Nutrient loss to erosion responds to rain characteristics under transformed landscapes in the Rio Grande basin, Colombian Andes

Article *in* Ecohydrology · January 2023

DOI: 10.1002/eco.2519

4 authors, including:

Diego Suescún
Universidad Industrial de Santander, Sede Málaga

Juan Diego León Peláez
National University of Colombia

Juan Camilo Villegas
University of Antioquia

Received: 8 February 2022 | Revised: 28 October 2022 | Accepted: 6 January 2023
DOI: 10.1002/eco.2519

RESEARCH ARTICLE

WILEY

Nutrient loss to erosion responds to rain characteristics under transformed landscapes in the Río Grande basin, Colombian Andes

Diego Suescún[1] | Juan Diego León[2] | Juan Camilo Villegas[3] | Guillermo Antonio Correa-Londoño[4]

[1]Instituto de Proyección Regional y Educación a Distancia (IPRED), Universidad Industrial de Santander - sede Málaga, Cl. 20 No 6-20, Málaga, Colombia

[2]Departamento de Ciencias Forestales, Grupo de Investigación en Restauración Ecológica de Tierras Degradadas en el Trópico, Universidad Nacional de Colombia sede Medellín, Cra 65 No 59A - 110, Medellín, Colombia

[3]Grupo de Investigación en Ecología Aplicada. Escuela Ambiental, Facultad de Ingeniería, Universidad de Antioquia, Cl. 67 No 53-108, Medellín, Colombia

[4]Departamento de Ciencias Agronómicas, Universidad Nacional de Colombia sede Medellín, Cra 65 No 59A – 110, Medellín, Colombia

Correspondence
Diego Suescún, Instituto de Proyección Regional y Educación a Distancia (IPRED), Universidad Industrial de Santander - sede Málaga, Cl. 5 No 7-28 int 201 C. P 682011, Málaga, Santander, Colombia.
Email: dsuescu@unal.edu.co

Funding information
Departamento Administrativo de Ciencia, Tecnología e Innovación (COLCIENCIAS), Grant/Award Number: 543-2011; Colombian Ministry of Science, Technology and Innovation (MINCIENCIAS), Grant/Award Number: 1115-852-70719

Abstract

The functioning of tropical montane ecosystems are key provider of environmental services. However, climate and land use change interactively affect the ecohydrological and biogeochemical processes that support the provision of such services. We evaluate the effect of land use/land coverand the seasonality and intensity of the rainfall on the ecological functions of erosion control and nutrient regulation in a gradient of human intervention in the Central Andes of Colombia. Our results show that soil erosion (kg/ha/year) was higher in the transitory crop (187.7), followed by the permanent crop (98.2), and much lower in the pasture (8.0) and native forest (7.2). Our results also indicate a differential effect of land use and rainfall seasonality on erosion and nutrient transport, both processes being significantly higher in crops and lower in forest, both for the wet and dry seasons. However, the relationships between erosion and rainfall intensity varied depending on the hydrological season (in the wet seasons, no linear model was significant, while in the dry seasons, linear models for maximum rainfall intensity were significant in both crops and in the oak forest, and linear models with mean intensity were significant for both types of crops). Nitrogen exhibited the highest rates of transport, which can have important implications for water and soil pollution. Nitrogen transport via erosion (g/ha/year) was consistent with erosion results, being higher in the transitory crop (399.9) and permanent crop (265.3) that in the oak forest (6.9) and pasture (6.8). These results indicate that converting forests affects the capacity of ecosystems to provide environmental services, which is further amplified by projections of climate change.

KEYWORDS
climate change, environmental services, oak forest, soil conservation, soil pollution

1 | INTRODUCTION

The soil, a dynamic system in time and space, represents an essential economic resource for society (Paroissien et al., 2015) as it is the main terrestrial reservoir of fundamental nutrients such as nitrogen and phosphorus and fulfils the function of fertility maintenance (Quinton et al., 2010). As a non-renewable resource, it is important to guarantee its sustainability, so that its current and future functionality is maintained (Paroissien et al., 2015). One of the multiple routes of soil degradation is loss through water erosion (Er), which involves the detachment of particles by the impact of raindrops, and their subsequent transport through surface runoff flow (Sr) (Field et al., 2011).

With Er, nutrient transport (Nt) associated with soil particles is also a contributor to soil degradation (Zhang et al., 2015), the three processes (Sr, Er and Nt) being closely related. In the analysis of ecohydrological interactions, those that integrate climate, vegetation and soil allow assessing the ecological functioning and the cycling of mass and energy in ecosystems (Silva & Lambers, 2021).

As a naturally complex process, Er can be affected by global change (Paroissien et al., 2015), as it is determined by rainfall intensity and seasonality (Sun et al., 2016; Zhang et al., 2011), land cover and land use (Xiao et al., 2015). Er and Nt have ecological, environmental (Field et al., 2011) and economic relevance at different spatial scales, negatively affecting ecosystem function (Cohen et al., 2006). Both processes (Er and Nt) are directly associated with environmental and socio-economic degradation (Ehigiator & Anyata, 2011) and specifically, with soil degradation (Xiao et al., 2015), thus representing a global threat to the environment (Zhang et al., 2011). The negative impacts of these processes include decreased soil productivity (Guo et al., 2015), water pollution and eutrophication (Recanatesi et al., 2013) and altered biogeochemical dynamics (Quinton et al., 2010). They also influence atmospheric composition and climate change, and threaten the provision of soil-related ecosystem services worldwide, especially in tropical humid areas where erosive potential is high due to heavy rainfall (Cohen et al., 2006).

Ecosystems respond to rainfall at different spatial and temporal scales, the timing and magnitude of rainfall events are important drivers of ecosystem processes. Understanding how the relationships between drivers, fluxes and ecosystem processes change through space and time is a key component of describing ecosystem functioning. This is particularly important in functions associated with nutrient regulation because the amounts of nutrients available and their circulation in an ecosystem have consequences for numerous ecological processes (Corman et al., 2015).

There is a continuous increase in the global demand for food that accelerates the conversion of natural ecosystems into agricultural lands, a conversion that modifies the potential provision of ecosystem goods and services (Balthazar et al., 2015). This is evident in tropical regions that, for centuries, have been subject to colonization for agriculture and pastoralism (Vanacker et al., 2014), which strongly impacts Er and Nt and, consequently, the capacity of soils to sustain agriculture, potentially threatening regional or global food security (Paroissien et al., 2015). In turn, one of the most direct impacts of climate change is the increase in rainfall intensity and the increase and intensification of dry periods (Pedersen et al., 2021), leading to higher occurrence and intensity of Sr and higher Er and Nt rates (Field et al., 2011).

