Science of the Total Environment 858 (2023) 159779

Contents lists available at ScienceDirect

Science of the Total Environment

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

What makes soil landscape robust? Landscape sensitivity towards land use changes in a Swiss southern Alpine valley

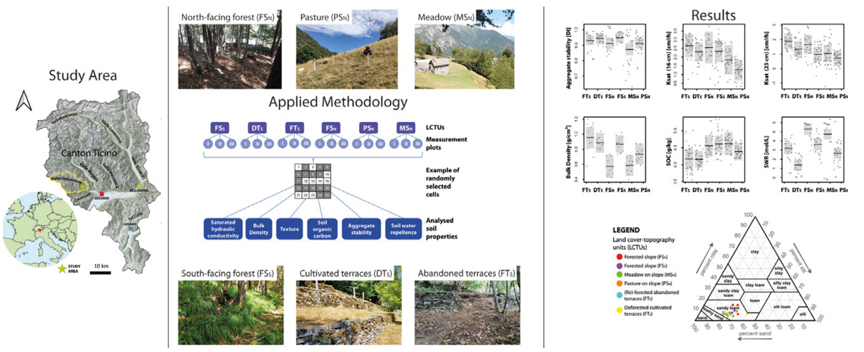
Manuele Bettoni [a,b], Michael Maerker [b,c,*], Roberto Sacchi [b], Alberto Bosino [d], Marco Conedera [e], Laura Simoncelli [b], Sebastian Vogel [a]

[a] Department Engineering for Crop Production, Leibniz Institute for Agricultural Engineering and Bioeconomy (ATB), Max-Eyth-Allee 100, 14469 Potsdam, Germany
[b] Department of Earth and Environmental Sciences, University of Pavia, Via A. Ferrata 1, 27100 Pavia, Italy
[c] Leibniz Centre for Agricultural Landscape Research, Department of Landscape Processes, Müncheberg, Germany
[d] Department of Earth and Environmental Sciences, University of Milano-Bicocca, Piazza Della Scienza 1, 20126 Milan, Italy
[e] Insubric Ecosystems Research Group, Swiss Federal Research Institute for Forest, Snow and Landscape (WSL), A Ramél 18, 6594 Cadenazzo, Switzerland

HIGHLIGHTS

- Soil of the Onsernone valley shows high aggregate stability irrespective of land use.
- High aggregate stability is caused by high amounts of SOC.
- Land use changes affect SOC but do not impact aggregate stability.
- Pastures and abandoned terraces are most susceptible to Hortonian surface runoff.
- Soil water repellence was the most sensitive parameter to land use changes.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Paulo Pereira

Keywords:
Soil key properties
Soil water repellence
Saturated hydraulic conductivity
Aggregate stability
Landscape stability
Linear mixed model

ABSTRACT

Landscape sensitivity is a concept referring to the likelihood that changes in land use may affect in an irreversible way physical and chemical soil properties of the concerned landscape. The objective of this study is to quantitatively assess the sensitivity of the southern Alpine soil landscape regarding land use change-induced perturbations. Alpine soil landscapes can be considered as particularly sensitive to land use changes because their effects tend to be enhanced by frequent extreme climatic and topographic conditions as well as intense geomorphologic activity. In detail, the following soil key properties for soil vulnerability were analysed: (i) soil texture, (ii) bulk density, (iii) soil organic carbon (SOC), (iv) saturated hydraulic conductivity (K_{sat}), (v) aggregate stability and (vi) soil water repellency (SWR). The study area is characterized by a steep, east-west oriented valley, strongly anthropized in the last centuries followed by a progressive abandonment. This area is particularly suitable due to constant lithological conditions, extreme topographic and climatic conditions as well as historic land use changes. The analysis of land use change effects on soil properties were performed through a linear mixed model approach due to the nested structure of the data. Our results show a generally high stability of the assessed soils in terms of aggregate stability and noteworthy thick soils. The former is remarkable, since aggregate stability, which is commonly used for detecting land use-induced changes in soil erosion susceptibility, was always comparably high irrespective of land use. The stability of the soils is mainly related to a high amount of soil

---

Abbreviations: LMM, Linear Mixed Model; SWR, Soil Water Repellency; SOC, Soil Organic Carbon; SOM, Soil Organic Matter; K_{sat}, Saturated Hydraulic Conductivity; AS, Aggregate Stability; USDA, United States Department of Agriculture; MED test, Molarity of Ethanol Droplet test; 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_N, North-facing pastures on slopes; MS_N, North-facing meadows on slopes, LCTUs: Land cover-topography units.

* Corresponding author at: Department of Earth and Environmental Sciences, University of Pavia, Via A. Ferrata 7, 27100 Pavia, Italy.
E-mail addresses: manuele.bettoni01@universitadipavia.it (M. Bettoni), michael.maerker@unipv.it (M. Maerker), roberto.sacchi@unipv.it (R. Sacchi), alberto.bosino@unimib.it (A. Bosino), marco.conedera@wsl.ch (M. Conedera), laura.simoncelli01@universitadipavia.it (L. Simoncelli), svogel@atb-potsdam.de (S. Vogel).

http://dx.doi.org/10.1016/j.scitotenv.2022.159779
Received 27 April 2022; Received in revised form 21 October 2022; Accepted 24 October 2022

organic matter favouring the formation of stable soil aggregates, decreasing soil erodibility and hence, reducing soil loss by erosion. However, the most sensitive soil property to land use change was SWR that is partly influenced by the amount of soil organic carbon and probably by the quality and composition of SOM.

