Geoderma 435 (2023) 116505

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Land use effects on surface runoff and soil erosion in a southern Alpine valley

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ARTICLE INFO

Handling Editor: Morgan Cristine L.S.

Keywords:
Rainfall simulation
Land use change
Landscape Stability
Soil water repellence
Soil erosion
Agricultural terraces

ABSTRACT

In mountain regions, soil landscapes are highly vulnerable against soil loss. Moreover, these environments are particularly affected by land use changes, which influence soil properties and related processes like surface runoff generation and soil erosion. These processes are in turn amplified by extreme climatic events and intensive geomorphological dynamics. The objective of this study is to quantitatively assess the effects of land use changes on surface runoff and soil erosion in a southern Alpine valley (Onsernone valley, Switzerland) characterized by a former intense land use followed by a progressive abandonment in the last decades. Surface runoff and related sediment transport has been analysed under controlled and reproducible conditions using a portable rainfall simulator device (1 m^2). The results show a statistically significant increase in surface runoff when the soil gets water repellent reducing the surface infiltration capacity and generating preferential flow paths, which prevent a homogeneous wetting of the soil. However, the documented high sensitivity of surface runoff to land use changes does not result in an equally high sensitivity to soil erosion processes. Instead, soils display a high aggregate stability leading to very low sediment transports except for abandoned and reforested agricultural terraces. There, the lack of maintenance and progressive collapse of terrace dry walls locally increase slope angles and directly exposes the soil to atmospheric agents and surface runoff, which causes soil erosion rates beyond the customary natural level.

1. Introduction

Steep mountain slopes combined with episodically intense and high erosive rainfall confer to the Alpine soil landscape a high vulnerability against erosion-induced soil loss. In such circumstances, land use has a specific influence on soil properties and the related sensitivity to surface runoff and soil erosion (Bettoni et al., 2022; Gordon et al., 2001; Panagos et al., 2015). As a consequence, land use changes are one of the most important causes for accelerated soil erosion (Borrelli et al., 2017; Zema et al., 2012), generally coming along with a loss of fertile topsoil (Bayramin et al., 2008). According to Panagos et al. (2015), in the Alps soil loss rates may exceed 5 t ha^{-1} yr^{-1}. In turn, soil erosion affects soil productivity and existing options for a sustainable soil management, eventually leading to a decrease in crop production, an overall decline of arable land, and subsequently to socio-economic problems (Bruce et al., 1995; Märker et al., 2008; Pelacani et al., 2008; Rasoulzadeh et al., 2019).

Specific and distinct influences of land use changes on soil properties

Abbreviations: SWR, Soil Water Repellence; SOC, Soil Organic Carbon; SOM, Soil Organic Matter; K_{sat}, Saturated Hydraulic Conductivity; PARS, Portable Automated Rainfall Simulator; TDR, Time domain reflectometry; MED test, Molarity of Ethanol Droplet test; RLF, Rising Limb Factor; FS_S, South-facing forested slopes; DT_S, South-facing deforested, cultivated terraces; FT_S, South-facing (re-)forested, abandoned terraces; FS_N, North-facing forested slopes; PS, Pastures on slopes; MS_N, North-facing meadows on slopes; LCTUs, Land cover-topography units.

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https://doi.org/10.1016/j.geoderma.2023.116505
Received 20 October 2022; Received in revised form 6 April 2023; Accepted 4 May 2023
Available online 15 May 2023

concern saturated hydraulic conductivity, aggregate stability (Bettoni et al., 2022; Cantón et al., 2009; Cerdà, 1998), and soil water repellence (Doerr et al., 2003; Lemmnitz et al., 2008; Miyata et al., 2007). Aggregate stability is strongly influenced by the amount of soil organic carbon (SOC) (Haynes and Swift, 1990; Le Bissonnais and Arrouays, 1997; Smith et al., 2015), which is often higher under forest vegetation, where a low biodegradability of soil organic matter (SOM) favours the accumulation of SOC (Guo and Gifford, 2002). However, under agricultural use, SOC is generally lower due to regular tillage and biomass harvesting (Guo and Gifford, 2002; Rehfuess, 1990; Vogel and Conedera, 2020). The amount of SOC together with the quality and composition of SOM (Doerr et al., 2000; Fu et al., 2021; Lozano et al., 2013) eventually influence soil water repellence, which may have a large effect on infiltration processes and surface runoff (Miyata et al., 2007; Ritsema et al., 1993; Ritsema and Dekker,1994; Ritsema and Dekker, 1995; Witter et al., 1991; Wang et al., 2000).

Despite such evident influence on soil properties, land use changes do not necessarily have a direct impact on the stability of the soil landscape and specific investigations are needed for understanding this relationship. One of the methodological approaches to assess these relationships consists of using controlled and reproducible precipitation simulations. As shown by several authors in the past, rainfall simulators have proved to be reliable instruments for the identification and quantification of hydrological processes and soil erosion rates (e.g. Iserloh et al., 2012; Iserloh et al., 2013a; Fister et al., 2012; Martínez-Murillo et al., 2013; Lassu et al., 2015; Prosdocimi et al., 2016; Mayerhofer et al., 2017). Iserloh et al. (2013c) compared 13 different typologies of portable automated rainfall simulators (PARS) and stated that rainfall simulators may differ for the area covered during simulation, the adjustable intensity of precipitation, the dimension of raindrops, and the homogeneity of coverage of the plot. However, the common criterion is that the kinetic energy reached by the simulator is lower compared to natural rainfall. This is explained by the much lower fall height provided by the rainfall simulator that does not allow to reach the terminal velocity of natural raindrops (Iserloh et al., 2013c). However, PARS allows the direct measurement of surface runoff and soil erosion under different land use conditions without any alteration of soil structure and surface. Moreover, it allows to measure the integrated effect of influencing factors such as slope steepness, surface roughness, soil permeability, soil water repellence, vegetation cover, aggregate stability, and soil moisture (Bowyer-Bower and Burt, 1989; Iserloh et al., 2013c). For the sake of simplicity and applicability, often a plot size of 1 m^2 is used as reported by Iserloh et al. (2013b). However, several experiments should be conducted due to varying site characteristics (Mayerhofer et al., 2017).

The overall aim of this study is to assess the effects of land use changes on surface runoff, soil erosion, and sediment transport in a southern Alpine valley, thus, allowing also to evaluate the effects of these processes on soil landscape sensitivity. Therefore, we conduct surface runoff and soil erosion measurements under controlled and reproducible precipitation conditions using a small PARS on sites characterized by different land use-topography settings.

2. Material and methods

2.1. Study area

The study area covers approximately 6 km^2 in the Onsernone Valley (Canton Ticino, Southern Switzerland; Fig. 1) at altitudes ranging from 400 to 1000 m asl. Following the Köppen climate classification, the climate is considered as oceanic (Cfb) (Kottek et al., 2006). Dry winters are followed by rainy springs and autumns with a mean annual precipitation of roughly 2,000 mm and a mean annual temperature of about 12° (MeteoSwiss, 2020). Moreover, the study area is characterized by intense summer rainfall events, which may exceed 400 mm/day (MeteoSwiss, 2020).