In consequence, land use, land cover and rainfall regimes control the intensity and frequency of Sr, Er and Nt. A better understanding of these relationships is important for proper soil and water management and conservation (Peng & Wang, 2012). Specifically, for an adequate control of Er and Nt, it is necessary to understand their spatial–temporal variability in different climatic conditions and land cover types, aspects that acquire greater importance given the current rate of change of both climate and land use change. This is of particular interest in tropical montane regions where ecosystems are highly vulnerable to anthropogenic and climatic changes and where land management is critical to the sustainability of communities living within and outside such regions (Balthazar et al., 2015). Although the impacts of land cover conversion on Er and Nt have received increasing attention worldwide (Suescún et al., 2017), few studies combine such impacts with rainfall seasonality and its implications on the regulation of ecosystem functions, particularly for erosion control and nutrient cycling.

Tropical ecosystems with healthy soils can support multiple ecosystem services, such as water and climate regulation that are important for the development of environmental policy and ecosystem management in these regions. Particularly, in the northern Andes, where our study area is located (the Río Grande basin), the landscape is dominated by combinations of mosaics of pastures and crops (with economic uses such as cattle ranching for dairy production) and relatively isolated patches of native forests. In these areas, deforestation is explained by socio-economic and biophysical factors. These land use practices can have an important effect on the supply of ecosystem (Ramírez, 2014). In fact, Suescún et al. (2021) found that, in the same area, phosphate fluxes in infiltration and surface runoff were higher in transformed systems than in natural forests, and a large part of the additional nutrient inputs in productive systems from fertilization can be lost due to surface runoff or infiltration. In this study, we evaluate the effect of vegetation cover type and rainfall seasonality and intensity on Sr, Er and Nt in a gradient of land cover types that resemble different stages of human intervention (oak forest, transitory crops, permanent crops and pasture) in tropical montane regions. Our results provide relevant information for the formulation of adaptation measures to global change, with emphasis on soil and water conservation in rural land production systems in tropical highlands.

2 | MATERIALS AND METHODS

In this study, we analysed the processes of Sr, Er and Nt, by establishing experimental plots in four land cover types that represent a gradient of human intervention (oak forest, transitory crop, permanent crop and pasture) in the tropical Andes. During 2 years of monitoring, rainfall (mm) and Es and Er were measured, as well as the depth of Sr (mm). Using this, Er (kg/ha) and Nt (g/ha) rates were determined for each cover. The nutrients studied were calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}), phosphate (PO_4^{3-}) and total nitrogen (N). The relationship between Sr and Er was verified by means of an exploratory correlation analysis. We compared Sr and Er between the four covers, and within each cover between wet and dry seasons, as a way to evaluate the potencial effect of vegetation cover type and rainfall characteristics (seasonality and intensity) on Sr, Er and Nt. Subsequently, linear regression models were fitted between Er as the dependent variable, and maximum and mean rainfall intensity as independent variables, following a statistical criterion (even if physically or conceptually the variables could have different association patterns, in the observed range, the relationships between the

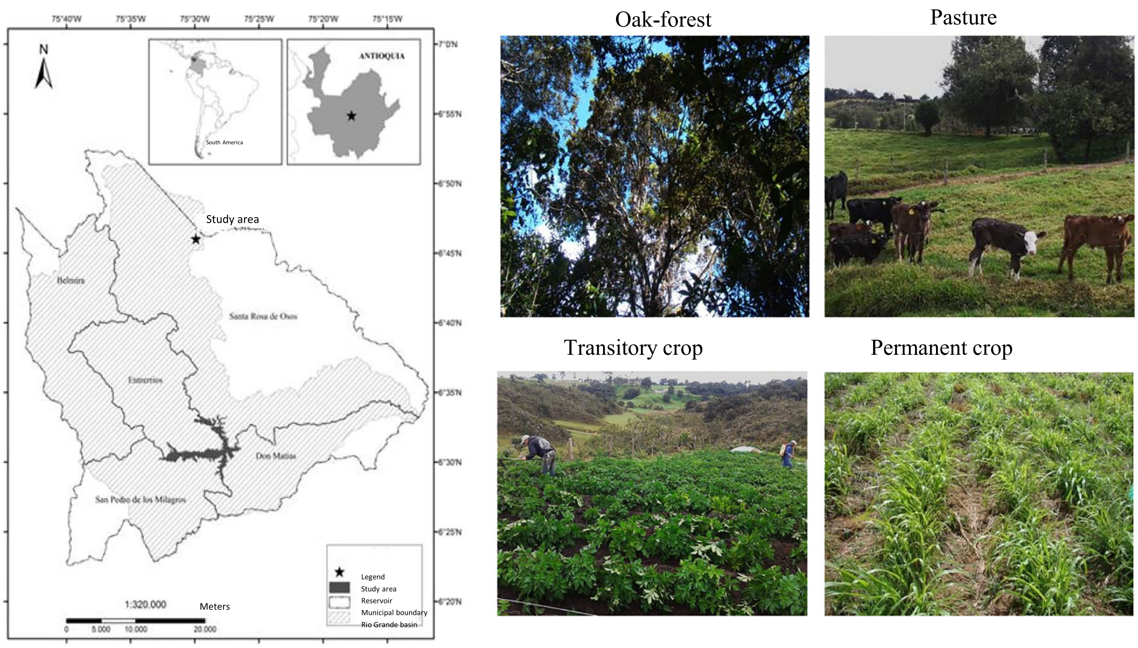

FIGURE 1 Location of the study area in the RÍo Grande basin (Colombia) and the four vegetation covers that represent a gradient of anthropic intervention

different variables were essentially linear, allowing us to compare these associations through simple slope comparisons). Correlations and linear regressions were performed both for the entire study period and discriminated between wet and dry seasons. Finally, the results were analysed in the context of the regulation of ecosystem functions (regulation of erosion control and nutrient retention), which are key in tropical montane ecosystems as they support ecosystem services related to water and soil.

2.1 | Study area

The study area is located in the upper part of the Río Grande basin, in the central Andes of Colombia, at an altitude of 2800 m a.s.l (Figure 1). This is a strategic basin in the country, as the Río Grande provides water to supply the demand of approximately half of the population of Medellín, the second largest city in the country, and is used for hydropower generation and is also known as the second largest producer of milk and dairy products in the country. The average annual rainfall is 1857 mm, with a bimodal distribution (two rainy seasons in MAM and SON and two drier seasons in DJF and JJA). The landscape is dominated by introduced pastures dedicated to dairy cattle ranching, with some relicts of native forests and patches of crops or stubble. Overall, the dominant land uses in this area correspond to pastures in combination with several kinds of crops. The traditional land conversion process in the Colombian Andes begins with forest clearing, followed by land preparation with tillage. Once crops are established, intensive use of agrochemicals and pesticides is common. After a few cultivation cycles, land is converted into pastures. These agricultural activities are determined by regional and national demands for agricultural products (García-Leoz et al., 2018). In particular, the Río Grande basin has a total area of 130,000 ha, of which forests cover 23,036.8 ha (22.3%), pastures 59,793.8 ha (58.0%), permanent crops 789.3 ha (0.8%) and transitory crops 1477.2 ha (1.4%). These four land cover types represent 82.5% of the basin. The soils are acidic (Andic Dystrudepts subgroup) high in organic matter and generally nutrient poor. We installed experimental plots in a relatively small area where these four dominant vegetation types were in proximity to each other. This allowed us to control for spatial variability in climatic, topographic and edaphic properties.