1. Introduction

The sensitivity of a landscape to changes is expressed by the likelihood that a given change in the controls of a system will produce a sensible, recognizable, and persistent response in its properties (Brunsden and Thornes, 1979; Thomas, 2001). Thus, landscape sensitivity can be related either to the capability of the system to prevent an impulse from having an effect (resistance) or to the post-disturbance ability to return to its initial state (resilience) (Brunsden and Thornes, 1979; Burt, 2001; Thomas, 2001; Usher, 2001).

Regarding their response to disturbances, landscapes can be distinguished as robust or sensitive (Usher, 2001; Werritty et al., 1994; Werritty and Brazier, 1994). Robust or resilient systems are characterized by the ability to absorb or buffer impacts or return to their former state in relatively short time by means of feedback mechanisms (Hill, 1987; Holling, 1973). Thus, the system retains its characteristic structure, functions and controlling processes (Walker et al., 2006).

In contrast, sensitive behaviour is defined by the magnitude of disturbance exceeding the magnitude of resistance of the landscape, which results in fundamental and permanent changes in the properties of the affected landscape components. The point at which the system disturbance exceeds the magnitude of resistance can be also seen as a switch to a qualitatively different system state having a different structure and being controlled by a different set of processes. Thus, the specific response of a landscape to external perturbations depends on single characteristics of individual components such as soils, topography or habitats (Gordon et al., 2001; Werritty and Leys, 2001).

This concept of landscape sensitivity can be applied to verify the likelihood that changes in land use may affect in an irreversible way physical and chemical soil properties of the concerned landscape (Gordon et al., 2001). In the past decades, most land use changes showing an effect on soils have been related to agricultural activities (Grieve, 2001), which represent a large-scale anthropogenic impact on soils. Alpine soil landscapes[1] can be considered as particularly sensitive to land use changes because of the combined effects of extreme climatic and topographic conditions and intense geomorphologic activity (Gordon et al., 2001). Moreover, the presence or absence of soils largely influence other landscape components such as vegetation, fauna, water, or micro-climate. Since land use and land use changes have a distinct effect on soils and soil degradation, e.g. by soil erosion that is a huge (if not the biggest) threat for soils in mountainous regions, the sensitivity of the entire landscape is influenced by the soils.

Soil parameters that are vulnerable to land use changes can be utilized as indicators or key properties regarding the sensitivity of a soil landscape. Following soil physical and chemical properties are particularly sensitive to agriculture (i.e., arable farming and grazing) and thus, particularly suitable as key elements of a self-contained causal structure for investigating soil landscape sensitivity.

1.1. Soil organic matter (SOM)

Agriculture has a strong effect on the content and distribution of SOM in soils (e.g. Reeves, 1997; Angers and Eriksen-Hamel, 2008; Paulino et al., 2014). This concerns e.g., the clearing of natural vegetation in the course of agricultural development of the landscape, the crop rotation during cultivation as well as the secondary succession of vegetation after abandonment of cultivation. During agricultural use, the SOM content is usually reduced (e.g. Grieve, 2001; Knox, 2001; Twongyirwe et al., 2013) due to soil erosion (Polyakov and Lal, 2004) and mechanical tillage that reduce the turnover time of SOM (e.g. Rowell, 1997; Pekrun and Claupein, 1998; Tebrügge and Düring, 1999). Declining SOM levels in agricultural soils are also related to periodic biomass removal when crops are harvested. These losses are partly compensated by organic fertilization (Oehmichen, 2000). Estimation of SOM is usually accomplished through a measure of soil organic carbon (SOC), total soil carbon, or weight loss on ignition (Tabatabai, 1996). In the following we use SOC.

1.2. Aggregate stability

Since SOM promotes the formation of a stable aggregate structure (Scheffer et al., 2010), reduced SOM content conversely causes a reduction in aggregate stability, especially in topsoil (Oades, 1984; Zhang and Hartge, 1992). This increases the erodibility of the soil during heavy rainfall events (Chaney and Swift, 1984; Le Bissonnais and Arrouays, 1997) as well as its susceptibility to mechanical stress (e.g., Nciizah and Wakindiki, 2015).

1.3. Saturated hydraulic conductivity (K_{sat})

Increased load due to regular traffic on the cultivated area or due to grazing can lead to soil compaction, especially at a reduced aggregate stability. This may induce a decrease in macroporosity and permeability of the soil and of the topsoil in particular (Wauchope et al., 1999; Drewry and Paton, 2000; Drewry et al., 2004). A soil parameter that has proven to be an effective indicator of such soil structural deterioration as a function of land use change is the saturated hydraulic conductivity (Ziegler et al., 2004; Hassler et al., 2011).

1.4. Surface runoff

A reduction in K_{sat} in the topsoil induced by agricultural land use results in a reduced infiltration capacity of the soil. This can lead to the formation of surface runoff as a result of infiltration excess (Hortonian runoff) especially during intensive precipitation events (Ziegler et al., 2004; Hassler et al., 2011).

An increase in surface runoff, combined with the above-mentioned increased soil erodibility due to reduced aggregate stability, may finally increase the potential for soil erosion. The irreversible loss of fertile topsoil material caused by soil erosion can be considered the main trigger for soil degradation in mountainous landscapes (Boardman and Poesen, 2006). For this reason, an increased susceptibility to soil erosion reflects the sensitivity of the Alpine soil landscape to land use changes, which was triggered by land use-related changes in the above cited indicator properties. In contrast, abandoning or extensifying agricultural use leads to the reverse process towards a gradual recovery of the anthropogenically modified soil properties (Zimmermann and Elsenbeer, 2008).

In the last decades, numerous studies have been published to quantify the stability and sensitivity of soils and landscapes (e.g. Friedman and Zube, 1992; Bayramin et al., 2008; Tamene et al., 2017; Vojteková and Vojtek, 2019). Nonetheless, an integrated method taking into account multiple, interconnected key soil parameters to investigate and assess soil landscape sensitivity in Alpine environments is still lacking.

