. 0.26 kg/m^2) in 2016: it remained relatively low throughout the rainy season in 2015 (Figure 2c).

Figure 2. Monthly variations of surface runoff coefficient in 2015 (a), in 2016 (b) and soil detachment in 2015 (c) in maize fields (M), young RT plantations with intercrop (YR), and mature RT plantations inter (OR_i) and within (OR_s) tree rows. Different letters indicate differences significant at 5% within each month.

In mature rubber tree plantations, annual runoff coefficient was highly variable. It ranged from 24% (median of the three OR_s microplots in 2015) to 51% ($OR_{1,h}$ in 2017). Both 2015 and 2016 considered, there was no significant difference in monthly runoff coefficient between OR_i and OR_s ($P > 0.3$). In both years, monthly runoff coefficient ranged between 4.4 % (June) and 65.6 % (September) in OR_i, and between 4.7 % (May 2016) and 65 % (September 2016, Figure 2a,b). It was low at the beginning of the rainy season (until August) and was significantly higher afterwards ($P < 10^{-6}$). From June onwards in 2016, runoff coefficient in OR_i and OR_s was always higher than in M or YR and increased steadily over the rainy season. Annual soil detachment varied from 3.1 kg/m^2 (OR_i in 2015) to 7.9 kg/m^2 (OR_s in 2016). It was significantly higher in the late rainy season ($P = 0.003$), with no difference between OR_i and OR_s. All rain events in 2015 and 2016 combined, runoff and soil detachment for individual rain events were also significantly higher in OR_i and OR_s than in M

Figure 3. Runoff and soil detachment variations with land use, rainfall height and time since the onset of the rainy season in 2016 in maize fields (M), young RT plantations with intercrop (YR), and mature RT plantations inter (OR_i) and within (OR_s) tree rows. Runoff and detachment were transformed using model-specific box-cox transformations, which λ parameter is indicated in each subfigure.

and YR (Figure 3).

We investigated the relationships between rainfall height and runoff and detachment only in 2016, when detailed data from the weather station was available. Both runoff and soil detachment (boxcox-transformed) significantly increased with rainfall and date in all land uses, but with larger slopes coefficients in OR_i and OR_s than in M and YR ($P < 10^{-3}$, Figure 3). This was also the case for other descriptors of rainfall, such as maximum EI_{30} (data not shown).

Besides, log-transformed soil detachment increased linearly with log-transformed runoff ($P < 10^{-6}$); with a steeper slope in OR_i and OR_s (slope coefficient confidence interval: 1.93 g/L ± 0.05 g/L) than in YR and M (slope coefficient confidence interval: 1.20 g/L ± 0.9 g/L; interaction: $P < 10^{-12}$; R^2 for fixed and random effects: 84 %; Figure 4).

Figure 4. Increase of log-transformed soil detachment with log-transformed surface runoff for all individual events causing detachment in 2016 in maize fields (M), young RT plantations with intercrop (YR), and mature RT plantations inter (OR_i) and within (OR_s) tree rows. The effects of log-transformed runoff ($P < 10^{-12}$) and land use ($P < 10^{-12}$) were significant. The slope coefficient in OR_i and OR_s (confidence interval: 1.70–1.95 g/L) was significantly higher than in YR and M (confidence interval: 1.05–1.52 g/L; interaction: $P < 10^{-7}$). R^2 for fixed and random effects was 85%.

3.3. Effect of soil crusting and ground-level plant cover on runoff

In both 2015 and 2016 in M and YR, structural crust covered most of the ground surface except at the end of the rainy season 2016, when free aggregates were particularly abundant in M (Figure 5). Runoff coefficient was not affected by the amount of crop residues (Figure S2, $P > 0.05$) but slightly increased with the proportion of crusts ($P = 0.046$), in both the early and late rainy season. However, the soil was rarely bare but covered by weeds or by the crop (Figure 6), therefore a high interception by vegetation occurred during the rainy season.