2.2 | Land cover types

In our study, the reference natural cover is the forest, which corresponds to an oak-forest dominated by *Quercus humboldtii* Bonpl, a species classified as vulnerable by the International Union for Conservation of Nature (IUCN). The dynamics of land use change begins with the clearing of the native forest to make way for transitional crops. After several harvests (approximately 2 years), the crop yields drop and pastures are established, which are the longer lasting covers over time. In this experiment, first, a potato crop was established for which, prior to planting, soil was prepared by applying 250 kg/ha of magnesium sulphate and 600 kg/ha of agricultural lime for the purpose of neutralizing soil acidity and increasing the pH. The crop was fertilized at planting with 300 kg/ha of 15–15–15 (15% N, 15% P_2O_5 and 15% K_2O) and 50 kg/ha of Agrimins® mineral supplement (total N 8.0%, ammoniacal N 1.0%, ureic N 7.0%, P_2O_5 5.0%, CaO 18.0%, MgO

6.0%, S 1.6%, B 1.0%, Cu 0.14%, Mo 0.005% and Zn 2.5%); then, foliar fertilizer was used every 15 days. Subsequently, a combined corn–beans system was planted, 700 kg/ha of poultry manure and 50 kg of 15–15–15 for each kg of seed were applied at the time of planting, and after 5 months, fertilization with 250 kg/ha of 15–15–15 was applied again.

The other agricultural cover was a permanent crop dominated by a grass (*Pennisetum americanum* [L.] Leeke), with a longer vegetative period than the transitory crop and requiring less intensive soil management and lower supply of agrochemicals. To prepare the soil for the establisment of this cover, 600 kg/ha of agricultural lime and 250 kg/ha of magnesium sulphate were applied. At planting, 200 kg/ha of 15–15–15 and 50 kg/ha of Agrimins were applied. Every 3 months, the grass was harvested at ground level. Finally, a pasture for direct grazing (*Pennisetum clandestinum* Hochst. ex Chiov) dedicated to dairy cattle, with management practices such as paddock rotation (with a 50-day rest period), pest control with commercial pesticides and fertilization applying 200 kg/ha every 50 days of Nitro-xtend (40% nitrogen and 6% sulphur). These pastures have been intensively managed for at least 35 years.

2.3 | Experimental design and field monitoring

The magnitude and intensity of rainfall events were recorded by with Davis Vantage Pro2 weather station in a location at the centre of the four covers and not father than 200 m from each one, with 5-min recording resolution, in addition to three analogue rain gauges distributed in open fields. To monitor runoff and erosion, we established two monitoring sites on each land cover type (two plots per land cover type). At each of those sites, a 10 $\times$ 2 m runoff plot (Sr) was established in the direction of the main slope, which was relatively uniform among cover types (19.5% in the oak forest, 21.6% for pasture, 18.9% in the transitory crop and 21.8% in permanent crop). Each runoff plot had a gutter at the bottom of the 10 m to collect surface runoff, which was connected to a container for water storage between measurements and sample collection periods. These gutters were also used as sediment traps (for Er measurement) by superimposing a fine mesh fabric on top of them, allowing the capture of soil particles entrained in the Sr flow. The characteristics of rainfall and Sr, Er and Nt fluxes were monitored in the four cover types for a period of 24 months (February/2014–January/2016). Weekly Sr fluxes were recorded in depth (mm) and Er in kg/ha. Weekly sediment samples, from each plot, were combined each month for chemical analysis in the laboratory. Representative values of Sr and Er were calculated as the average from both plots.

2.4 | Laboratory analysis

Sediment samples from each plot were oven dried at 65°C for 48 h, then sieved and weighed. Subsequently, the samples from different plots in the same cover for each month were combined and subjected to chemical analysis. Calcium, magnesium and potassium cations were extracted using neutral 1 N ammonium acetate ($CH_3COO\ NH_4$) and determined by atomic absorption spectrophotometry (Klute, 1986). Phosphate was determined using the Bray-II method (Kalra & Maynard, 1991). Finally, the Kjeldahl method was used for the analysis of total nitrogen (Jones et al., 1991).

2.5 | Data processing

2.5.1 | Rainfall characteristics and effects on Sr and Er

To analyse the relationships between seasonality and intensity of rainfall and both Sr and Er processes, weekly amounts (mm/week), and the maximum and average intensity (mm/h) of precipitation were determined using the 5-min records from the weather station. The criteria for differentiating wet (or dry) seasons was the occurrence of at least four consecutive weeks in which the average weekly precipitation was greater (or lower) than the weekly average for the 2-year observation period (27 mm/week). Relationships between Sr and Er were examined by Pearson correlation analysis, considering both the total study time and wet and dry hydrological seasons independently, for each cover type.

2.5.2 | Nutrient transport via soil erosion (Nt)

The Nt as particulate material (via soil erosion) was determined from average monthly concentrations of each nutrient in the total amount of transported soil (Er). Thus, Nt was calculated as the product of the concentration of each nutrient by the weight of particulate material, expressed in g/ha/year.

2.5.3 | Effect of vegetation cover and rainfall seasonality and intensity on Es and Er

To determine the potential effect of vegetation cover and rainfall seasonality on Sr and Er rates, a two-way analysis of variance with interaction was applied (after verification of normality). A transformation was applied to satisfy assumptions (mainly to overcome the lack of normality), for Sr it was $\log(Sr + 0.01)$ and for Er it was $\log(Er + 0.01)$. To determine the relationship between Er and the maximum and average rainfall intensity in each cover type, regression models were adjusted for the total study time and for both wet and dry hydrological seasons. Subsequently, to evaluate differences in rainfall–runoff–erosion relationships between cover types, the slope values of the significant regression models were compared using a slope parallelism test. All analyses were performed in the R statistical application.

3 | RESULTS

3.1 | Rainfall characteristics and effects on Sr and Er

For the 2 years of monitoring, a total rainfall of 2786 mm was recorded, with a mean monthly value of 116 mm. This period was separated into five wet seasons and six dry seasons (Figure 2a). Annual rainfall generally exhibited a bimodal behaviour, with 34.2% of total rainfall concentrated in the dry seasons and 65.8% in the wet seasons. The maximum weekly rainfall value recorded was 121 mm/week in the wet season. The mean value of maximum intensity was 18.9 mm/h (maximum 62.4 mm/h and minimum 2.4 mm/h), while the mean value of average intensity was 3.0 mm/h (maximum 5.5 and minimum 0.7 mm/h). In all weeks the pasture had higher Sr values than the other cover types, with peaks parallel to rainfall in all wet seasons except in the fourth (Figure 2b). Similarly, both crops exhibited the highest Er values, particularly in the second year (Figure 2c).