The Onsernone valley is E-W oriented with morphological evidences

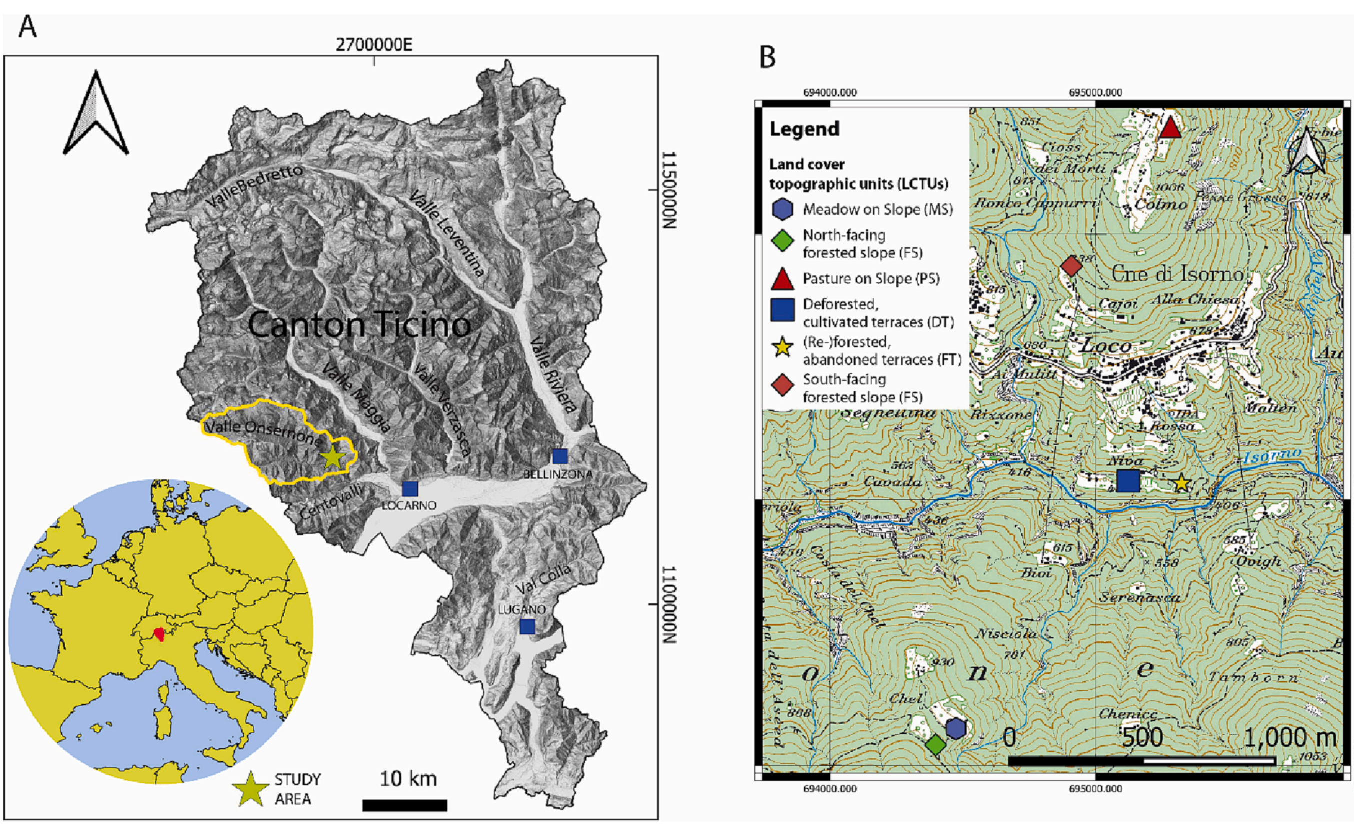


Fig. 1. A: Map of Canton Ticino with the location of the study area (Federal Office of Topography, swisstopo) after Bettoni et al. (2022), B: Land cover-topographic units (LCTUs). Based on Swiss Map Raster 10 (Federal office of Topography, Swisstopo) SR: CH1903/LV03.

related to the dominant fluvio-glacial processes resulting in deep incisions and steep slopes between 30 and 50° (average 36°). The Quaternary evolution of the valley was significantly influenced by fluvial, glacial, and gravitational processes (Fig. 2a, d, e). The valley presents a typical V-shaped profile indicating fluvial processes as dominant during morphogenesis (Fig. 2e and f). However, some evidence of glacial phases, i.e., transfluence passes, erratic boulders as well as glacial deposits can be observed in the field (Bettoni et al., 2022). Other geomorphological evidence relates to the slope evolution resulting from deposits associated to debris flows as well as rockfalls (Fig. 2d and g). In general, the morphological evolution of the valley follows the geological and structural settings of the area. It is enclosed in a tight synform fold, and the bedrock is composed of gneiss rich in plagioclase, quartz, biotite and muscovite (Blaser, 1973) belonging to the Antigorio-Mergoscia complex (Pfeifer et al., 2018). Following the Word Reference Base for Soil Resources (WRB) (IUSS Working Group WRB, 2015), the soil cover of the study area consists of tick sequences of Podzols and Cambisol depending on vegetation, agricultural use and microclimate (Blaser et al., 1999, 1997). In particular, Podzols are characterized by a thick topsoil A horizon, rich in SOM, which tend to macroscopically mask the eluvial horizon. Hence these soils have also been classified as Cryptopodzols (Blaser, 1973; Blaser et al., 1999, 1997; Blaser and Klemmedson, 1987). Soils are generally characterized by sandy loam textures following the ASTM standards (American Society for Testing Materials, 1988) (see also Bettoni et al., 2022). This favours water drainage, leaching into the subsoil, and deep and well-developed soil profiles even on steep slopes and close to the watershed divide.

On the north-facing slopes, the vegetation cover is characterized by extended European beech (*Fagus sylvatica L.*) forests, whereas south-facing slopes are composed of mixed hardwood stands of *Castanea sativa* Mill., deciduous oaks (*Quercus* spp.), *Alnus glutinosa* (L.) Gaertn., and *Tilia cordata* Mill. in variable compositions according to specific site characteristics and local management (Muster et al., 2007; Vogel and Conedera, 2020). Land use and the related vegetation cover have an influence on the intensity of soil acidification and podzolisation processes (Vogel, 2005; Vogel and Conedera, 2020). As a result, Cryptopodzols are prevalent under forest vegetation, while Cambisols are found on deforested sites.

2.2. Land use history

The Onsernone valley is characterized by a long land use history starting from Roman times (Crivelli, 1943) and intensifying during the Middle Ages. The absence of a recent valley floor led to the deforestation of the south-facing slopes and a strong anthropic reshaping of the valley related to the construction of agricultural terraces in order to increase the arable land (Canale, 1958; Wähli, 1967; Zoller, 1960). The peak in the spatial extension of terraces was reached during the 16th century in relation to the rye cultivation for straw plaiting (Waehli, 1967; Zoller, 1960). However, north-facing slopes remained widely excluded from permanent settlements and have been mostly exploited by intense silviculture and charcoal production. In areas of lower steepness, small-size pastoral farming was established.