Rubber leaf litter covered a significant part of all microplots in RT plantations, while the rest of the soil was mostly structural crust (Figure 5). Runoff coefficient between 2015 and 2018 significantly increased with soil crusting and decreased with crop residues at the beginning of the rainy season in OR plantations (May to Mid-August, Figure S2, $P = < 10^{-2}$). Contrarily to M and YR plots, herbicide application in late July 2016 in OR_i and OR_s had lasting effects, maintaining a quasi-null living plant cover until the end of the rainy season and corresponded to a leap in runoff coefficients (Figure 6 and see runoff leap in August on Figure 2b). Focusing more specifically on ground cover by low-growing plants in 2017 and 2018 we found that it was often relatively sparse, with one third of the ground cover estimates under 2.9% (low cover), one third between 2.9 and 31% (medium cover), and one third over 31% (high cover). When controlling for rainfall height and for the plot, low ground cover generated significantly higher runoff coefficient (34% +/4%) compared to medium (28% +/4%) or high (23% ± 4%) soil cover ($P < 0.05$). Besides, runoff (square-root transformed) increased with rainfall height (square-root transformed) with a larger slope coefficient when ground cover was low than when it was high (Figure 7). Runoff was also usually higher ($P < 10^{-3}$), and increased more strongly with rainfall ($P < 10^{-3}$), in plot OR_2 compared to OR_1.

Figure 5. Variations of soil surface type during the 4 years of experiment in a. maize fields (M), young RT plantations with intercrop (YR), and mature RT plantations inter (OR_i) and within (OR_s) tree rows and b. the two studied RT plantations, with (OR_h) or without (OR_{nh}) herbicide application.

(a)

(b)

Fig. 6. Evolution of soil cover between May and November 2016 in maize fields (M), young RT plantations with intercrop (YR), and mature RT plantations inter (OR_i) and within (OR_s) tree rows. Symbols indicate actions realised during the considered month.

4. Discussion

4.1. Erosion monitoring on steep slopes

It is common in soil erosion studies to discard small rainy events as insignificant (generally less than 0.5 inch, i.e. 12.7 mm, (Wischmeier & Smith, 1978; Renard *et al.*, 1997) and focus on medium to large events to quantify erosion. We found that indeed, medium and large events accounted for a large part of the runoff and erosion. These large events are the most visible for farmers and public authorities as they can cause gullies, floods or even landslides. On the contrary, small events tend to be overlooked because they have little individual impact. However, we found that events under 25 mm, the most numerous, added up to on average 34% of annual rainfall. All years and land uses together, they accounted on average for 20 % of total runoff and 15 % of total detachment. This last figure was probably underestimated because from 2016 onwards we did not measure detachment for events generating runoff < 2 L/m^2. Such results are likely to depend on the context of a given event: for instance, a small event occurring when the soil is still saturated from previous rainfalls is likely to produce relatively high runoff. Besides, small events mobilise particles, which will then be more easily displaced by later events (especially on steep slopes such as the fields investigated here) thus contributing to high detachment during large rain events. Thus, overlooking the cumulative effect of small events could introduce significant underestimations of soil loss assessments.

4.2. Afforestation by RT plantations increases runoff and soil detachment

Maize is widely recognised as a very erosion-prone crop in South-East Asia (Valentin *et al.*, 2008). Detachment rates observed under maize in this study were slightly lower than those usually reported in the region (e.g. 6 t/ha/year in Patin *et al.,* 2018)), possibly due to relatively high cover by weeds in our study plots and to the absence of mechanical soil preparation. However, we found that in both 2015 and 2016, and despite variations in soil types and meteorological conditions, runoff and soil detachment were consistently higher under OR than M or YR with annual soil detachment rates in OR_i and OR_s on average 10 times (in 2015) and 23 times (in 2016) higher than in M and YR.