Table 1 shows the annual values of Sr and Er in each cover for the total study time and discriminating between wet and dry hydrological seasons. In general, for the four cover types, weekly mean values of Sr and Er were higher in the wet than in the dry seasons (2.9 and 2.4, respectively). On average, for both wet and dry seasons, and without discriminating between seasons, pasture exhibited a mean weekly Sr of 23.5 mm/week; 6.0, 4.3 and 4.7 times higher than transitory crop, permanent crop and oak forest, respectively (Table 1). Similarly, for both the wet and dry seasons, on average, as well as without discriminating between seasons, the transitory crop had a weekly mean Er of 187.7 kg/ha/year; 26, 23.5 and 1.9 times higher than oak forest, pasture and permanent crop, respectively. An effect

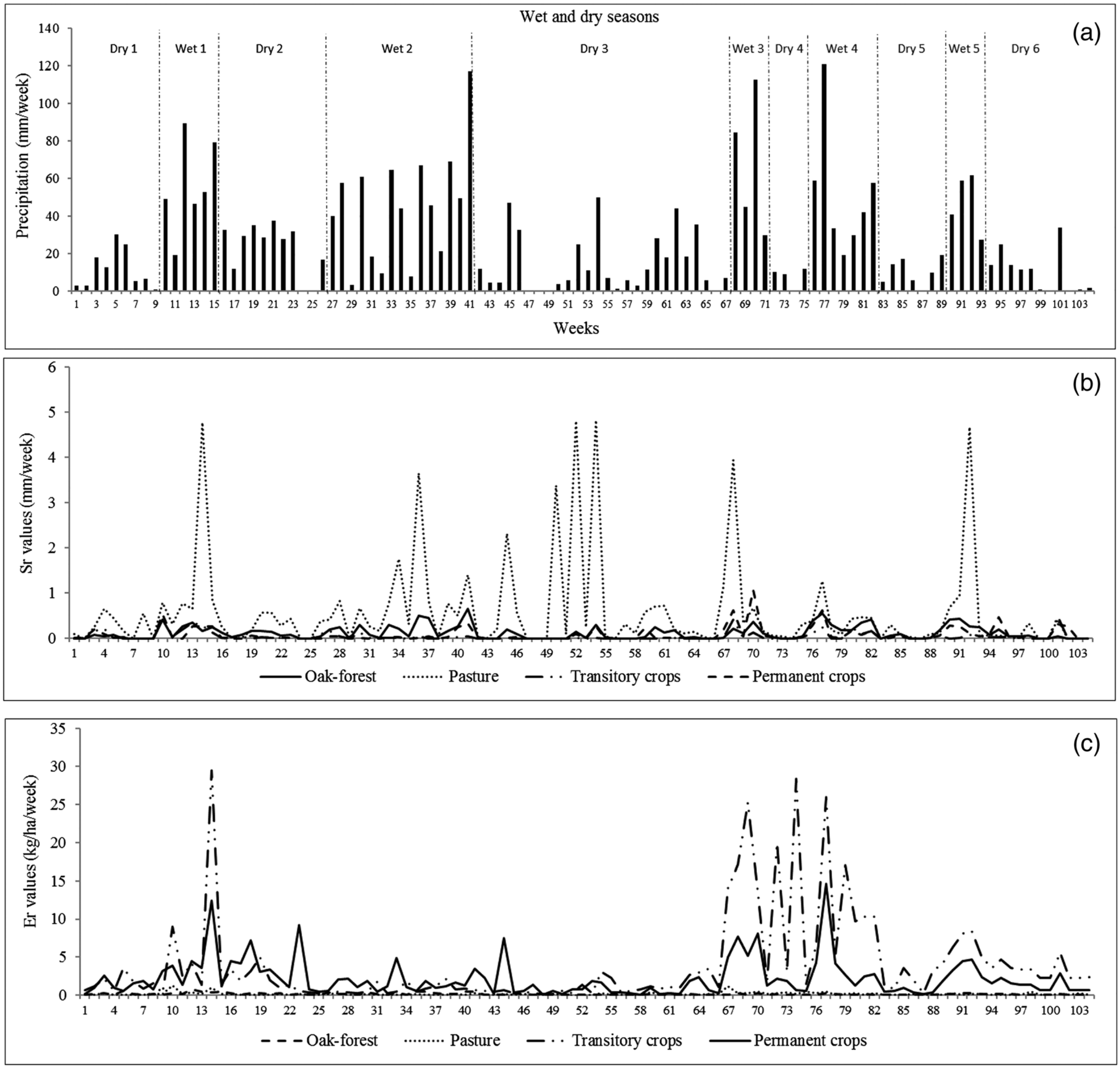

FIGURE 2 Temporal evolution at weekly scale of (a) precipitation (mm/week), (b) Sr (mm/week) and (c) Er (kg/ha/week) during the study period (February/2014–January/2016). Precipitation exhibited a bimodal behaviour with five wet and six dry seasons.

TABLE 1 Mean values of Sr (mm/year) and Er (kg/ha/year) in each cover type for the total study time and discriminating between wet and dry hydrological seasons (standard deviation in parenthesis)

Surface runoff (mm/year)			
Land cover	**Total period**	**Wet season**	**Dry season**
Oak forest	4.9 (3.6)	14.3 (2.5)	2.2 (1.3)
Pasture	23.5 (15.6)	51.1 (0.1)	16.0 (10.3)
Transitory crop	3.9 (2.4)	5.4 (0.4)	2.9 (3.2)
Permanent crop	5.5 (2.3)	9.6 (5.6)	3.8 (3.4)
Soil erosion (kg/ha/year)			
Land cover	**Total period**	**Wet season**	**Dry season**
Oak forest	7.2 (3.8)	12.2 (5.1)	5.6 (2.4)
Pasture	8.0 (1.1)	14.4 (0.1)	6.8 (1.4)
Transitory crop	187.7 (96.9)	371.5 (311.7)	136.3 (58.9)
Permanent crop	98.2 (32.0)	185.5 (78.7)	79.3 (38.1)

of seasonality was observed in the correlations between Sr and Er, as significant correlations were present in all cover types when not discriminating between seasons, and only in both crops in the wet seasons and in the forest in the dry season (cells with stars in Table 2).

3.2 | Nutrient transport via soil erosion (Nt)

Both crops (the transitory crop higher than the permanent crop) had, on average, higher Nt than the oak forest and the pasture, which had low and similar values between them. In general, for all four cover types, the highest Nt values were recorded for nitrogen, followed by calcium, potassium, magnesium and the lowest for phosphorus. In fact, Nt values for nitrogen were twenty nine, fourteen, nine and two times higher than those for phosphorus, magnesium, potassium and calcium, respectively. The annual Nt values for the 2 years of monitoring are presented in Table 3.

3.3 | Effect of land cover and rainfall seasonality and intensity on Sr and Er

We found significant differences for both Sr and Er between hydrological seasons and between cover type. In the wet season, both Sr and Er were significantly higher ($P < 0.05$) than in the dry season (in the four covers) (Figure 3). Sr was significantly different between pasture and the other cover types (being higher in pasture) and with no significant differences between both crops (Figure 3a). Both crops had significantly higher Er than the oak forest and pasture ($P < 0.05$) but without differences neither between both crops nor between oak forest and pasture ($P > 0.05$) (Figure 3b). Finally, Nt was directly correlated (strong linear relationship, $P < 0.05$) to Er. Therefore, the effect of cover type and rainfall seasonality and intensity on Er was also reflected in Nt.