Hence, the main objective of the present study is to assess the sensitivity of the southern Alpine soil landscape of the Onsernone valley (Ticino, Switzerland) for human-induced perturbations in terms of land use changes. This is of special relevance due to the long and diverse land use history as well as the extreme climatic and topographic conditions of the study area (Carraro et al., 2020). In the Swiss southern Alps, the abandonment of mountain farming and the related reforestation

---

[1] In this article, the term 'soil landscape' is used synonymously to 'soil landscape system' defined by Huggett (1975): A three-dimensional body of soil known as a soil landscape system or a "valley basin" (1) is bounded by the soil surface, valley watershed and weathering front at the base of the soil; (2) forms part of a more extensive valley basin network; and (3) functions as an open system.

appeared to be particularly early and intensive in comparison to the northern Alps. This is related to the following predisposing factors (Bertogliatti, 2013):

- the climatic conditions that favour the rapid growth of bushes and trees,
- the terrain that is generally steeper compared to the northern Alps,
- difficulties concerning the infrastructural accessibility of the higher and steeper parts of the valleys,
- socio-economic changes since World War II including their regional and subregional effects.

To this purpose, we investigate the effects of different land use changes on physical and chemical soil parameters such as (i) SOC, (ii) aggregate stability, and (iii) K_{sat}, which are generally considered as key sensitivity indicators. We further complemented them by (iv) SWR, which is a particular characteristic of the soils of the Onsernone valley (Zehe et al., 2007). SWR is strongly related to soil texture and SOC and hence can have a large effect on surface runoff generation (Burch et al., 1989; Keizer et al., 2005).

2. Material and methods

2.1. Study area

The study area is located in the Onsernone Valley near Lago Maggiore, in the southern Swiss Alps (Fig. 1) and covers approximately 6 km^2 with an altitudinal range going from 400 to 1000 m a.s.l.

North-facing slopes are covered by extended European beech (*Fagus sylvatica L.*) forests, whereas settled south-facing slopes are poorer in forests characterized by mixed hardwood stands dominated by European chestnut (*Castanea sativa Mill.*), deciduous oaks (*Quercus* spp.), alder (*Alnus glutinosa (L.) Gaertn*) and lime (*Tilia cordata Mill.)* in differing composition according to site characteristics and forest management (Muster et al., 2007; Vogel and Conedera, 2020).

The climate of the study area is characterized as oceanic (Cfb) climate following the Köppen climate classification (Kottek et al., 2006) showing dry winters as well as rainy springs and autumns. Mean annual precipitation is about 2000 mm (Swiss average: 1300 mm/year) with rainfall intensities reaching 400 mm per day and more. The mean annual temperature is 12 °C (1991–2020; MeteoSwiss, 2020).