The extent of the difference between OR and M/YR was lower in 2015 than in 2016, which can be related both to soil and climatic factors. Firstly, a later monsoon in 2016 with higher rainfall and erosivity at the end of the rainy season (when RT leaf litter had partly disappeared but weeds protected soil surface in M and YR) can explain the stronger effect of land use on runoff in 2016 than in 2015. Secondly, there might be an impact of soil variability: the two soil series found in the area are quite similar, both Haplustalfs characterised by moderate runoff and permeability (Moormann *et al.*, 1966). Nevertheless, Ultic Haplustalfs (M and YR in 2015; OR_i and OR_s in 2016) are thinner soils often truncated by erosion; in such case initially deep clayey horizon can reach shallow position. The effect of soil type on runoff was confirmed in 2017 and 2018, were the more clayey soils observed for OR_2 (same plantation as in 2016) generated higher runoff for similar rainfall than the more loamy soils observed for OR_1 (same plantation as in 2015). We changed soil series-land use pairing between the 2015 and 2016 and obtained similar results: the annual runoff and soil detachment observed at $1m^2$ scale were systematically higher for OR_i and OR_s than for M or YR. Thus, while direct comparison between 2015 and 2016 is not possible, the higher rates of runoff and detachment for OR_i and OR_s compared to M and YR are consistent; and the possible soil- or weather-related variation in sensitivity to erosion did not exceed nor compensate land-use effects.

The higher rates of soil detachment and runoff for OR_i and OR_s were combined with notable soil surface degradation. In 2016, the a_1 coefficients of the linear regressions ($Y=a_0+a_1 \times X$) between runoff or detachment and rainfall were higher for OR_i and OR_s than for M or YR. Runoff coefficient and soil detachment rates also increased with time along the rainy season with larger a_1 slope coefficients for OR_i and OR_s than for M and YR. This could be explained by higher soil moisture in the late rainy season under mature RT. However, we also found larger a_1 coefficients for the regression of detachment versus runoff for OR_i and OR_s than for M and YR. All these elements suggest a gradual decay of soil cohesion and infiltration capacities during the rainy season in mature RT plantations, and overall a higher susceptibility of RT plantations to soil detachment. It is thus important to quantify the resilience of these soil characteristics and to investigate physical (e.g. drying, cracking) or biological (earthworm activity, plant growth) factors that may contribute to the regeneration of both infiltration and cohesion for such degraded soils.

4.3. Factors affecting runoff and detachment in RT plantation

Other recent studies suggested a strongly negative impact on soil erosion of afforestation by tree plantations without convenient understorey management. The transition from open environments to teak plantations caused a large increase of overland flow and soil detachment (Ribolzi *et al.*, 2017) and mature RT are known to be quite prone to erosion (Lacombe *et al.*, 2018). The combination of three main factors, i.e. the presence of a high canopy, ground cover by litter, and the low ground cover by living plants, can explain these high erosion rates.

Canopy effect

Even though the size of the leaves of RT and teak trees are very different, both canopies concentrate raindrops, and hence increase their kinetic energy (Liu *et al.*, 2016b; Lacombe *et al.*, 2018). In particular, the tree canopy is usually dense close to the tree lines, but sparser between rows, resulting in increased kinetic energy close to the trees. Microplots within tree rows (OR_s) were also located closer to the trees, thus more prone to disturbance from trampling and tapping operations. Thus, we expected higher runoff and detachment within RT rows (OR_s) than between rows (OR_i). However, we did not observe higher soil detachment or runoff under OR_s. This was possibly due to high local variability in the response of individual microplots, as well as in the proportion of cover by leaf litter.

Soil surface: residues and soil crusting

While higher cover by residues under mature RT plantations compared to M or young RT was expected to provide better protection against soil crusting and to decrease runoff (Podwojewski *et al.*, 2008; Patin *et al.*, 2012, 2018), we found that on the contrary runoff and detachment were overall higher under mature RT plantations. This apparent paradox suggests that it is not possible to directly compare the effects of different types of crop residues. Indeed, rubber leaves are waxy (Prüm *et al.*, 2013) and form a tight tiling on the soil surface. Although this cover is still likely to effectively protect the soil from falling raindrops, it might be less effective in controlling surface runoff than (for instance) maize residues, especially in steep areas.