An exploratory analysis of the relationships between Er and the maximum and average intensity, discriminating between wet and dry seasons, was carried out for the four cover types and for the total monitoring time (Table 4). An effect of rainfall seasonality was observed for the entire period (when not discriminating by season). All models were significant (except in the pasture with maximum intensity). In the wet seasons, no model was significant, while in the dry seasons, models for maximum rainfall intensity were significant in both crops and in the oak forest, and models with mean intensity were significant for both types of crops.

According to the results of the slope parallelism test performed in the significant models, we found significant differences in only three cases (Table 4). Thus, for the entire study period, and considering the maximum rainfall intensity, an increase in one unit of the latter determines on average increases in the Er of up to 31 times in the oak forest and pasture, with respect to the permanent crop. Similarly, a one-unit increase in average rainfall intensity leads to an average increase in Er of up to 23 times in the oak forest with respect to the permanent crop (Table 4).

4 | DISCUSSION

4.1 | Effect of rainfall seasonality and intensity on Sr, Er and Nt rates across a land cover gradient

Sr, Er and Nt processes varied significantly among different land cover types and between hydrological seasons. Previous studies have verified a positive association between Sr and Er (Wang et al., 2010). Our results showed that in all cover types, Sr and Er correlate significantly without discriminating between hydrological seasons, but when discriminating between seasons, this significant correlation only occurs in both crops during the wet season and in the oak forest in the dry season (Table 2). This is potentially associated with higher rainfall during the wet season that generates higher Sr and Er in the crops, while in the oak forest and pasture, there is a greater soil protection, since in these cover types, a higher rainfall does not necessarily generate higher Sr and Er.

Since cover type and land use affect Sr, Er and Nt rates, we found that the highest Er and Nt occurred in the cover with the lowest Sr, with Nt being directly proportional to Er. Sr was significantly higher in the pasture (Figure 3a; $P < 0.05$) where low Er and Nt values were present, while Sr was low in both crops where significantly higher Er and Nt values were present (Figure 3b; $P < 0.05$). The low Er in the pasture may be the result of soil compaction because of cattle trampling, which decreases the impact and detachment of surface soil particles by the raindrop (Basant et al., 2020; Magliano et al., 2019). Also the protective effect of grass cover in contact with the soil surface, which decreases the kinetic energy of the raindrop, and with it its erosive potential has been reported. However, the high Sr in the pasture, associated with lower infiltration (Peng & Wang, 2012), carry a different problem of high nutrient losses in solution (Suescún et al., 2017). Other studies reported similarly higher Er values under bare soil conditions as in our crop sites (Zhang et al., 2011), although they did not differentiate between hydrological seasons.

Crop type and tillage practices can generate higher Er and Nt with consequences on soil degradation and loss of sustainable land production. Our results show a strong interaction between Er and the cropping system and management, an interaction that governs the rate and magnitude of soil degradation in this type of cover (Ehigiator & Anyata, 2011). Transitory crops, by not providing a permanent protective cover to the soil surface, are more susceptible to Er and Nt generation, particularly in very rainy and hilly areas. Consequently, permanent crops, compared to transitory crops, would appear to be less impactful in terms of natural resource conservation, particularly for maintaining soil and water quality regulation. The implementation of soil conservation practices such as minimum tillage is of particular interest for these purposes in tropical montane regions, where factors such as high slope relief and high rainfall intensity are often combined. There, the replacement of transitory crops with permanent crops could have a positive impact on the control of Er and Nt rates (Wang et al., 2010).

In contrast, the oak forest exhibited a significantly lower Er than crops ($P < 0.05$), as reported by other studies (Sun et al., 2016), contributing to soil and water conservation (Zhang et al., 2015), a result that is constant through both wet and dry seasons (Figure 3b). This is due to the presence of a canopy and a litter layer, which protect the soil surface from the impact of raindrops, jointly absorbing their kinetic energy and temporarily storing water. As a result, Es, Er and Nt rates are reduced, and the infiltration process is favoured (Sun et al., 2016) which supports ecosystem services related to hydrologic regulation (Zhang et al., 2015).

TABLE 2 Pearson's correlation coefficient values for Sr and Er in each cover type

Land cover	Total period ($n = 102$)	Wet season ($n = 35$)	Dry season ($n = 67$)
Oak forest	0.54*	0.31	0.41*
Pasture	0.36*	0.28	0.10
Transitory crops	0.54*	0.63*	0.12
Permanent crops	0.23*	0.42*	0.05

*Correlations that were significant ($P < 0.05$).

TABLE 3 Annual values (±standard deviation) of nutrient transport associated with erosion (Nt) in g/ha for the four vegetation cover types

Nt mean (g/ha/year)					
Vegetation cover	**Ca**	**Mg**	**K**	**P**	**N**
Oak forest	0.74 ± 0.94	0.11 ± 0.14	0.18 ± 0.23	0.04 ± 0.03	6.90 ± 3.39
Pasture	0.75 ± 0.50	0.11 ± 0.07	0.13 ± 0.09	0.21 ± 0.17	6.81 ± 6.45
Transitory crop	205.25 ± 128.79	25.43 ± 15.67	56.84 ± 35.45	20.04 ± 7.85	399.92 ± 158.30
Permanent crop	174.53 ± 40.57	22.58 ± 7.45	22.47 ± 11.83	7.52 ± 1.03	265.26 ± 127.32

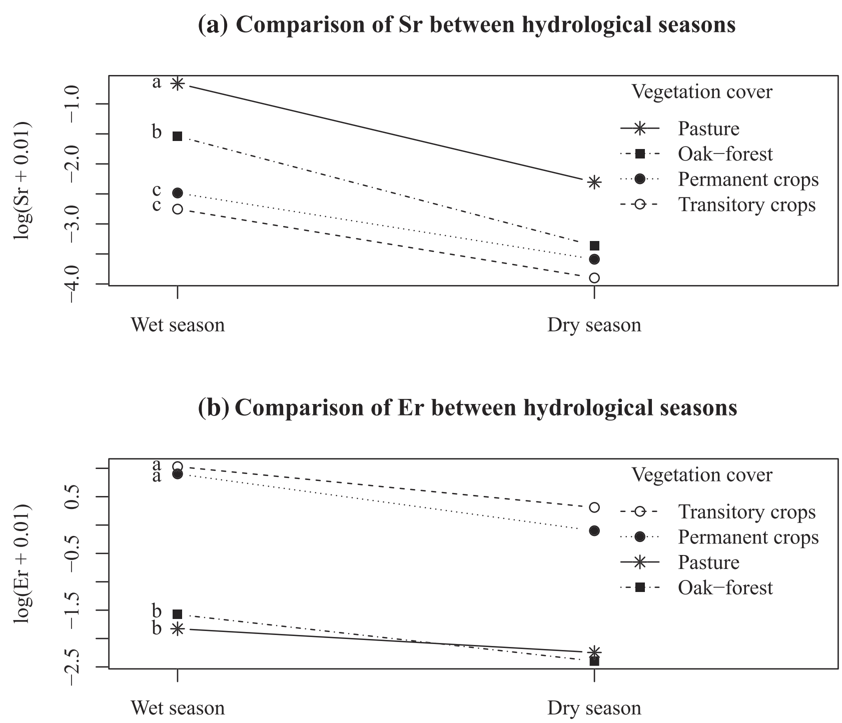

FIGURE 3 Comparison of Sr and Er rates between wet and dry hydrological seasons and between vegetation covers. Inside the figure, letters a, b and c denote similarities or differences between cover types.