Starting with the cessation of straw plaiting at the end of the first world war and with the decline of traditional, marginal Alpine farming in the 1950s, a successive abandonment of land use is documented, which resulted in a progressive reforestation of formerly cultivated sites. Consequently, nowadays the man-made terraces are poorly maintained and only partially used as vineyards or orchards characterized by a dense grass cover (Fig. 2b and c). Furthermore, pastoral farming is still

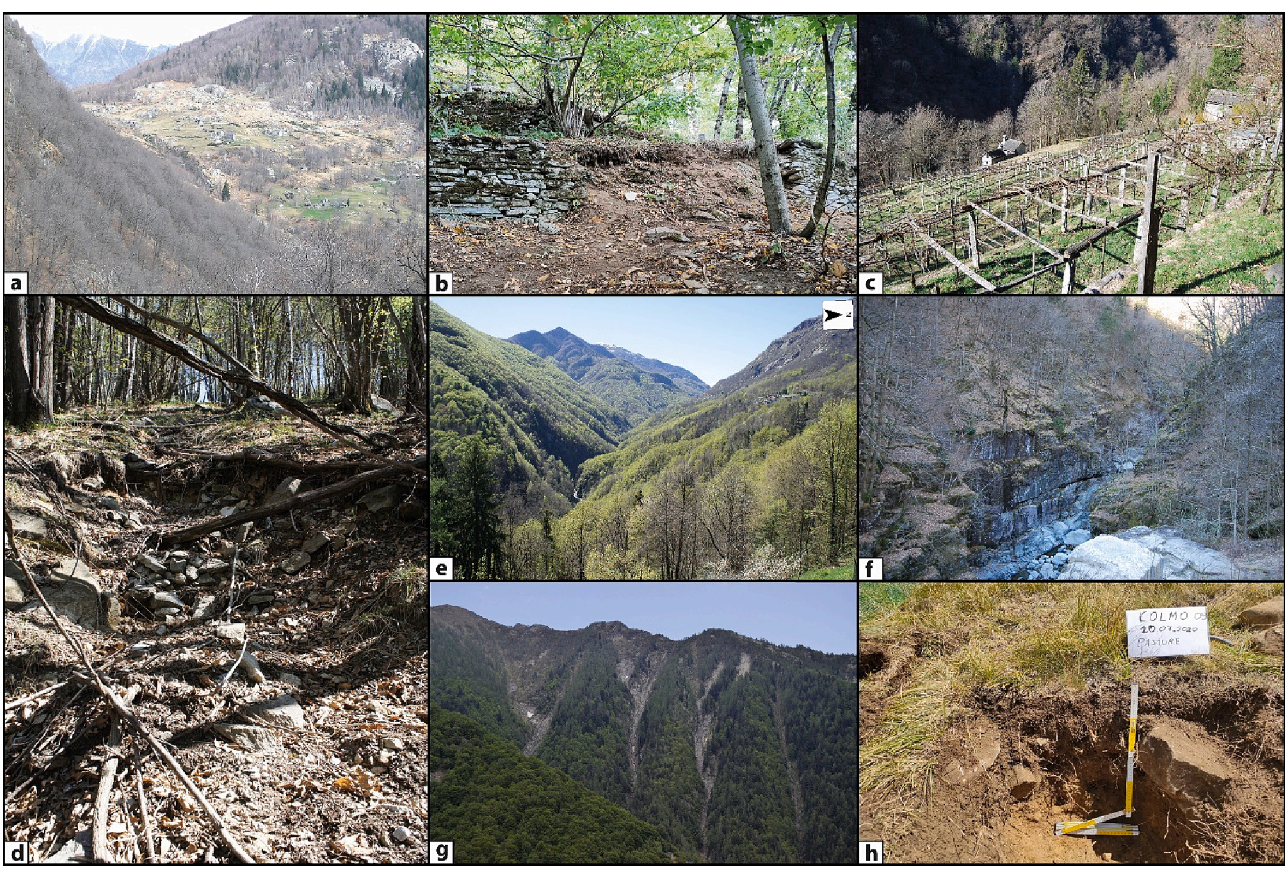


Fig. 2. Field evidence in the area: a) transfluence pass b) abandoned agricultural terraces. c) Vineyard on the still used terraces. d) Debris flow channel and associated deposits e) V-shaped Onsernone valley. f) Isorno stream flowing in the bedrock bed. g) Couloir with debris discharge. h) Glacial evidence of decametric blocks into subsoil.

present today in a restricted area on south-facing slopes, whereas some former pastures are now used as meadows, which are mowed once or twice a year.

2.3. Experimental design

The historical land use and land cover dynamics in the study area resulted in the following six land cover-topography units (LCTUs), which are heterogeneously represented on the south- and north-facing slopes (see Bettoni et al., 2022):

(i) Forested south-facing slopes (FS_S),
(ii) Deforested, cultivated terraces on south facing slopes (DT_S),
(iii) (Re-)forested, abandoned terraces on south-facing slopes (FT_S),
(iv) Forested north-facing slopes (FS_N),
(v) Pastures on slopes (PS)*,
(vi) Meadows on north-facing slopes (MS_N).

For each of the six LCTUs, a single 6 × 4 m plot was selected paying attention to keep the range of the slope angles similar for all LCTUs. At every plot, four 1.2 × 1.2 m replicates have been subjected to a rainfall simulation experiment (Fig. 1C).

* Due to the progressive abandonment of animal husbandry in the study area as well as accessibility problems with the rainfall simulator no pasture site was available on the north-facing slopes. Consequently, a study site under active pasture was selected on the south-facing slopes. Pastures on both slopes are characterized by the same conditions in terms of geology and vegetation. Even though microclimate may be slightly different, we identified lithology and vegetation as the main soil forming factor and hence, we consider the exposition of minor importance for soil physics.

2.4. Soil property assessment

In this study, the following soil properties and related processes were measured and analysed:

i. Soil profile description

In each of the six LCTUs, a soil profile was dug and described following the soil profile description guideline proposed by Jahn et al. (2006).

For each soil profile, standard properties of the different soil horizons were described and analysed such as:

a) soil horizon thickness,
b) soil texture of each soil horizon using lab analysis following the ASTM Standard (American Society for Testing Materials, 1988),
c) percentage of rock fragments and artefacts (>2 mm) present in each horizon,
d) soil colour code of each horizon using the Munsell colour chart (Munsell Color (Firm), 2010),
e) carbonate content using 10% HCl acid,
f) field soil pH measured using a pH meter with a ruggedized glass membrane electrode by PCE Instruments (PCE Deutschland GmbH, Meschede, Germany),
g) soil structure types,
h) presence and number of roots in a sampling window of 10 square centimetres on each soil horizon.
i) Soil bulk density

ii. Surface runoff and infiltration rate

Surface runoff generation and soil erosion have been assessed through sprinkling experiments using a portable automated rainfall simulator (PARS) (Ritschard, 2000) (Fig. 3). The instrument is characterized by an aluminium frame, which rests on four adjustable legs. The frame supports a sprinkling plate, which consists of a Plexiglas cylinder being connected with 100 nozzles regularly arranged on a 90 × 90 cm plate producing the raindrops. The sprinkling plate is driven by an electric motor and two inversion spindles that move horizontally in perpendicular directions providing a uniformly irrigated area of 1 m^2. The amount of water per unit of time, which corresponds to the amount of rain per minute on an area of 1 m^2 can be adjusted up to 60 mm/h by a flow meter. In this study, we set the flow rate to 833 cm^3/min, which corresponds to 50 mm/h. For the study area this is equivalent to a precipitation event occurring with a return period of five years (MeteoSwiss, 2020). Surface runoff was measured using a 70 cm wide aluminium drainage collector pushed into the ground at a depth of 1 to 2 cm. It collects the surface runoff from the central 0.7 m^2 of the totally irrigated area since only the central part of the plot is constantly irrigated all the time due to the movement of the irrigation plate. The measured runoff from the 0.7 m^2 is later extrapolated to a plot size of 1 m^2. The collector conveys the water into measuring cylinders, which are exchanged at a constant time interval of one minute and the volume of water is measured in ml/min with an accuracy of +/− 2 ml/min. The surface runoff intensity is then converted to mm/h to standardize the measurement units to be consistent with the precipitation intensity. Every 5 min, a sample of one minute of runoff is collected in a plastic bottle to measure the sediments eroded by the surface runoff. The sprinkling experiments were carried out for 30 min to obtain constant runoff values. Four replicates were conducted on each of the six LCTUs. For the experiments, slope water of local springs was used. It is characterized by slightly acidic pH values and a relatively low electric conductivity (Dipartimento del territorio, 2021a).