When considering only RT plantations, runoff significantly increased with soil crusting and decreased with crop residues cover at the beginning of the rainy season. It was not possible to precisely distinguish between the effect of residues and crust: due to the method of evaluation of soil surface characteristics, a lower crust cover might be due either to actual "uncrusted" surface or to the presence of abundant litter partly covering the crusts. Soil covered by residues is, though, usually less crusted due to direct protection against splash effect and to the presence of microorganisms improving soil structure. Crop residues also slow down runoff, limiting further detachment and favouring redeposition of soil particles.

For instance, on gentle slopes, Liu *et al.* (2015) showed that in the early rainy season, runoff and soil detachment were much lower in control RT plantations (>70% litter cover) than in RT plantations with litter removal. However, the dynamics of litter cover under RT are quite specific. In most forests of the area, trees shed leaves continuously ensuring permanent cover. Conversely, defoliation in RT plantations occurs over two weeks in February-March and is rapidly followed by leaf flush. Thus, in our study plots, soil cover by leaves was high at the beginning and middle of the rainy season (>75%); but leaves were progressively destroyed by microorganisms, insects (termites, ants...) or abiotic processes (fragmentation, displacement...). This might explain why the relationship between residues and runoff was not significant in the late rainy season, as the partly decomposed leaves failed to effectively protect soil surface and the proportion of bare soil (on average 45% of the surface) was sufficient to cause surface crusting and high detachment. This supports previous findings by Liu *et al*. (2017) who showed that rubber litter was efficient in controlling runoff and soil detachment only when it covered >70% of the soil surface – hence at the onset of the rainy season.

Ground cover by living plants

Soil cover by plants is known to decrease splash erosion (Liu *et al.*, 2016a; Lacombe *et al.*, 2018) and to increase infiltration rates. In 2016, while ground cover by weeds was relatively important in M and YR, it was very low in OR_i and OR_s and quasi null from August onwards. Very low ground-level plant biomass in this area has been reported elsewhere (e.g. Neyret *et al.*, 2018) and is probably due to low light availability under the canopy and to a low resilience of the system after herbicide application (part of the usual management process of RT plantation owners in the area). Low ground cover by plants was thus a major factor of high runoff and detachment rates in mature RT plantations.

Our estimations of soil cover, available with an extremely high temporal resolution, allowed us to quantify precisely this effect on a rain event basis. We showed that increased cover by ground-level plants significantly reduced soil vulnerability to large rain events. Above 30% of soil cover by ground-level plants, runoff was strongly decreased, suggesting high infiltration capacities. Besides, ground-level plants not only slow down runoff but can also act as sediment traps. Even though soil detachment was not measured for this last experiment, data from previous years showed that detachment increased exponentially with runoff volume. It is thus likely that the effect of soil cover by ground-level plants would be even stronger on soil detachment than on runoff.

4.4. Soil detachment rates in tree plantations of tropical mountainous regions

While high runoff and soil detachment in mature RT plantations are supported by the literature, the amount of runoff and soil detachment we found in this study was higher than previously reported. Our estimation of annual soil detachment in mature RT plantations ranged from 2.8 $kg/m^2/year$ to 8.6 $kg/m^2/year$ in 2015 and 2016, which was relatively high compared to previous results. At the catchment scale, Ribolzi *et al.* (2017) found a raise of soil loss from 98 to 609 $t/km^2/year$ (i.e. 0.01 to 0.61 $kg/m^2/year$) in a Laotian mountainous catchment, after conversion from upland rice to teak plantations. On a larger scale, and using a generic soil erosion model, Borrelli *et al.* (2017) estimated erosion rates ranging between 0 and 1 t/ha/year (i.e. 0.1 $kg/m^2/year$) in mountainous Northern Thailand. Nevertheless, it is not possible to directly compare soil detachment measured at the $1m^2$ scale with gross soil loss measured at the catchment or regional scale. Indeed, depending on the rainfall and topographical characteristics, a large part of the sediment is redistributed shortly after detachment. Using $1m^2$ microplots on similarly steep slopes (40-55% on average) and under similar meteorological conditions, Patin *et al.*, (2018) also found lower annual soil detachment under upland rice or maize (resp. 0.60 ± 0.09 $kg/m^2/year$ and 0.80 ± 0.08 $kg/m^2/year$) than under mature teak tree (2.9 ± 0.5 $kg/m^2/year$), and this last figure was significantly lower than our data.