In addition to the effect of vegetation cover and land use on Sr, Er and Nt rates, climatic conditions can significantly influence these processes (Cano-Arboleda et al., 2022; Xiao et al., 2015). In fact, rainfall characteristics such as magnitude and intensity exhibit a linear correlation with Sr and Er (Cortés et al., 2020; Wang et al., 2010). The wet and dry conditions associated with rainfall seasonality during the monitoring time provided us with the opportunity to quantify the variation in Er and Nt because both processes are driven by rainfall and Sr. Our results showed that the differences in Sr and Er between cover types vary depending on the hydrological season. Thus, Er was not different between both crops ($P < 0.05$; Figure 3b).

In the oak forest, Er was significantly lower than in both types of crops, both for both wet and dry seasons, indicating a high resilience of this cover to the change of hydrological seasons, again exhibiting a better role as a regulator of the ecosystem functions of erosion control and nutrient regulation. This is important considering that ongoing climate variability may alter the rainfall regimes, increasing the likelihood of increasingly intense hydrological extremes (Pedersen et al., 2021), and potentially altering rainfall behaviour and seasonality.

Different studies have found that Er increases linearly with increasing rainfall intensity (Luo et al., 2013), a relationship that we analysed between hydrological seasons. All regression models were significant when not discriminating between seasons (except in the pasture with the maximum intensity, Table 4), but in the wet seasons, no model was significant, while in the dry seasons, only the models in both crops and oak forest with the maximum intensity were significant. The effect of rainfall seasonality on the relationship between rainfall intensity and Er was evident. Apparently, in the wet season, when the soil is saturated, it does not matter if rain is more or less intense as the infiltration capacity will be low, allowing the generation of Sr and Er.

4.2 | Implications of Er and Nt on water and soil quality

Our results indicate that the greatest effects on erosion and loss of nutrients (due to erosion) occur in both crops, which in the case of the Río Grande basin represent 2.2% of the basin. In contrast, the forests that represent a larger area (22.3% of the basin) had less erosion and loss of nutrients. The most dominant cover in the watershed (pastures with 58.0%) also had low nutrient loss due to erosion, but high nutrient loss due to surface runoff, as indicated in previous studies (García-Leoz et al., 2018; Suescún et al., 2017).

In general, the highest Nt values occurred for nitrogen, while phosphorus was the lowest, Nt being higher in both crops compared to the forest and pasture. The biological availability of nitrogen and phosphorus has important implications for a variety of ecological processes, including the regulation of water and soil quality (Corman et al., 2015). In fact, in agricultural areas, nitrogen and phosphate are the main indicators of soil fertility and soil quality (Xu et al., 2015). However, in agriculture, the excess use of both is recognized as the main cause of surface and groundwater contamination (Martínez et al., 2009; Vadas et al., 2015; Xu et al., 2015). Future nitrogen deposition from the atmosphere to the land surface is predicted to be particularly high in many forests, due to increased biomass burning and fertilizer use, with important implications for biogeochemical cycling. However, the impact of processes occurring in the soil (such as Er and Nt) on biogeochemical cycling is one of the major uncertainties in the understanding of global climate change (Quinton et al., 2010).

The use of agrochemicals can lead to degradation in water quality. This is particularly important in high mountain ecosystems with steep slopes, where intensive agriculture increases Er and Nt by driving agrochemicals into surface and groundwater, potentially reducing soil fertility, causing sedimentation and increasing nutrient content in water bodies (eutrophication) (Recanatesi et al., 2013). This pollution by agrochemical discharge from productive systems is one of the main environmental concerns in the world, as it limits the use of water for drinking, recreation and industry (Vadas et al., 2015).

4.3 | Implications of land cover conversion and rainfall variability on the provision of ecosystem services in tropical mountain areas

Water and nutrient flows within and between ecosystems are provisioning and regulating ecosystem services. Many processes occurring in the canopy provide essential ecosystem services that humans depend on for survival. When the canopy, as a provider of global services, is altered, the resulting changes can have global-scale repercussions (Lowman & Schowalter, 2012). Particularly, tropical montane

TABLE 4 Slope values of the regression models for Er in each cover type, with maximum and mean intensity as independent variables

	Total period		Wet season		Dry season	
Vegetation cover	Maximum intensity	Mean intensity	Maximum intensity	Mean intensity	Maximum intensity	Mean intensity
Oak forest	**0.002[a]**	**0.043[c]**	0.001	0.025	**0.002[e]**	0.022
Pasture	**0.002[a]**	0.023	0.001	1.267	0.002	0.016
Transitory crop	**0.110[a]**	**1.882[c]**	0.086	0.020	**0.084[e]**	**1.257[g]**
Permanent crop	**0.062[b]**	**0.968[d]**	0.061	0.992	**0.046[f]**	**0.657[g]**

Note: Numbers in bold denotes significant models ($P < 0.05$). For each column, different superscripts indicate significant differences ($P < 0.05$) between slopes according to the slope parallelism test for the regression models. Only the slopes of the models that were significant were compared.

forests and mountain rivers maintain important services to society, such as water supply and quality and baseflow during dry periods (Martínez et al., 2009; Vanacker et al., 2014).

One of the hydrological effects of forest canopies is the partitioning of incoming precipitation into throughfall, stemflow and evaporation of intercepted water (Parker, 1983). This partitioning determines water and nutrient fluxes to soil. Water fluxes in the canopy (stemflow and throughfall) are controlled by climate, meteorology, type and structure of forest and spatial configuration of the canopy (Van Stan et al., 2016). These conditions affect both nutrient concentrations and their fluxes in water which reach the soil (Van Stan & Pypker, 2015). In the oak forest of the present study, Suescún et al. (2019) found that throughfall represented 87% total precipitation, while stemflow represented only 0.4%. In both wet and dry seasons, forest canopies produced nutrient concentration enrichment in throughfall and stemflow. The results indicate that the increase and intensification of droughts, and increases in the transformation of forests Andes, could affect the capacity to regulate functions of these ecosystems.

The conversion of forests to agriculturally productive systems is associated with a decrease in ecosystem services (Balthazar et al., 2015; Grizzetti et al., 2016), soil degradation and deterioration of water quality. This conversion also implies a significant economic loss for society in terms of ecosystem services, although market gains drive landowners to convert for improved income (Martínez et al., 2009). Our results support this assertion, since both crops exhibited a significantly higher Er than the oak forest, in addition to having, on average, the highest Nt (Table 3). Consequently, the regulatory effect of the oak forest, controlling the Er and Nt processes, is affected by its conversion to crops and reflects the alteration of the capacity of natural ecosystems to provide environmental services associated with water and soil quality.