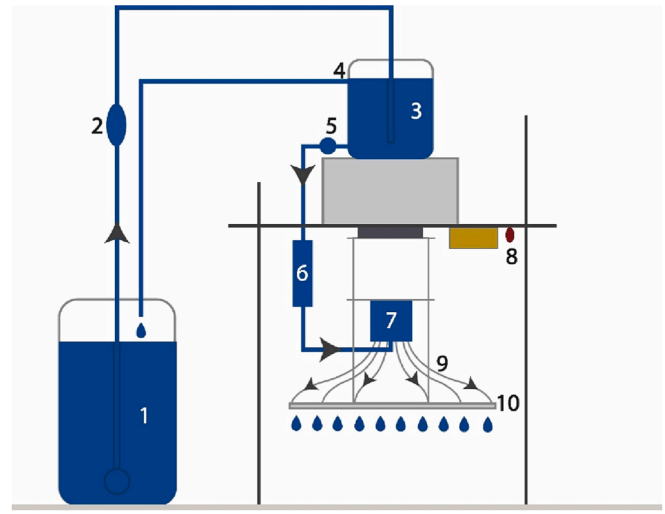


Fig. 3. Schematic representation of the rainfall simulator. 1: water tank, 2: water pump, 3: second water tank, 4: overflow drain, 5: water flow regulator, 6 flow meter in cl/min, 7: plexiglass cylinder, 8: regulator of velocity of horizontal movement, 9: connecting pipes to metal plates, 10: metal plates with 100 nozzles. Scheme revised from Ritschard (2000).

To carry out the sprinkling experiments in dry soil conditions, the test plots were covered by a plastic sheet arranged like a tent for 21 days before the experiments took place. Moreover, on the upslope side of the plots, metal strips were installed into the ground to protect the plots from surface and near-surface runoff during the drying period. Right before the sprinkling experiments, soil moisture was measured using a time domain reflectometry (TDR) device. In addition, to verify the increase in soil moisture, another TDR measurement was carried out at the end of each experiment. For each replicate measurement, in addition to the rain simulation in dry starting conditions, another simulation was carried out in moist starting conditions at the same position. To maintain constant conditions for each simulation, the moist condition test was performed 30 min after the end of simulation in dry conditions. On forested slopes additional simulations were done with and without the organic litter layer on top of the soil surface to assess the effect of the litter layer on runoff generation and sediment transport.

A total number of 64 rainfall simulations were carried out, 32 (i.e., 6 LCTUs × 4 replicates and 2x4 replicates of forests slopes without litter) in dry conditions and 32 in moist conditions.

As considered by other studies (Bhardwaj and Singh, 1992; Holden and Burt, 2002; Sepaskhah and Bazrafshan-Jahromi, 2006), the infiltration rate was calculated by subtracting the surface runoff from the rainfall input. This is an approximation that do not take into account the influence of evaporation, local surface depressions, which might store water or the vegetation storage capacity (Holden and Burt, 2002).

We assessed the surface runoff generation dynamics based on the ascending and falling limb of the hydrograph (Fig. 4). In this study we use the rising limb factor (RLF) proposed by Frasier et al. (1998). The RLF is calculated by multiplying the ratio between the maximum discharge (q_{pk}) and the time at which the first runoff is occurring (t_{rg}) with the ratio between the time from the onset of surface runoff (t_{rg}) to the peak of the surface runoff (t_{pk}) (Equation (1):

$$RLF:\ \frac{q_{pk}}{t_{pk}}\cdot\frac{t_{rg}}{t_{pk}} \tag{1}$$

where q_{pk} is the surface runoff at the peak flow, t_{rg} is the time needed for surface runoff genesis and t_{pk} is the time needed to reach the surface runoff peak.

The analysis of the falling limb factor (FLF) of the hydrograph (Fig. 4) followed the same procedure (Frasier et al., 1998) on the section of the curve following the peak flow till the end of the simulated precipitation (Equation (2):

$$FLF:\ \frac{q_{pk}-q_e}{t_e-t_{pk}}\cdot\frac{t/2-t_{pk}}{t_e-t_{pk}} \tag{2}$$

where q_{pk} is the peak surface runoff, q_e is the surface runoff at the end of simulated rainfall, t_e is the time at the end of the simulated precipitation, t_{pk} is the time needed to reach peak surface runoff, t/2 is half of the entire measurement period.

iii. Soil water repellence (SWR):

The effective SWR was assessed for each measurement plot in the field on samples of the uppermost mineral soil horizon using the molarity of ethanol droplet (MED) test (Roy and McGill, 2002). For the MED test, numerous droplets of a solution of ethanol characterized by different molarity were placed on a flattened soil surface. The droplet with the lowest molar ethanol concentration, which infiltrates into the soil in 10 s time is reported as result in molarity units. Soil water repellence was classified using the scale proposed by King (1981), i.e.: slight (MED $\leq$ 1.0 M), moderate (1.0 M $<$ MED $<$ 2.2 M) and severe (MED $\geq$ 2.2 M) water repellence.

iv. Sediment transport

Using the one-minute surface runoff collected in sampling bottles every 5 min of the rainfall simulation, the eroded sediments were measured using the vacuum filtration technique. The sample of surface runoff was poured into a Büchner funnel, and the sediments were collected on a paper filter. Finally, the paper filter was oven-dried at a temperature of 70 °C for 24 h. The dried filters were measured with a precision balance of 0.1 mg resolution. Knowing the weight of the paper filter, the exact amount of soil eroded by surface runoff was calculated. Since also the quantity of surface runoff for each minute is known, the data of the eroded sediments were expressed in grams per litre of surface runoff. Given that the amount of sediments transported in most of the samples was very low, the mean of the first and the last 15 min of surface runoff were calculated.

2.5. Statistical analysis

Unless otherwise stated, for descriptive statistics, the arithmetic mean and standard deviation of the measured properties were calculated. Furthermore, box-and-whisker plots were used for graphical examination of the data sets. Notches surrounding the median were used where the length of notches indicate the 95% confidence interval providing a measure of the statistical significance of the difference between the medians of two LCTUs (Mcgill et al., 1978). In addition, to test for statistically significant differences (P-value $<$ 0.05) in surface runoff between the six LCTUs, pairwise comparisons were carried out using the Wilcoxon rank-sum tests for non-normally distributed data.