We consider that the high soil detachment rates observed in this study result from a combination of management practices and topographical characteristics. Indeed, Liu et al. (2015) found that in RT plantations of SW China, bare soil and soil covered with leaf litter produced soil detachment of 4.7 and 1.9 $kg/m^2/year$, respectively, on gentle slopes. While a steeper slope may decrease soil erosion on bare soils and in open field conditions (Janeau *et al.*, 2003; Ribolzi *et al.*, 2011), in this case we think that combined with clear-weeding it favours the exposition of bare soil by partially washing away RT leaves. It has also been observed that the proportion of bare soil under trees increased with slope in both temperate and tropical areas (C. Valentin, personal communication).

Conclusion

Afforestation by rubber tree plantations is currently ongoing in various marginal areas of Southeast Asia. We showed that in mountainous areas, far from promoting soil conservation, this transition increased soil susceptibility to erosion. Particularly high soil detachment under mature RT plantations, either intra- or inter-rows, was related to high proportions of bare soil, especially at the end of the rainy season with little or no understorey and largely degraded litter. Yet we showed that these very high erosion rates could be mitigated by the adoption of less intense weeding practices encouraging the growth of understorey in RT plantations. We propose three main research axes to work towards a better protection of soils in mountainous areas. (i) investigating farmers' motivations and practices in understorey management, in order to identify new sets of agroforestry practices more favourable to soil protection and involving less intense weeding. (ii) further understanding of climatic parameters influencing soil detachment and runoff is needed to identify high-risk periods and areas; in this regard, large-scale modelling should always be supported by extensive field measurements. Specifically addressing these erosion hot moments and hot spots may reduce efficiently gross erosion rates by focusing soil conservation efforts on the most erosive periods and on lightly degraded areas, in order to avoid the expansion of strongly degraded areas and compensate their detrimental outputs. And (iii) additional analyses of the relationships between plant cover and soil erosion processes are needed, especially regarding plant traits that are most appropriate to mitigate erosion. These three axes will shed light on better solutions for striking a balance between soil conservation and farmers' income.

Data accessibility

The data and code used in this paper are available online : https://doi.org/10.5281/zenodo.3614709, and https://github.com/mneyret/Catena_Neyret_et_al_2020

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- Supplementary information -

Supplementary method: Image analysis

To segment the images, we used a convolutional network architecture (Krizhevsky *et al*. 2012) for semantic segmentation, modified from PSP-Net (Zhao et al., 2017). Our model used a ResNet-50 (He et al., 2016) pretrained on ImageNet dataset (Russakovsky et al., 2015) and we used [1, 2, 3, 6] as levels in the spatial pyramid module. Instead of using dilated convolutions as in the original paper, we use hyper-columns strategy (Hariharan et al., 2015) to augment the size of the feature maps, which sped up the training and increased the performance of the network. Each image was resized such as its maximum size was 1000 pixels, and was normalised with the mean and the variance of ImageNet dataset. During training, each image was randomly cropped by 512 x 512 and we used a batch size of 8 images. The random crop operation during training is a data augmentation strategy that significantly increases performances. During testing, we used the whole image as input and the model predicts the label of each pixels. To learn the weights of the model, we used a cross-entropy loss per pixel. The model was optimised with stochastic Gradient Descent (SGD) (Bottou, 1998) on a single GPU. The model is implemented in PyTorch (Paszke et al., 2017) and the code to evaluate the model is available at https://github.com/durandtibo/segmentation_sol.