5 | CONCLUSION

In this work, we show how the dynamics of land cover change and land use interact with the seasonality and intensity of rainfall to alter the processes of Sr, Er and Nt. In the oak forest, we found minimum values of Er and Nt, processes that accelerated in the crop stage, but decrease to values very similar to those of the oak forest in the pasture stage. Er and Nt increase and decrease following the dynamics of land use change in the study area. Thus, Er increases with the conversion of oak forests to crops and with the increase in rainfall intensity, so that soil formation cannot compensate for its losses and its capacity to regulate ecosystem functions such as erosion control regulation and nutrient regulation decreases, which depletes soil resources and environmental services that support ecosystems.

ACKNOWLEDGEMENTS

Funding was provided by Departamento Administrativo de Ciencia, Tecnología e Innovación (COLCIENCIAS) (Convocatoria 543-2011). J. C. Villegas was supported by Colombian Ministry of Science, Technology and Innovation (MINCIENCIAS) through the research programme 'Sostenibilidad de sistemas ecológicos y sociales en la cuenca Magdalena-Cauca bajo escenarios de cambio climático y pérdida de bosques' (Code: 1115-852-70719). Field and laboratory support was provided by C. P. Flórez, V. García-Leoz, A. I. Cardona, A. M. Martin, J. Sánchez, L. I. Arango, Y. A. Vélez, C. J. Caraballo, E. J. Guana and J. S. Orozco. We also thank Óscar and Martha Pérez for access and logistics at field site.

SIGNIFICANCE STATEMENT

Forests provide essential environmental services to society, particularly in mountain regions in the Tropics. Nevertheless, climate and land use affect these services. We evaluate the effect of land use and the characteristics of rainfall on erosion control and nutrient regulation for 2 years, contrasting wet and dry seasons. Our results show an effect of land use and rainfall seasonality on erosion and nutrient loss, both processes being higher in croplands and lower in forest, both for the wet and dry seasons. These results highlight the impacts of converting forests into crops, affecting the capacity of ecosystems to provide environmental services.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Juan Diego León https://orcid.org/0000-0002-3442-7649
Juan Camilo Villegas https://orcid.org/0000-0001-5048-921X

REFERENCES

Balthazar, V., Vanacker, V., Molina, A., & Lambin, E. F. (2015). Impacts of forest cover change on ecosystem services in high Andean mountains. *Ecological Indicators*, *48*, 63–75. https://doi.org/10.1016/j.ecolind.2014.07.043

Basant, S., Wilcox, B. P., Leite, P. M., & Morgan, C. L. (2020). When savannas recover from overgrazing, ecohydrological connectivity collapses. *Environmental Research Letters*, *15*(5), 054001. https://doi.org/10.25412/iop.11608233.v1

Cano-Arboleda, L. V., Villegas, J. C., Restrepo, A. C., & Quintero-Vallejo, E. (2022). Complementary effects of tree species on canopy rainfall partitioning: New insights for ecological restoration in Andean ecosystems. *Forest Ecology and Management*, *507*, 119969. https://doi.org/10.1016/j.foreco.2021.119969

Cohen, M. J., Brown, M. T., & Shepherd, K. D. (2006). Estimating the environmental costs of soil erosion at multiple scales in Kenya using emergy synthesis. *Agriculture, Ecosystems & Environment*, *114*(2–4), 249–269. https://doi.org/10.1016/j.agee.2005.10.021

Corman, J. R., Moody, E. K., & Elser, J. J. (2015). Stoichiometric impact of calcium carbonate deposition on nitrogen and phosphorus supplies in three montane streams. *Biogeochemistry*, *126*(3), 285–300. https://doi.org/10.1007/s10533-015-0156-6

Cortés, S. S., Whitworth-Hulse, J. I., Piovano, E. L., Gurvich, D. E., & Magliano, P. N. (2020). Changes in rainfall partitioning caused by the replacement of native dry forests of *Lithraea molleoides* by exotic plantations of *Pinus elliottii* in the dry Chaco mountain forests, central Argentina. *Journal of Arid Land*, *12*(5), 717–729. https://doi.org/10.1007/s40333-020-0070-1

Ehigiator, O. A., & Anyata, B. U. (2011). Effects of land clearing techniques and tillage systems on runoff and soil erosion in a tropical rain forest in Nigeria. *Journal of Environmental Management*, *92*(11), 2875–2880. https://doi.org/10.1016/j.jenvman.2011.06.015

Field, J. P., Breshears, D. D., Whicker, J. J., & Zou, C. B. (2011). On the ratio of wind-to water-driven sediment transport: Conserving soil under global-change-type extreme events. *Journal of Soil and Water Conservation*, *66*(2), 51A–56A. https://doi.org/10.2489/jswc.66.2.51A

García-Leoz, V., Villegas, J. C., Suescún, D., Flórez, C. P., Merino-Martín, L., Betancur, T., & León, J. D. (2018). Land cover effects on water balance partitioning in the Colombian Andes: Improved water availability in early stages of natural vegetation recovery. *Regional Environmental Change*, *18*(4), 1117–1129. https://doi.org/10.1007/s10113-017-1249-7

Grizzetti, B., Lanzanova, D., Liquete, C., Reynaud, A., & Cardoso, A. C. (2016). Assessing water ecosystem services for water resource management. *Environmental Science & Policy*, *61*, 194–203. https://doi.org/10.1016/j.envsci.2016.04.008

Guo, Q., Hao, Y., & Liu, B. (2015). Rates of soil erosion in China: A study based on runoff plot data. *Catena*, *124*, 68–76. https://doi.org/10.1016/j.catena.2014.08.013

Jones, J. B. Jr., Wolf, B., & Mills, H. A. (1991). *Plant analysis handbook. A practical sampling, preparation, analysis, and interpretation guide*. Micro-Macro Publishing, Inc.

Kalra, Y. P., & Maynard, D. G. (1991). *Methods manual for forest soil and plant analysis* (Vol. 319). Northern Forestry Center, Canada.

Klute, A. (1986). *Methods of soil analysis. Part 1. Physical and mineralogical methods*. SSSA Book Series 5. Soil Science Society of America.