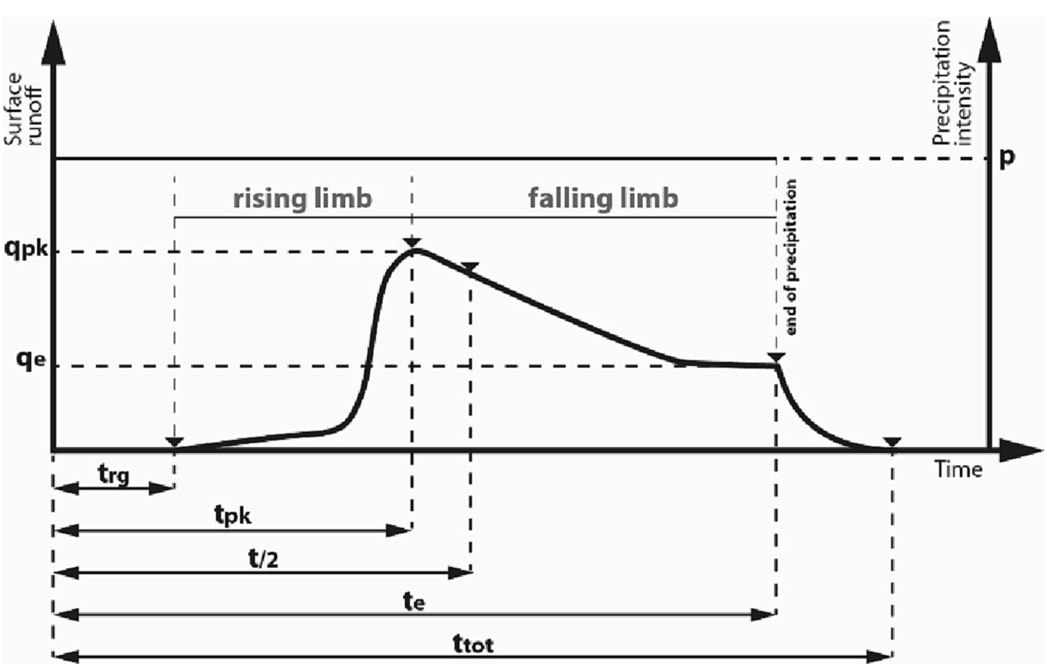


Fig. 4. Example of a Hydrograph of surface runoff during a rainfall simulation. qpk: surface runoff peak, trg: time for surface runoff genesis, tpk: time for surface runoff peak. t_{rg}: time runoff generation, t_{pk}: time of the peak, t/2: half of the total time of the measurement period, t_e: time of the end of simulated precipitation, t_{tot}: total time of the measurement period, p: amount of precipitation expressed in mm/hour, q_{pk}: surface runoff intensity of the peak expressed in mm/hour, q_e: surface runoff intensity at the end of simulated precipitation expressed in mm/h. .
Adapted from Ritschard (2000)

3. Results

3.1. Soil profile description

The six soil profiles ranged in depth from 42 (FS_S) to 121 cm (FS_N). Generally, all soil profiles were characterized by gneiss parent material resulting in high fractions of soil skeleton for most profiles showing boulders and blocks of different dimensions. The skeleton is ranging from a minimum of 2% to a maximum of 30% and is mainly composed by gneissic rock increasing towards the bottom of the profiles. The soil texture was mainly sandy throughout the soil profile with sandy loam being the predominant soil texture class following USDA (see Bettoni et al., 2022). The soils are generally acidic, with a minimum pH value of 4 and a maximum of 5.9. Forested sites are characterized by an organic surface horizon of a thickness ranging from 5 to 17 cm. Topsoil mineral horizons rich in SOM show a granular structure, whereas subsoil horizons reveal a subangular or angular structure. Table 1 shows the main soil characteristics for the different LCTUs.

3.2. Surface runoff and infiltration rate

Fig. 5A shows the notched box plots of surface runoff and infiltration rate during the sprinkling experiments for the six LCTUs (including the options with and without litter on forested slopes) under dry and moist conditions.

There are statistically significant differences in surface runoff and infiltration rate between the different LCTUs (Fig. 5B). The highest surface runoff was measured on south-facing natural forested slopes (FS_S) with litter and (re-)forested abandoned terraces (FT_S) showing median values of 36.9 mm/h (73.8% of rainfall input) and 34.2 mm/h (68.4% of rainfall input), respectively. In contrast, for all other LCTUs the values are more than halved showing 16.5 mm/h (33% of rainfall input) for pasture (PS) and 14.6 mm/h (29.2% of rainfall input) for south-facing natural forests (FS_S) without litter. This is followed by north-facing forest (FS_N) without litter with a median of 9.8 mm/h (19.6% of rainfall input) as well as north-facing forests (FS_N) with litter and deforested cultivated terraces (DT_S) showing median values of 5.8 mm/h and 5.2 mm/h, respectively (i.e., 11.6 and 10.2% of rainfall input). Lowest surface runoff was observed on meadows (MS_N) with a median value of 2.7 mm/h, corresponding to 5.4% of rainfall input.

A generally lower surface runoff in dry conditions was detected in all LCTUs except for the deforested, cultivated terraces. However, the lower values are statistically significant for abandoned terraces and meadows only. Furthermore, on forested slopes, surface runoff has always significantly increased after removal of the organic litter layer, especially on south-facing forests.

The analysis of the rising limb factor shows lower mean values for dry conditions in all LCTUs except for abandoned terraces, which are characterized by lower values in the dry setting (Table 2). Instead, the analysis of the falling limb factor reveals a slight decrease from dry to moist conditions in most of the LCTUs. Generally, similar values between dry and moist conditions were observed on the north- and south-facing forests without litter and only a slightly higher value on abandoned terraces.

The soil moisture measurements before and after the sprinkling experiments showed no significant difference for most LCTUs (Table 2), except for meadows and deforested terraces, where soil moisture increased after the sprinkling experiments in dry condition by 6 and 12%, respectively. In contrast, soil moisture in moist condition increased by 17 and 8%, respectively.

3.3. Soil water repellence (SWR)

The effective SWR (Table 2) was lowest on meadows and cultivated terraces indicating mean values of 2 mol/L and 1.8 mol/L, respectively. Following the classification proposed by King (1981), SWR was moderate for these two LCTUs. In contrast, all other LCTUs show severe SWR, i.e. abandoned terraces with 3 mol/L, pasture with 4.2 mol/L and north- and south-facing forests with 4.7 and 4.5, respectively.

3.4. Sediment transport

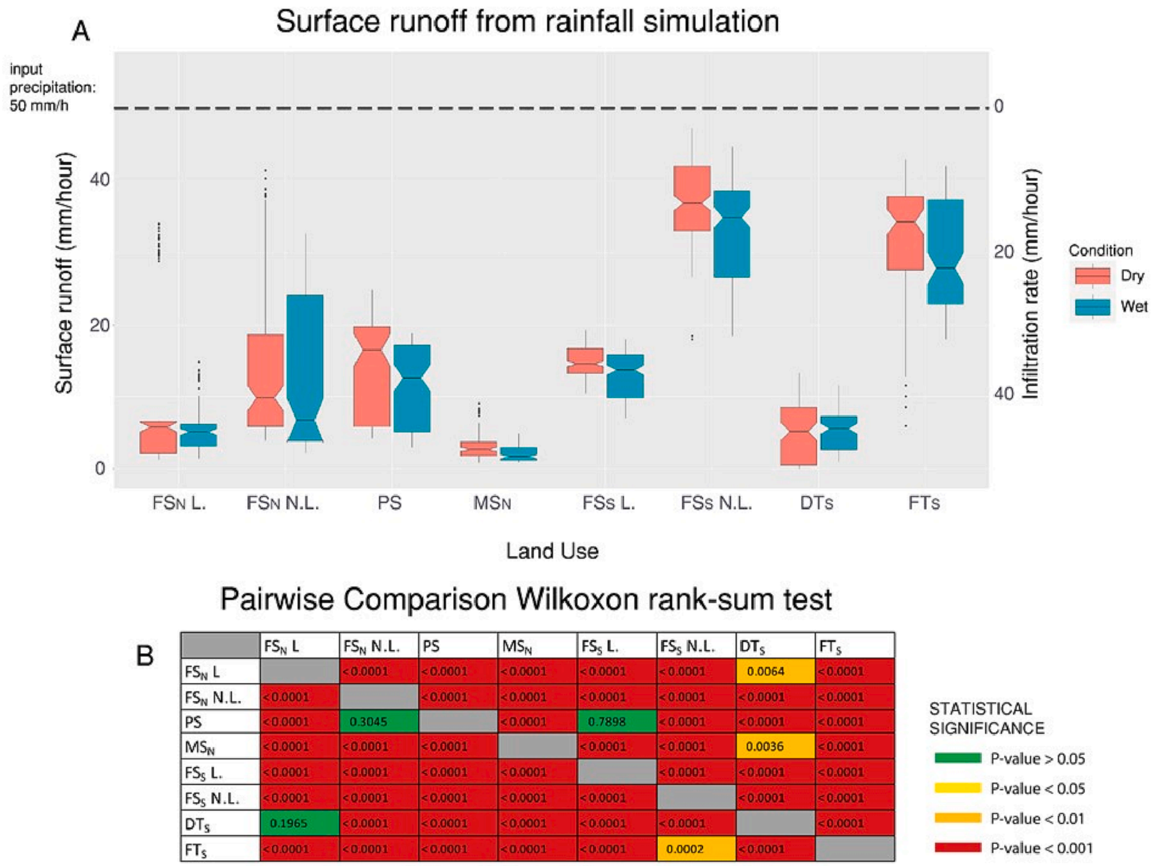
In all LCTUs, sediment transport related to the detachment of soil during the PARS experiment (Table 2) never exceeded 0.4 g/L with average values between 0 and 0.2 g/L. The only exception is given by abandoned terraces where maximum values of 5.5 g/L and average values of 2.5 g/L were measured under dry conditions, and maximum values of 3.4 g/L and average values of 1.4 g/L under moist conditions.