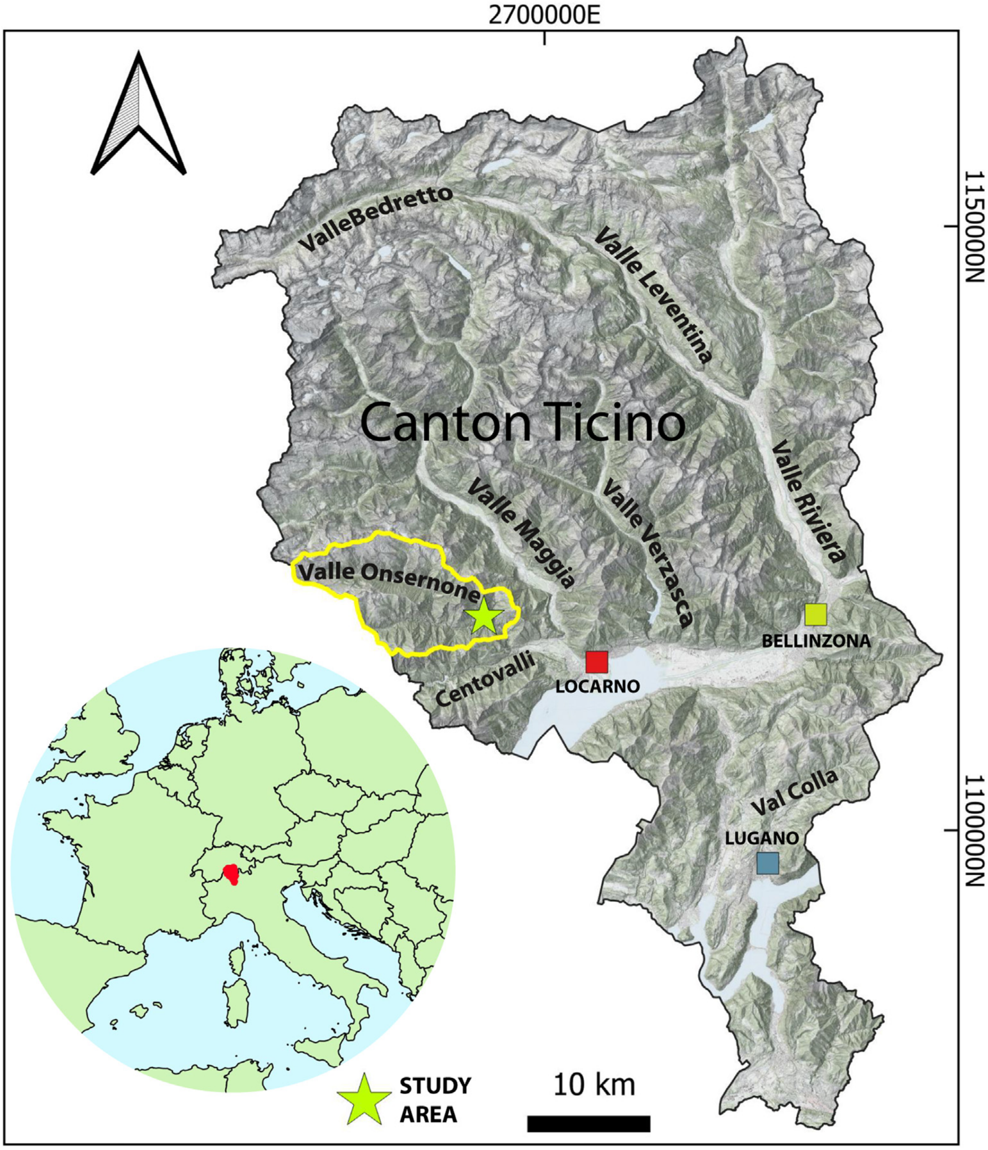


Fig. 1. Map of Canton Ticino with the location of the study area (Federal Office of Topography, swisstopo).

From the geological point of view, the study area is located in the Penninic Nappe and belongs to the Antigorio-Mergoscia complex (Pfeifer et al., 2018). The bedrock is rather homogenous and mainly consists of gneiss rich in plagioclase, quartz, biotite, and muscovite (Blaser, 1973). Moreover, the bedrock is mantled by Quaternary glacial (relict moraines) and slope deposits. The homogeneous lithology of the Onsernone valley is ideal to study effects of land use change on soil properties.

The valley is deeply incised with steep slopes ranging from 30 to 50° and an average gradient of 36° (Vogel and Conedera, 2020). Due to its pronounced East-West orientation, the valley can be subdivided into a south-facing and a north-facing slope with different microclimatic conditions and vegetation as well as a distinct economic development (Muster et al., 2007). The morphology of the valley is the result of the geological and structural settings of the area and was finally shaped by gravitational as well as fluvio-glacial processes (Canale, 1958). The V-shaped valley is enclosed in a tight synform fold indicating an intense fluvial forming of the area. Furthermore, glacial evidences are noticeable in the field and glacial deposits as well as erratic boulders can be observed. Finally slope debris and rockfall blocks appear on both sides of the valley. Following the Word Reference Base for soils (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., 1997, 1999). A common feature of these soils is the formation of a thick topsoil A horizon rich in organic matter (average value about 18 % of SOM), which tends to macroscopically mask the eluvial horizon of the Podzol. Consequently, the soils in the study area are called Cryptopodzols (Blaser, 1973; Blaser and Klemmedson, 1987; Blaser et al., 1997, 1999). Furthermore, the soils are characterized by a strong acidification showing pH values between 3.5 and 5.3. One of the main drivers for soil acidification is the presence or absence of forest vegetation, promoting or inhibiting podzolisation processes, respectively. Under natural forests, Cryptopodzols are predominant, whereas on deforested sites a recursive pedogenesis towards Cambisols takes place. Hence, land use changes tend to have a distinct influence on pedogenetic processes in the study area (Vogel, 2005; Vogel and Conedera, 2020). The soil texture is sandy loam (average values are 26 % of silt, 8 % of clay and 66 % of sand) following ASTM Standards. This coarse texture is related to a good drainage with high hydraulic conductivities (KA5; Ad-hoc-Arbeitsgruppe-Boden, 2006). Another important characteristic of the sandy and SOM-rich soils in the Onsernone valley is their tendency to be water repellent when dry.

2.2. Land use changes in the Onsernone Valley

The colonization of the Onsernone valley started during Roman times (Crivelli, 1943) and was intensified during the Middle Ages initially involving the deforestation of the south-facing slopes. The absence of a recent valley floor and the steepness of the slopes implied significant obstacles to the economic development of the valley. For that reason, arable land was created by terracing the rather gentle sloping areas that are related to relicts of former valley floors (Canale, 1958; Waehli, 1967). The first recorded reference of agricultural terraces dates to the end of the 13th century. However, the climax of terracing in the area was reached during the 16th century in relation to the rye cultivation for straw plaiting (Waehli, 1967; Zoller, 1960).

In contrast to the south-facing valley side, the north-facing slopes remained widely excluded from settlements and were rather used for silviculture, with patches of permanent and intensive pastoral farming on the gentler slopes of former valley floors.

The decline of straw plaiting at the end of the first world war and at the latest the cessation of marginal Alpine farming in the 1950s marked a significant alteration of the socio-economic conditions in the Onsernone valley. The strongly specialized and labour-intensive terrace cultivation was successively abandoned or only marginally cultivated (Muster et al., 2007). This led to a progressive reforestation accompanied by a partial collapse of the abandoned terraces (Muster et al., 2007; Bozzini et al., 2012; Vogel and Conedera, 2020). Likewise, animal husbandry on the north-facing slopes ceased and resulted in secondary reforestation of former pastures as documented by aerial photographs (starting in 1933). The abandoned pastures where reforestation has not yet taken place are characterized by meadows that are still today mowed once or twice a year.