Lowman, M. D., & Schowalter, T. D. (2012). Plant science in forest canopies—The first 30 years of advances and challenges (1980–2010). *New Phytologist*, *194*(1), 12–27. https://doi.org/10.1111/j.1469-8137.2012.04076.x

Luo, H., Zhao, T., Dong, M., Gao, J., Peng, X., Guo, Y., Wang, Z., & Liang, C. (2013). Field studies on the effects of three geotextiles on runoff and erosion of road slope in Beijing, China. *Catena*, *109*, 150–156. https://doi.org/10.1016/j.catena.2013.04.004

Magliano, P. N., Mindham, D., Tych, W., Murray, F., Nosetto, M. D., Jobbágy, E. G., Niborski, M. J., Rufino, M. C., & Chappell, N. A. (2019). Hydrological functioning of cattle ranching impoundments in the Dry Chaco rangelands of Argentina. *Hydrology Research*, *50*(6), 1596–1608. https://doi.org/10.2166/nh.2019.149

Martínez, M. L., Pérez-Maqueo, O., Vázquez, G., Castillo-Campos, G., García-Franco, J., Mehltreter, K., Equihua, M., & Landgrave, R. (2009). Effects of land use change on biodiversity and ecosystem services in tropical montane cloud forests of Mexico. *Forest Ecology and Management*, *258*(9), 1856–1863. https://doi.org/10.1016/j.foreco.2009.02.023

Parker, G. G. (1983). Throughfall and stemflow in the forest nutrient cycle. *Advances in Ecological Research*, *13*, 57–133. https://doi.org/10.1016/S0065-2504(08)60108-7

Paroissien, J. B., Darboux, F., Couturier, A., Devillers, B., Mouillot, F., Raclot, D., & Le Bissonnais, Y. (2015). A method for modeling the effects of climate and land use changes on erosion and sustainability of soil in a Mediterranean watershed (Languedoc, France). *Journal of Environmental Management*, *150*, 57–68. https://doi.org/10.1016/j.jenvman.2014.10.034

Pedersen, J. S. T., Santos, F. D., van Vuuren, D., Gupta, J., Coelho, R. E., Aparício, B. A., & Swart, R. (2021). An assessment of the performance of scenarios against historical global emissions for IPCC reports. *Global Environmental Change*, *66*, 102199. https://doi.org/10.1016/j.gloenvcha.2020.102199

Peng, T., & Wang, S. J. (2012). Effects of land use, land cover and rainfall regimes on the surface runoff and soil loss on karst slopes in southwest China. *Catena*, *90*, 53–62. https://doi.org/10.1016/j.catena.2011.11.001

Quinton, J. N., Govers, G., Van Oost, K., & Bardgett, R. D. (2010). The impact of agricultural soil erosion on biogeochemical cycling. *Nature Geoscience*, *3*(5), 311–314. https://doi.org/10.1038/ngeo838

Ramírez, C. D. (2014). *Spatially explicit determinants of land cover transitions with significant impact on the provision of ecosystem services: Temporal and spatial analysis 1986-2012*. Thesis. MSc in Environment and Development. Universidad Nacional de Colombia, Sede Medellín.

Recanatesi, F., Ripa, M. N., Leone, A., Luigi, P., & Luca, S. (2013). Land use, climate and transport of nutrients: Evidence emerging from the Lake Vicocase study. *Environmental Management*, *52*(2), 503–513. https://doi.org/10.1007/s00267-013-0060-6

Silva, L. C., & Lambers, H. (2021). Soil-plant-atmosphere interactions: Structure, function, and predictive scaling for climate change mitigation. *Plant and Soil*, *461*(1), 5–27. https://doi.org/10.1007/s11104-020-04427-1

Suescún, D., Villegas, J. C., León, J. D., Flórez, C. P., García-Leoz, V., & Correa-Londono, G. A. (2017). Vegetation cover and rainfall seasonality impact nutrient loss via runoff and erosion in the Colombian Andes. *Regional Environmental Change*, *17*(3), 827–839. https://doi.org/10.1007/s10113-016-1071-7

Suescún, D., León, J. D., Villegas, J. C., García-Leoz, V., Correa-Londoño, G. A., & Florez, C. P. (2019). ENSO and rainfall seasonality affect nutrient exchange in tropical mountain forests. *Ecohydrology*, *12*(2), e2056. https://doi.org/10.1002/eco.2056

Suescún, D., Villegas, J. C., León, J. D., & Correa-Londoño, G. A. (2021). Observational insights on the effects of land use and precipitation seasonality on water-driven circulation of phosphorus in the Tropical Andes. *Water, Air, & Soil Pollution*, *232*(6), 1–14. https://doi.org/10.1007/s11270-021-05195-z

Sun, J., Yu, X., Li, H., Chang, Y., Wang, H., Tu, Z., & Liang, H. (2016). Simulated erosion using soils from vegetated slopes in the Jiufeng Mountains, China. *Catena*, *136*, 128–134. https://doi.org/10.1016/j.catena.2015.02.019

Vadas, P. A., Busch, D. L., Powell, J. M., & Brink, G. E. (2015). Monitoring runoff from cattle-grazed pastures for a phosphorus loss quantification tool. *Agriculture, Ecosystems & Environment*, *199*, 124–131. https://doi.org/10.1016/j.agee.2014.08.026

Van Stan, J. T. II, & Pypker, T. G. (2015). A review and evaluation of forest canopy epiphyte roles in the partitioning and chemical alteration of precipitation. *Science of the Total Environment*, *536*, 813–824. https://doi.org/10.1016/j.scitotenv.2015.07.134

Van Stan, J. T., Gay, T. E., & Lewis, E. S. (2016). Use of multiple correspondence analysis (MCA) to identify interactive meteorological conditions affecting relative throughfall. *Journal of Hydrology*, *533*, 452–460. https://doi.org/10.1016/j.jhydrol.2015.12.039

Vanacker, V., Bellin, N., Molina, A., & Kubik, P. W. (2014). Erosion regulation as a function of human disturbances to vegetation cover: A conceptual model. *Landscape Ecology*, *29*(2), 293–309. https://doi.org/10.1007/s10980-013-9956-z

Wang, L., Tang, L., Wang, X., & Chen, F. (2010). Effects of alley crop planting on soil and nutrient losses in the citrus orchards of the Three Gorges Region. *Soil & Tillage Research*, *110*(2), 243–250. https://doi.org/10.1016/j.still.2010.08.012

Xiao, L., Yang, X., Chen, S., & Cai, H. (2015). An assessment of erosivity distribution and its influence on the effectiveness of land use conversion for reducing soil erosion in Jiangxi, China. *Catena*, *125*, 50–60. https://doi.org/10.1016/j.catena.2014.10.016

Xu, G., Cheng, Y., Li, P., Li, Z., Zhang, J., & Wang, T. (2015). Effects of natural rainfall on soil and nutrient erosion on sloping cropland in a small watershed of the Dan River, China. *Quaternary International*, *380*, 327–333. https://doi.org/10.1016/j.quaint.2015.02.010

Zhang, G. H., Liu, G.-B., Wang, G.-L., & Wang, Y.-X. (2011). Effects of vegetation cover and rainfall intensity on sediment-bound nutrient loss, size composition and volume fractal dimension of sediment particles. *Pedosphere*, *21*(5), 676–684. https://doi.org/10.1016/S1002-0160(11)60170-7

Zhang, L., Wang, J., Bai, Z., & Lv, C. (2015). Effects of vegetation on runoff and soil erosion on reclaimed land in an opencast coal-mine dump in a loess area. *Catena*, *128*, 44–53. https://doi.org/10.1016/j.catena.2015.01.016

How to cite this article: Suescún, D., León, J. D., Villegas, J. C., & Correa-Londoño, G. A. (2023). Nutrient loss to erosion responds to rain characteristics under transformed landscapes in the Río Grande basin, Colombian Andes. *Ecohydrology*, e2519. https://doi.org/10.1002/eco.2519