4. Discussion

In the following, we discuss in detail the characteristics and related dynamics of the single land cover-topography units (LCTUs) for the north and south facing slopes.

Table 1
Main soil properties for the 6 land cover-topography unit (LCTUs).

LCTU	Soil depth	Lithology	Skeleton [%]	Texture	Munsell Color Code	pH	Structure
FS_N	0–11 cm		25%	loamy sand	7.5 YR 3/2	4	granular
	11–35 cm		25%	sandy loam	7.5 YR 3/3	4.3	granular
	35–105 cm		30%	sandy clay loam	7.5 YR 3/4	4.2	sub angular
	105–121 cm	gneiss	20%	sandy clay loam	7.5 YR 4/6	4.1	angular
MS_N	0–10 cm		2%	sandy loam	7.5 YR 3/2	4	/
	10–38 cm		10%	sandy clay loam	7.5 YR 3/3	4.1	/
	38–80 cm	gneiss	20%	sandy clay loam	7.5 YR 3/4	4.3	/
PS	0–17 cm		20%	sandy loam	10YR 2/2	4.2	granular
	17–30 cm		25%	sandy loam	10YR 3/2	4.1	granular
	30–47 cm	gneiss	30%	sand/sandy loam	10YR 3/3	4.3	granular
FS_S	0–5 cm		20%	sandy loam	10YR 2/1	4.7	granular
	5–20 cm		15%	sandy loam	10YR 3/2	4.2	granular
	20–35 cm		10%	sandy loam	10YR 3/1	4.8	sub angular
	35–40 cm	gneiss	15%	sandy loam	7.5YR 3/2	4.9	sub angular
DT_S	0–15 cm		20%	sand	10YR 2/2	5.8	granular
	15–35 cm		10%	sandy loam	10YR 3/2	5.5	granular
	35–60 cm		10%	sand	10YR 3/4	5.8	sub angular
	60–80 cm	gneiss	10%	sand	10YR 3/6	5.9	angular
FT_S	0–10 cm		15%	sandy loam	7.5 YR 2.5/1	5	granular
	10–40 cm		25%	sandy loam	5YR 2.5/2	5.5	sub angular
	40–70 cm	gniess	20%	sandy loam	10YR 3/3	5.5	sub angular



	FS_N L	FS_N N.L.	PS	MS_N	FS_S L.	FS_S N.L.	DT_S	FT_S
FS_N L		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0064	<0.0001
FS_N N.L.	<0.0001		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
PS	<0.0001	0.3045		<0.0001	0.7898	<0.0001	<0.0001	<0.0001
MS_N	<0.0001	<0.0001	<0.0001		<0.0001	<0.0001	0.0036	<0.0001
FS_S L.	<0.0001	<0.0001	<0.0001	<0.0001		<0.0001	<0.0001	<0.0001
FS_S N.L.	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001		<0.0001	<0.0001
DT_S	0.1965	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001		<0.0001
FT_S	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0002	<0.0001	

Fig. 5. A: Notched boxplot of the surface runoff and infiltration rates expressed in mm/hour for each LCTUs in dry and wet conditions, B: Upper triangle: Pairwise comparison between LCTU in dry condition using Wilcoxon rank-sum test to calculate statistically significant difference expressed in level of significance. Lower triangle: Pairwise comparison between LCTU in moist condition using Wilcoxon rank-sum test to calculate statistically significant difference expressed in level of significance. FS_N L.: north-facing forested slope with litter layer, FS_N N.L.: north-facing forested slope without litter layer, FS_S L.: south-facing forested slope with litter layer, FS_S N.L.: south-facing forested slope without litter layer, DT_S: Deforested cultivated terraces, FT_S: re-forested abandoned terraces, PS: pasture on slope, MS_N: meadow on slope.

Table 2
Rising limb factor (RLF), falling limb factor (FLF), Surface runoff, Soil moisture increase, Soil water repellence and Soil erosion expressed with mean values for each land cover-topography unit (LCTUs).

	Land cover-topography unit	Condition	RLF [DI]	FLF [DI]	Surface runoff [mm/hour]	Soil moisture increase [%]	SWR [mol]	Soil Erosion [g/L]
North-facing slope	Forested slopes with litter (FS_N)	Dry	0.31	0.03	5.82	3	4.7	0.02
		Wet	0.17	0.01	5.16	1		0.03
	Forested slopes without litter (FS_N)	Dry	0.94	0.08	9.84	1	4.7	0.22
		Wet	0.84	0.08	6.78	1		0.12
	Pasture on Slopes (PS)	Dry	0.70	0.05	16.5	4	4.2	0.08
		Wet	0.49	0.02	12.63	2		0.05
	Meadow on slopes (MS_N)	Dry	0.45	0.03	2.73	6	2	0.04
		Wet	0.18	0.01	1.74	17		0.02
South-facing slope	Forested slopes with litter (FS_S)	Dry	0.41	0.01	14.58	2	4.5	0.04
		Wet	0.26	0.00	13.74	1		0.06
	Forested slopes without litter (FS_S)	Dry	0.72	0.00	36.86	2	4.5	0.24
		Wet	0.47	0.00	34.86	2		0.15
	Deforested, cultivated terraces (DT_S)	Dry	0.67	0.04	5.22	12	1.8	0.10
		Wet	0.14	0.01	5.61	8		0.02
	Re-forested, abandoned terraces (FT_S)	Dry	0.70	0.02	34.26	5	3	2.47
		Wet	1.06	0.05	27.84	4		1.36

4.1. Forested slope (FS_N)

On forested north-facing slopes (FS_N), the anthropogenic disturbances have been negligible at least over the last decades. Hence, this LCTU is considered as a reference state. Forested plots without litter always show higher runoff than plots with litter. This behaviour is related to the capacity of litter to store water on its irregular surface or in its microcavities, thus, reducing runoff (Marin et al., 2000; Sato et al., 2004). Furthermore, without litter, surface runoff is produced earlier since the soil surface is wetted more directly but an equilibrium surface runoff is reached later. This is in agreement with Guevara-Escobar et al. (2007) and Sato et al. (2004), who state that the composition and thickness of the litter layer play an important role, i.e. the thicker the litter layer the bigger its storage capacity and the lower surface runoff. Comparing the infiltration rates obtained from the sprinkling experiments (44.2 mm/h with litter, 40.2 mm/h without litter) with a proxy infiltration rate calculated based on precipitation intensity minus saturated hydraulic conductivity (K_{sat}) (132 mm/h, see Bettoni et al., 2022), a rather high difference was observed. This behaviour may be explained by the severe soil water repellence (SWR) that strongly reduces the infiltration capacity of the soil surface favouring surface runoff generation (Doerr et al., 2003, Miyata et al., 2007, Lemmnitz et al., 2008). Moreover, no or a very low increase in soil moisture of not more than 3% was observed after the rainfall experiment of 30 min using an intensity of 50 mm/h. This may be explained by the generation of preferential flow paths through the unsaturated layer. Thus, most of the soil volume is bypassed and remains dry (e.g., Ritsema et al., 1993; Ritsema and Dekker, 1995; Wang et al., 2000). Despite the high percentage of surface runoff, soil loss due to erosion is negligible and mostly represented by leaf fragments or organic material from the litter layer. For the $FS_{N,}$ this indicates a generally high stability of the soil landscape.