2.3. Sampling design

The particular land use and land cover dynamics in the study area resulted in the establishment of the following six land cover-topography units, which are further distinguished between south- and north-facing slopes (LCTU; Fig. 2):

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

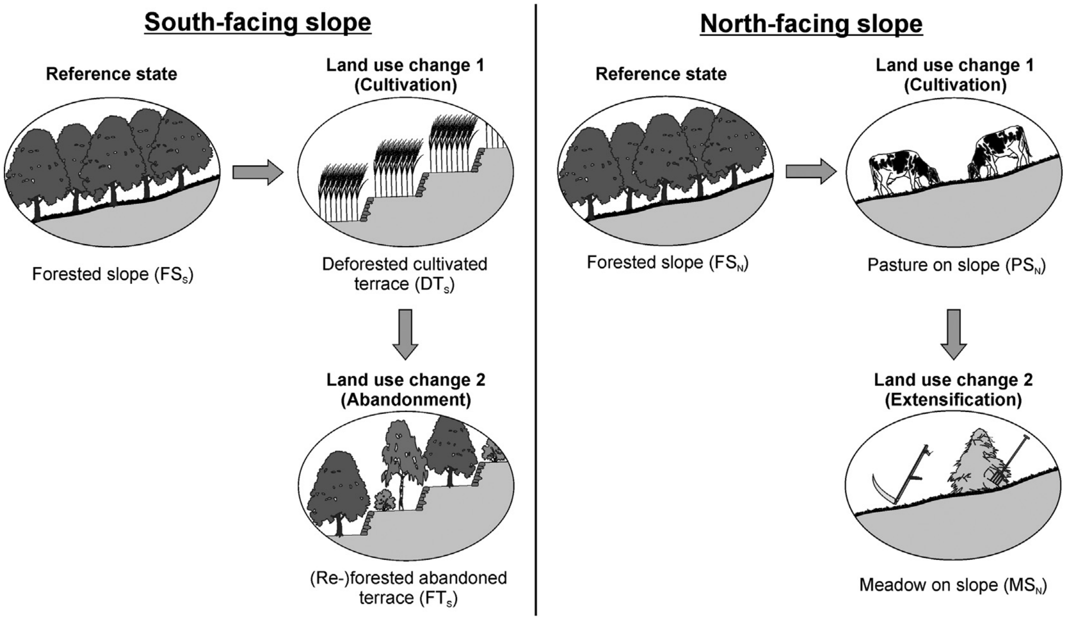


Fig. 2. Land use changes in the Onsernone valley.

The so defined LCTUs differ especially in terms of: (i) type of land use (pasture; meadow; agriculture; forest), (ii) land use status (cultivated; abandoned/extensified), and (iii) topography (terraced; natural slope). On both sides of the valley, forested slopes (FS) are considered as the natural reference state where, today, the anthropogenic influence is negligible. Own dendrochronological analyses of the trees revealed a minimum age of 70 to 80 years. On the other hand, pastures on slopes (PS) and deforested, cultivated terraces (DT) correspond to the situation of past agricultural utilization (Muster et al., 2007). Pastures were grazed by cows, sheeps and goats whereas terraces are predominantly used as vineyards or horticulture. Finally, post-abandonment (re-)forested, abandoned terraces (FT_s) and meadows on slopes represent the post-cultural soil evolution in our study. These LCTUs originate from the abandonment of cultivation at the latest with the cessation of alpine farming in the 1950s (Vogel and Conedera, 2020). FTs are characterized by 40 years old trees according to our own dendrochronological analyses.

For each of these six LCTUs, three replicate sites were selected resulting in a total amount of 18 measurement plots (Fig. 3A). Each plot, characterized by an extension of 20 × 20 m, was further divided into a matrix of 5 × 5 m cells. On the resulting 25 cells, a simple random sampling algorithm was applied selecting 5 to 15 measurement cells (Fig. 3B) on which the soil properties were analysed.

Since for PS_N, not enough (3) active replicate sites were found, one additional pasture site was selected from the south-facing slopes.

2.4. Analysed soil properties

As reported below the following soil properties have been analysed.

2.4.1. Soil texture

Grain size distribution was analysed collecting topsoil samples from the A horizon in three locations in each of the 18 measurement plots following the ASTM Standard (American Society for Testing Materials, 1988). Due to the high amount of organic matter soil samples were pre-processed with hydrogen peroxide for organic matter removal and dispersed using sodium pyrophosphate. Thereafter, the sand fractions were sieved, while for the analysis of fine fraction Stoke's law settling methods was used as described by Murthy (2002). In total 54 samples were analysed.

2.4.2. Bulk density

Bulk density of the upper soil was analysed on five samples randomly selected from each of the 18 measurement plots resulting in a total number of 90 samples. Undisturbed samples were collected by using a ring cylinder of 100 cm^3 following the methodology described in Blake (1965). In the laboratory, samples were weighted, oven-dried at 105 °C and reweighted. The known volume of the cylinder and the dry weight of the soil were then used to calculate the dry bulk density expressed in g/cm^3.

2.4.3. Soil Organic Carbon (SOC)

As stated above SOM was quantified through the analysis of SOC (see also Howard and Howard, 1990) on fifteen samples randomly selected from each of the 18 measurement plots resulting in a total number of 270 samples. SOC was analysed in laboratory by elementary analysis using the dry combustion method (Italian normative: DM 13/09/1999 SO n 185 GU n248 21/10/1999 Met VII.1) after removing the inorganic carbon with hydrochloric acid on air-dried and 0.5 mm-sieved samples. The SOC content is expressed in g/kg.

2.4.4. Saturated hydraulic conductivity (K_{sat})

K_{sat} was measured in the field in two different depths of 16 and 23 cm using a constant-head permeameter (Amoozegar, 1989a). The measurements were carried out in 15 randomly selected cells from each of the 18 measurement plots resulting in 270 measurement cells and a total of 540 measurements. Finally, K_{sat} was calculated in cm/h using the glover solution proposed by Zangar (1953) and adopted by Amoozegar (1989b). K_{sat} is used as a proxy for infiltration as already suggested in other studies (e.g. Miyata et al., 2007). Comparing K_{sat} with the precipitation intensity of the study area, the potential for surface runoff generation (Hortonian runoff) can be evaluated. Therefore, we calculated for each LCTU the difference between K_{sat} and hourly precipitation of different return periods reported by MeteoSwiss (2020).