Figure S1. To automatically segment the images, we use a segmentation network called PSP-Net. This network takes as input a RGB image and outputs a segmentation mask. For each pixel, a label is predicted.

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Figure S2. Variation of annual runoff coefficient with the proportion of a. cover by crop residues and b. total proportion of crusts (erosion, structural and gravel crusts) from 2015 to 2018, in the early (resp. late) rainy season, i.e. before (resp. After) August 14th. Colours indicate land-use type and point shape indicate the year. Shaded areas indicate the confidence interval of the slope coefficient.

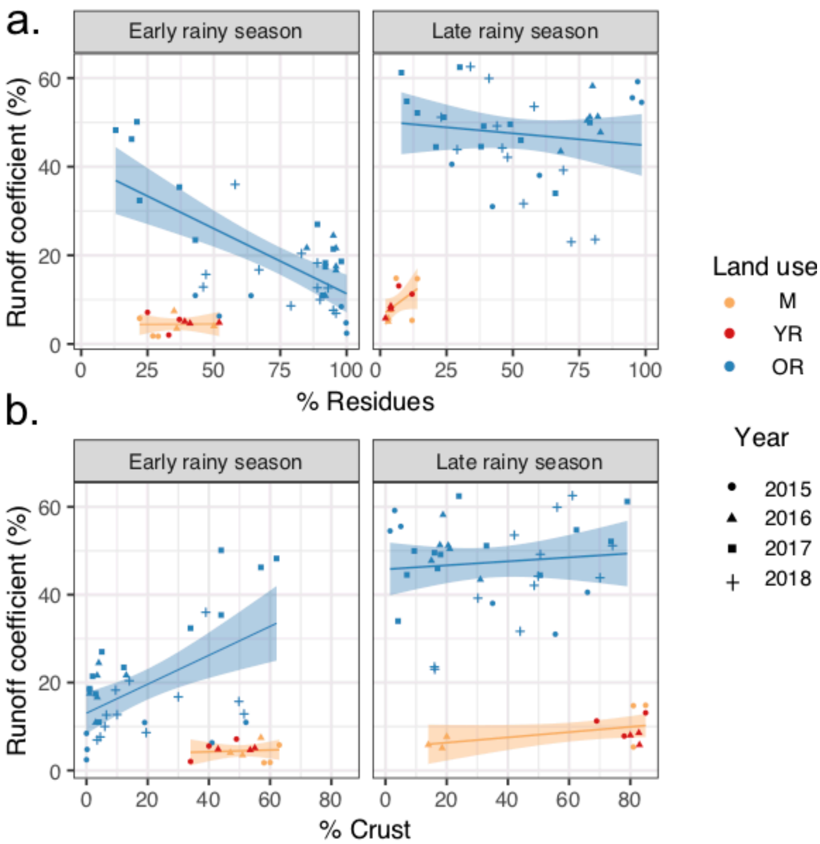

Table S2 Description of soil characteristics in the studied plots (mean ± standard deviation).

Year	Land use	Bulk density (g/cm³)	Sand (%)	Silt (%)	Clay (%)	N (%)	C (%)	pH
2015	**M - YR**	1.2 ± 0.1	17.5 ± 0.8	33.5 ± 1.3	49.0 ± 1.3	0.16 ± 0.3	1.9 ± 0.3	5.0 ± 0.3
	OR$_i$ /OR$_s$	1.2 ± 0.1	18.5 ± 0.92	27.9 ± 0.8	53.6 ± 1.4	0.17 ± 0.4	2.2 ± 0.6	4.6 ± 0.1
	M	1.3 ± 0.1	46.8 ± 2.4	37.2 ± 1.8	16.1 ± 1.9	0.15 ± 0.3	2.0 ± 0.6	6.2 ± 0.2
2016	**YR**	1.2 ± 0.1	21.8 ± 3.1	4.7 ± 2.4	37.5 ± 2.8	0.2 ± 0.3	2.6 ± 0.5	5.9 ± 0.2
	OR$_i$/OR$_s$	1.3 ± 0.1	18.2 ± 7.1	29.5 ± 3.5	52.3 ± 8.0	0.17 ± 0.03	2.1 ± 0.5	
2017-2018	**OR$_1$**	1.1 ± 0.1	28.5 ± 3.1	30.0 ± 1.4	41.5 ± 2.2	0.19 ± 0.05	2.7 ± 0.8	4.8 ± 0.1
	OR$_2$	1.3 ± 0.1	18.2 ± 7.1	29.5 ± 3.5	52.4 ± 8.0	0.17 ± 0.03	2.1 ± 0.2	5.3 ± 0.2