4.2. Pasture on slope (PS)

According to the above-mentioned land use change scenarios during the first intensive cultivation phase, the FS_N were partly converted to pastures (PS) (see Bettoni et al., 2022). The significant increase in surface runoff induced by such a conversion may be the result of soil compaction and the related reduction in K_{sat} (e.g., Germer et al., 2010, 2009; Zimmermann et al., 2006). This was also reported for the Onsernone study area by Bettoni et al. (2022). The runoff peak is reached earlier but more time is needed to reach an equilibrium flow. However, comparing the real infiltration rate based on the PARS measurements corresponding to 33.5 mm/hour with the one using the K_{sat} as a proxy corresponding to 53 mm/hour (Bettoni et al., 2022), surface runoff is not expected due to the high K_{sat} values. Thus, besides K_{sat}, other factors such as the SWR may control infiltration, as indirectly demonstrated by the high SWR values, which are classified as severe for both FS_N and PS. The analysis of the wetting front through TDR measurements showed difficulties in wetting the soil. Hence, the increase in soil moisture never exceeded 4%. As explained before, this behaviour is due to the high SWR favouring the generation of preferential flow paths impeding a homogeneous wetting of the soil (Ritsema et al., 1993; Ritsema and Dekker, 1995; Wang et al., 2000). However, the increase in surface runoff did not lead to an increase in sediment transport. In fact, the dense grass cover reduces the erosive power of surface runoff. Thus, a great stability can be stated for PS highlighted by the fact that an increase in surface runoff did not induce an increase in soil erosion.

4.3. Meadow on slope (MS_N)

The second land use change on north-facing slopes corresponds to the extensification phase caused by the conversion from PS to meadow. This resulted in a statistically significant decrease in surface runoff by 83.6%. This decrease can be explained by a significant reduction of SWR (i.e., from severe to moderate), which causes an increased infiltration capacity of the soil (Doerr et al., 2003; Lemmnitz et al., 2008; Miyata et al., 2007). As a result, 95% of the precipitation (47.3 out of 50 mm/hour) is infiltrating into the soil. Nonetheless, it must be considered that this is still lower than the potential infiltration capacity obtained by K_{sat}, which corresponds to 87 mm/hour. Comparing the rising limb factor of MS_N and PS, a decrease of 36% was observed indicating a delay in reaching the peak surface runoff under MS_N. However, this is coming along with an increased equilibrium flow highlighted by the values of the falling limb factor, which are similar to the FS_N with litter. In MS_N, the analysis of the wetting front from TDR shows a maximum of 11% and an average increase of 7% in respect to FS_N and PS. This indicates a more regular matrix flow within the soil with less influence by preferential flow paths. In turn, it implies a faster wetting of the whole soil layer as confirmed by an excavation carried out at the end of the sprinkling experiment. This behaviour is also observed when comparing K_{sat} of north facing forests and meadows. It shows that on FS_N K_{sat} is very high (see Bettoni et al., 2022) but the wetting front is slow and runoff values are quite high. On the contrary, and despite the lower surface runoff in $MS_{N,}$ K_{sat} is lower (see Bettoni et al., 2022) and the wetting front is progressing faster. This seems to be a contradiction since normally high K_{sat} corresponds to a fast wetting front and low surface runoff. However, in the study area SWR, not K_{sat} is the triggering factor in surface runoff generation dynamics displaying higher values in forests and lower ones on meadows. Finally, meadows also showed a very low surface runoff and sediment transport, highlighting a high stability favoured by the dense grass cover reducing the speed and energy of surface runoff favouring infiltration and decreasing its erosive power.

4.4. Forested slope (FS_S)

Natural forests (FS_S) also serve as the reference state of negligible anthropogenic influence on south-facing slopes. Here, significantly higher surface runoff values were obtained with respect to the north-facing forests (FS_N) both with (i.e., 151.7%) and without (i.e., 275.5%) litter cover. Likewise, forested plots without litter also show higher runoff than plots with litter as a result of its intrinsic water storage capacity (Marin et al., 2000; Sato et al., 2004). The infiltration capacity of the soil is 35.4 mm/hour, which is quite low compared to the potential infiltration capacity of 81 mm/hour measured using K_{sat}. Concerning the higher runoff in absence of litter on FS_S compared to FS_N, a slight difference in the slope angle (30° on FS_S and 22° on FS_N) needs to be considered. Another reason for the higher surface runoff and erosion on FS_S may be the lower K_{sat} and higher bulk density (see Bettoni et al., 2022) resulting in lower infiltration rates. This may be explained by a higher soil compaction due to a more intense use of the areas surrounding the settlements on the south-facing slopes. The rising limb factor showed slightly higher values in FS_S in respect to FS_N with litter. Anyway, the difference is not significant, while the falling limb factor is constant, indicating that a certain equilibrium is maintained when the peak flow is reached. A similar behaviour is shown by FS_S without litter. Having a closer look to the vertical wetting dynamics through TDR measurements, a delay in the progress of the wetting front was identified for FSs. This is again explained by the genesis of preferential flow paths favouring drainage and prevent the wetting of the soil (Ritsema et al., 1993; Ritsema and Dekker, 1995; Wang et al., 2000). Finally, sediment transport by soil erosion is very low highlighting a high landscape stability of FS_S.

4.5. Deforested cultivated terrace (DT_S)

During the intensive cultivation phase, south-facing forests (FS_S) were cleared, and slopes were terraced and cultivated (DT_S). This resulted in significantly lower surface runoff (i.e., 64.2%), which is partially explained by the lower SWR favouring the infiltration capacity of the soil (Doerr et al., 2003; Lemmnitz et al., 2008; Miyata et al., 2007). However, the main reason for the decrease in surface runoff is related to the strongly modified topography and the reduced slope steepness of the agricultural terraces (Schönbrodt-Stitt et al., 2013) resulting in higher infiltration rates (e.g., Arnáez et al., 2015; Moreno-de-las-Heras et al., 2019; Schönbrodt-Stitt et al., 2013). Consequently, soil erosion is very low indicating a high stability similar to the previous LCTUs. Low soil erosion rates are also favoured by the dense grass cover of the investigated terraced sites leading to a reduced speed and energy of the water flow and higher infiltration rates of 90% of precipitation (44.8 out of 50 mm/hour). Analysing the rising limb factor of DTs, values higher than FS_S were obtained, considering that the median surface runoff decreased with respect to FS_S and peak surface runoff is more quickly reached. The analysis of the wetting front shows an average increase of 12% with a maximum of 18%. As mentioned above for MS_N, this indicates a lower tendency concerning the formation of preferential flow paths leading to a rather uniform wetting of the entire soil layer.