2.4.5. Aggregate stability

Aggregate stability was measured on a total number of 180 undisturbed soil samples taken from the uppermost part of the mineral A horizon in 10 randomly selected measurement cells from each of the 18 measurement plots. A laboratory-based wet sieving apparatus (Eijkelkamp Soil & Water, Giesbeek, The Netherlands) was used following the procedure suggested by Kemper and Rosenau (1986). The analysis was performed on 4 g of aggregates of a diameter of 1 to 2 mm that were previously air-dried and sieved. Measurements were carried out on three replicates per sample. After drying, samples were prewetted in distilled water for ten minutes and then put in a cylindrical sieve of 250 μm mesh width and placed in one of the eight sieve holders of the wet sieving apparatus. Then, the samples were repeatedly immersed into cans of distilled water for three minutes at a frequency of 35 times/min. The cans containing all unstable aggregates were oven-dried at 105 °C, and weighted. Afterwards, the stable aggregates that remained in the sieves were completely destroyed using a dispersion solution of distilled water and 2 ‰ of sodium hexametaphosphate. Finally, the cans containing the stable aggregates were dried, and the weight was quantified.

The aggregate stability (AS) is calculated using Eq. (1):

$$AS = \frac{W1}{W1 + W2} \tag{1}$$

where W1 is the weight of stable aggregates minus the weight of the solution (0.2 g) and W2 the weight of unstable aggregates.

2.4.6. Soil water repellency (SWR)

Potential SWR was assessed in the laboratory using the Molarity of Ethanol Droplet (MED) test (Roy and McGill, 2002) on air-dried samples. A total of ten samples of the uppermost mineral soil horizon were collected from each sampling cell, at the same position where the samples for aggregate stability were taken. For the MED test, several droplets of a solution of increasing molar concentrations of ethanol are placed on a previously flattened soil surface. Then, the lowest molar ethanol concentration is determined at which the droplet takes 10 s to infiltrate into the soil. The result is reported in units of molarity. The arbitrary scale proposed by King (1981) was used to classify the various categories of SWR, which is divided into three classes based on molarity: slight (MED ≤ 1.0 M), moderate (1.0 M < MED < 2.2 M) and severe (MED ≥ 2.2 M).

2.5. Statistical analysis

For descriptive statistics, the arithmetic mean, standard deviation and coefficient of variation for all soil properties were calculated and reported in a table.

The effects of land use changes on the measured soil properties of the six LCTUs were assessed though random intercept linear mixed models (LMM). LMM are particularly suitable for this kind of data that is lacking of independence due to their nested structure. Moreover, LMM was chosen since the traditional methods like one way ANOVA, Wilcoxon Rank