Table S2. Description of rainfall indices a. at the individual rain event level, i.e. directly calculated from rainfall data and b. at the cumulative rain event level, i.e. indices calculated for each event generating runoff and taking into account rainfall history since the last event generating runoff. Rh_{n1}: rainfall height of the previous rain event (mm). API_{n-1}: API at the beginning of the previous rain event. t: time since last rain event (days). Rainfall kinetic energy was calculated based on measurements made with a disdrometer in an experimental catchment located in Lao PDR, in a similar topographical and climatological context (Lacombe et al. 2018).

a. Indices for single rain events

	Name	Unit	Equation
Rh	Rainfall height	mm	
I_{30}	Maximum rainfall intensity (t= 30min sliding windows)	mm/h	$\max\left(\frac{Rh}{t}\right)$
KE	Rainfall kinetic energy	kJ/m^2	$2.7952 + 11.953 \times \log_{10}(I_{30})$
EI_{30}	Storm rainfall erosivity	$kJ\ mm/m^2/h$	I_{30} x KE

b. Indices for cumulative rain event (calculated since the last event generating runoff)

	Name	Unit	Equation
Rh_c	Cumulated rainfall height	mm	$\sum_{since\ last\ event} Rh$
KE_{cum}	Cumulative kinetic energy	kJ/m^2	$\sum_{since\ last\ event} KE$
$EI_{30,\ max}$	Maximum EI30	$kJ\ mm/m^2/h$	$\max_{since\ last\ event} EI_{30}$
R	Rainfall-runoff erosivity factor	MJ mm /h	$\sum_{since\ last\ event} EI_{30}/100$
API	Antecedent precipitation index		$(API_{n-1} + Rh_{n-1})\ x\ e^{\frac{-\Delta t}{2}}$

Table S3 Description of the protocol and different measured variables in the different years.

<table>
<tr><th>Year</th><th>Objective</th><th>Distance from weather station</th><th>Protocol</th><th>Source of weather data</th><th>Ground cover data</th></tr>
<tr><td>2015</td><td>Comparison of detachment and runoff in M, YR and OR on a monthly or annual basis</td><td>750 m at the north of M, YR and 800 m at the west-south-west of OR sites</td><td>Runoff measured after each rain. 300mL aliquot sampled when cumulated runoff over possibly multiple events reached a minimal threshold of 2L (i.e. 2mm runoff).</td><td>Rain gauges close to study sites</td><td rowspan="2">2-3 field assessment per year of soil surface characteristics</td></tr>
<tr><td>2016</td><td>Comparison of runoff and detachment in M, YR and OR on an event basis,</td><td>160m at the south of M, YR sites and 180 at the south-east of OR sites</td><td rowspan="2">Runoff measured after each rain. 300mL aliquot sampled when runoff from a single event reached 2L, discarded otherwise (i.e. not taking into account small events).</td><td>Weather station</td></tr>
<tr><td>2017-2018</td><td>Estimation of the effect of soil cover by ground-level plants on runoff on an event basis</td><td>800 m at the west-south-west of OR_1 sites and 180 m at the south-east of OR_2 site</td><td>Rain gauge (OR_1) and Weather station, daily sums (OR_2)</td><td>Weekly measurements of soil cover by ground-level plants</td></tr>
</table>