4.6. (Re-)forested abandoned terrace (FT_S)

The extensification phase on south-facing slopes resulted in a succession of forest vegetation on the abandoned terraces (FT_S). Here, the infiltration capacity is very low (15.7 mm/hour in average) with respect to the potential infiltration capacity measured using K_{sat} (71 mm/hour). This results in the highest surface runoff values compared to the other LCTUs excluding FS_S without litter. The latter however is not "natural" because of the manual removal of the litter layer. The surface runoff on FT_S is about 135% higher with respect to the reference state (FS_S) with litter. This corresponds to results of similar studies (e.g. Lasanta et al., 2000; Sabir, 2021). SWR on FTs is considered as severe and displays higher values than DT_S but lower values than FS_S. However, surface runoff generation also depends on the stage of terrace abandonment. The absence of terrace maintenance and their colonization by trees lead to a successive collapse of the terrace dry walls and consequently to a local increase of the slope gradient up to 40°. This reduces or removes the protecting litter layer exposing the mineral soil surface and favouring soil detachment by surface runoff. Finally, this strongly increases sediment transport by an order of magnitude comparable to all other LCTUs. Consequently, the soils on FT_S are considered instable due to their significantly increase in soil erosion susceptibility (e.g., Arnáez et al., 2015; Lasanta et al., 2000; Lesschen et al., 2008). The TDR measurements revealed an intermediate state of the wetting front with an increase in the topsoil moisture of about 5%.

4.7. Synthesis of LCTU characteristics and related dynamics

The present study clearly shows that surface runoff generation in the Onsernone valley is land use-specific (Fig. 5). Bettoni et al. (2022) presented a schematic graph showing the specific interdependencies between land use changes, soil properties and soil erosion in the Onsernone valley. Generally, runoff is higher under dry conditions compared to moist conditions. Moreover, the rising limb factor indicates that peak surface runoff is reached faster under dry than under moist conditions except for FT_S. This behaviour may be explained by the SWR characteristics. Where SWR is high, under dry conditions, the rain drops fall on a semi-impermeable surface favouring a quicker generation of surface runoff (Miyata et al., 2007; Ritsema and Dekker, 1994; Witter et al., 1991). In contrast, under moist conditions infiltration increases and surface runoff decreases, and the peak is reached later. This is due to the fact that SWR generally decreases with the increase of soil moisture content (Witter et al., 1991). Under dry conditions and higher SWR, the surface runoff showed a slower post-peak decrease. Thus, more time is required for the falling limb to reach the equilibrium flow. Though, under moist conditions and lower SWR, the equilibrium is almost immediately reached.

The comparison of forested plots with and without litter layer indicated that removing the litter layer results in a statistically significant increase in surface runoff generation with respect to forested plots with litter layer. The reason is the capacity of litter to store water in microcavities and thus, to reduce runoff compared to forested slopes without litter where the soil surface is directly wetted and hence, produce more surface runoff and much earlier. Moreover, the thicker the litter layer, the higher its storage capacity and the lower the surface runoff. Our study reveals that the estimation of surface runoff using K_{sat} as proxy for the potential infiltration capacity and rainfall intensity does not provide a reliable measure of surface runoff and soil erosion susceptibility (see Bettoni et al., 2022). In fact, other soil properties, in our case especially SWR, are playing an important role limiting the infiltration capacity of the soil and favouring surface runoff generation. This can lead to great inconsistencies between the effective and the potential infiltration capacity of the soil. However, these effects are not considered in traditional hydrological modelling approaches like the Soil Conservation Service - Curve Number model (e.g., Hawkins et al., 2002) and may lead to an underestimation of surface runoff.

In our case we found that SWR has the most significant effect on surface runoff. Particularly, severe SWR reduces the infiltration capacity of the soil surface favouring surface runoff and the generation of preferential flow paths through unsaturated layers that leave most of the topsoil layer dry.

SWR is depending on SOM content and composition but also on the meteorological conditions and hence soil moisture. MeteoSwiss (2022) recorded exceptionally dry periods especially during the last years, which is in line with the result of Emeis (2021) who documented a slight increase in the number of dry days in the Alps during the last century. This coincides with a decrease of snow cover periods in the Swiss Alps in the last decades, especially at mid and low altitudes (Beniston, 1997; Klein et al., 2016). Soil moisture is directly related to snow cover (Potopová et al., 2016), as snow releases water slowly keeping the soil moist for longer periods. Since SWR is also controlled by soil moisture content (Dapaah and Vyn, 1998; Doerr and Thomas, 2000; Witter et al., 1991), an increased number of dry days and the reduced timespan of snow cover may lead to extended water repellent soil conditions.

Generally, surface runoff in the different LCTUs was <20 mm/h for a 50 mm/h event with the exception of the abandoned terrace (FT_s), which produced more than 30 mm/h. However, we registered very low amounts of soil erosion due to a high SOM content and hence, high aggregate stability of the soils (see Bettoni et al., 2022). Nonetheless, we have to take into account that surface flow accumulates with increasing slope length. Hence, a higher soil erosion potential is expected in case of the downslope areas with accumulating surface runoff. However, these effects have not been considered in this study due to the PARS utilized and the setup of our experiments.

5. Conclusion

Due to own previous investigations of chemical and physical key soil properties showing a very high SOM content and aggregate stability and thus, a reduced soil erodibility, we hypothesized that the Onsernone valley and the six selected LCTUs represent a stable environment that is quite insensitive to land use changes. However, the PARS experiments in the different LCTUs revealed a very high variability of surface runoff generation characteristics, with minimum values in meadows (MS_N) and maximum values on (re-) forested abandoned terraces (FT_S). Although high surface runoff can lead to soil loss, the different LCTUs generally show very low soil erosion rates indicating a high stability of the soil landscape. While key soil properties are affected by land use changes as shown by Bettoni et al. (2022), soil erosion is almost negligible or very limited. The only exception are FT_S where erosion and hence, sediment transport was significantly increased by an order of magnitude, particularly in areas where terrace walls collapsed as a result of lacking terrace maintenance and the regrowth of trees. This led to a local increase in slope steepness and an exposure of bare soil that is without any protection to the action of atmospheric agents facilitating surface runoff and soil erosion and finally leading to a loss of precious and limited soil resources in this alpine environment. Consequently, abandoned terraces have to be considered as instable soil landscapes. This is a serious problem due to the enormous spatial extent of terraces in the Onsernone valley. To avoid or mitigate this situation, terrace dry walls should be maintained limiting the potential of collapses. Moreover, terraces should be covered by a dense vegetation to provide a natural protection to soil erosion.

Our experiments reveal that surface runoff is higher at higher SWR, which may also increase soil erosion susceptibility especially during high-intensity precipitation events. This has also implications for traditional approaches used to assess flood risk like SCS-CN based models that does not take into account these dynamics and hence, may underestimate surface runoff and river discharge especially for events after long dry periods. In future, these events might be more relevant since e.g. Jacob et al. (2014) predict a reduction in the annual precipitation of up to 15% for southern Europe and an increase in rainfall intensity. In this study, we used a five years return period to assess surface runoff dynamics. As stated above, it is very likely that in future the precipitation values of these return periods might be higher leading to a change in surface runoff characteristics and soil landscape sensitivities. Thus, the planning and dimensioning of measures to fight, cope with and/or mitigate effects of heavy rainfall events should especially focus on the most sensitive soil landscape entities.

Funding

This work was funded by the German Research Foundation (DFG) [Grant No. VO2293/2-1].

Ethical approval

Not required.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The authors are thankful for the contribution of Geraldine Quénéhervé and Janusch Bach for their help during the field campaigns.

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