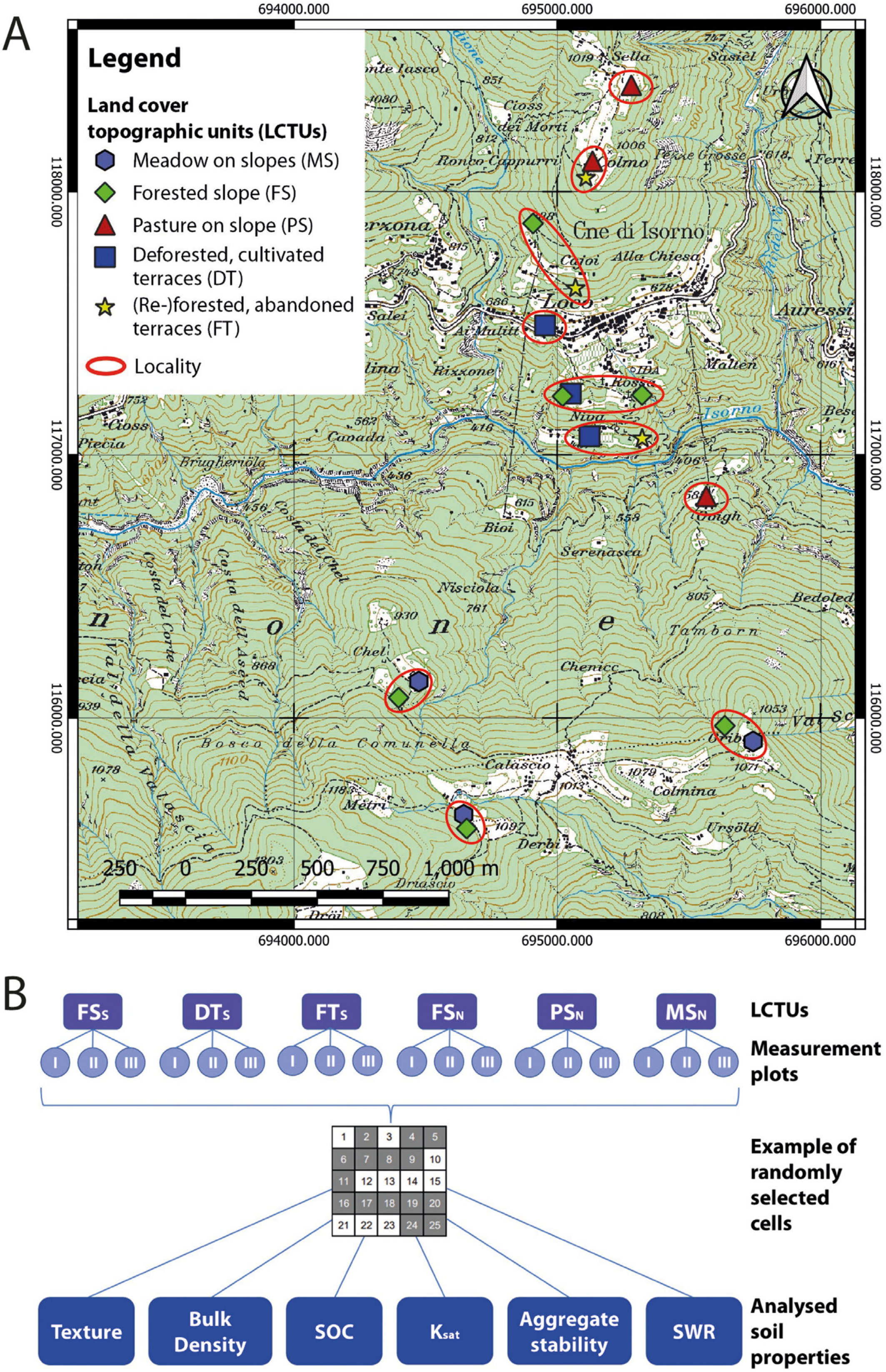


Fig. 3. (A) Spatial distribution of LCTU-locations based on Swiss map raster 10 (© swisstopo, reference system CH1903 / LV03 EPSG: 21781), (B) sampling design adopted for the measurement of the soil properties.

Sum Test, Kruskal-Wallis test and others are not suitable for the obtained value distributions. The normal distribution of all datasets was assessed through Shapiro-Wilk normality test (Shapiro and Wilk, 1965). All physical and chemical soil properties were normally distributed except for saturated hydraulic conductivity and soil organic carbon, which were log-transformed to meet the requirements of LMM.

For the assessment of the random and fixed effects, data were distinguished in three levels:

(i) data at the six LCTU levels,
(ii) data at the 10 locality levels, defined based on proximity to each other, irrespectively of the LCTU the individual data is belonging to (Fig. 3),
(iii) data at the 18 plot levels, consisting of three repetitions for each LCTU where the soil parameters were measured.

The LCTU is considered the fixed effect while the locality and plot entered the model as random effects to account for unexplained variation at the locality (σ^2loc) and plot (σ^2plot) levels when controlling for the explanatory variables. Analyses were performed using the lme4 package (Bates et al., 2015) in R version 4.0.1 (R Core Team, 2021). Unless otherwise stated, data are reported as arithmetic means ± standard errors. Finally, for each key soil property we used pairwise comparisons between marginal means predicted by the LMM as post hoc test to identify significant differences among LCTUs.

In order to identify linear correlations of the physical and chemical properties among LCTUs, a Spearman correlation matrix (on not transformed data) reports the coefficients and the p-values for the correlation tests (statistically significant: p-value <0.05).

3. Results

Table 1 gives a descriptive overview on the results obtained for the five analysed soil physical and chemical key properties used to assess the soil landscape sensitivity. Instead the parameters of the LMM models are reported in the supplementary material (see Appendix A) as well as the LMM-based pairwise comparisons between the LCTUs for each key soil property (see Appendix B).

3.1. Soil texture

Fig. 4 reports the distribution of the grain size classes using the soil texture ternary diagram with the USDA-based (United States Department of Agriculture) soil texture classes. It shows that the soil texture is quite homogeneous over the different LCTUs plotting mainly in the sandy loam texture class. Generally, the clay content is <15 %. Mean and standard deviation content expressed in percentage of silt, clay and sand of each LCTU are reported in the supplementary material (see Appendix C, Table C.1).

3.2. Bulk density

Values of bulk density range between 0.4 and 1.3 g/cm^3. Forests on north facing slopes and meadows show the lowest bulk density values (Table 1) while the highest values are measured on cultivated and abandoned terraces. The LMM analysis partially confirms these outputs. Indeed, the effect of land use on the bulk density was significant (see Appendix A, Table A.1), but only for FS_N, MS_N (see Fig. 5). Instead no significant difference in bulk density is reported for DT_S, FT_S, FS_S, and PS_N. In contrast, DT_S have significantly higher bulk densities compared to FS_N, MS_N and PS_N. Furthermore, FS_S showed significantly higher values than FS_N, MS_N and PS_N (see Appendix B, Table B.1). A significant variability in bulk density was found among localities (σ^2loc) independent of LCTU, which accounts for 47.5 % of the whole bulk density variability not explained by land use. In contrast, the effect of the σ^2plot was not significant (see Appendix A, Table A.1).

3.3. Soil organic carbon

The amount of SOC ranges from 39.5 to 280.4 g/kg and differs between the different LCTUs as shown in Table 1. The highest values were obtained for FS_N with values >100 g/kg. Instead, DT_S are characterized by the lowest values amounting to 60 g/kg. The results from the LMM confirmed these observations indicating a highly significant effect of the different LCTUs on the amount of SOC. In detail, DT_S and FT_S did not significantly differ from each other but showed a significantly lower amount of SOC than all other LCTUs (see Appendix B, Table B.2). For both, DT_S and FT_S, the random effects were significant, suggesting that SOC had a relevant variability not related to the LCTUs but among replicate sites and measurement plots (see Appendix A, Table A.1). In detail, σ^2loc and σ^2plot accounted for 36.8 % and 15.8 % of the unexplained variance, respectively.

3.4. Saturated hydraulic conductivity

K_{sat} at depths of 16 and 23 cm was high to extremely high following the German pedological mapping guidelines (KA5; Ad-hoc-Arbeitsgruppe-Boden, 2006) (Table 1). Values range from 0.2 to 33.5 cm/h and are always

Table 1
Descriptive statistics of the five analysed soil properties in the six LCTUs.

	Land cover-topography unit	Aggregate stability [DI]	K_{sat} (16 cm) [cm/h]	K_{sat} (23 cm) [cm/h]	Bulk density [g/cm^3]	Soil Organic carbon [g/Kg]	Soil water repellence [mol/L]
South-facing slope	Forested slope (FS_S)	0.9 ± 0.0 (0.8–1.0) [0]	8.1 ± 4.2 (0.8–17.5) [0.5]	2.8 ± 1.7 (0.7–7.4) [0.6]	0.9 ± 0.1 (0.6–1.1) [0.1]	90.2 ± 35.7 (42.7–214.3) [0.4]	3.5 ± 1.0 (1.6–5.2) [0.3]
	Deforested cultivated terrace (DT_S)	0.9 ± 0.0 (0.9–1.0) [0]	9.9 ± 6.4 (2.0–26.6) [0.7]	3.5 ± 1.9 (1.3–8.0) [0.5]	0.9 ± 0.2 (0.7–1.1) [0.2]	58.1 ± 11.5 (39.5–85.2) [0.2]	1.3 ± 1.0 (0.0–3.6) [0.8]
	(Re-)forested abandoned terrace (FT_S)	0.9 ± 0.1 (0.8–1.0) [0.1]	7.1 ± 3.1 (0.9–13.5) [0.4]	4.9 ± 2.9 (1.1–12.0) [0.6]	0.9 ± 0.2 (0.4–1.3) [0.2]	94.4 ± 44.7 (38.0–236.8) [0.5]	3.2 ± 1.2 (0.3–4.5) [0.4]
North-facing slope	Forested slope (FS_N)	0.9 ± 0.1 (0.7–1.0) [0.1]	13.2 ± 6.7 (1.7–33.5) [0.5]	5.6 ± 3.2 (0.8–11.9) [0.6]	0.6 ± 0.2 (0.3–0.8) [0.3]	107.8 ± 58.5 (53.5–280.4) [0.5]	5.3 ± 1.1 (2.6–6.0) [0.2]
	Pasture on slope (PS_N)	0.9 ± 0.1 (0.7–1.0) [0.1]	5.3 ± 3.3 (1.0–14.0) [0.6]	2.5 ± 1.2 (0.8–6.7) [0.5]	0.7 ± 0.1 (0.5–1.0) [0.1]	93.4 ± 18.8 (63.9–147.5) [0.2]	2.8 ± 1.5 (0.0–6.0) [0.5]
	Meadow on slope (MS_N)	0.9 ± 0.1 (0.6–1.0) [0.1]	8.7 ± 6.3 (1.8–29.3) [0.7]	4.5 ± 5.1 (0.2–25.9) [1.1]	0.6 ± 0.1 (0.4–0.8) [0.1]	98.5 ± 19.1 (58.8–131.9) [0.2]	4.7 ± 2.2 (0.0–6.0) [0.5]

Descriptive statistics (mean ± standard deviation, range in brackets and coefficient of variation in square brackets) of the five key soil properties measured in the six land cover-topography units. Aggregate stability is dimensionless [DI] and is reported in scale from zero to one, zero means absence of stable aggregates, one means absence of unstable aggregates.

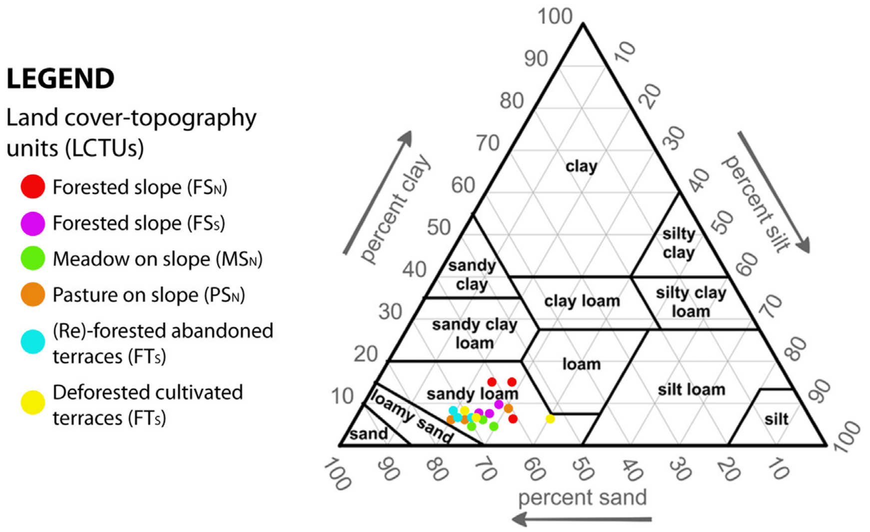


Fig. 4. Texture and grain size composition of each LCTU plot reported on ternary diagram with the USDA-based soil texture classes.

significantly higher at a depth of 16 cm compared to 23 cm (Welch Two Sample t.test: $t = 11.177$, $P < 0.001$). Furthermore, the variation of K_{sat} between the LCTUs is higher at 16 cm and decreases at 23 cm depth. A strong significant effect was found of the different LCTUs on K_{sat} (see Appendix A, Table A.1). K_{sat} decreases from terraces over forested slopes, to MS_N and PS_N, in both 16 and 23 cm soil depth (Fig. 5). Regarding K_{sat} in 16 cm, no significant difference was detected among DT_S and FT_S, as well as FS_N and FS_S. Nonetheless, all these LCTUs are significantly higher than PS and MS_N (see Appendix B, Table B.3). A higher number of significant differences among LCTUs were found for K_{sat} measured at 23 cm soil depth. No significant differences occurred between MS_N, PS and DT_S, which in turn have significantly lower values than the other LCTUs (see Appendix B, Table B.4). The random effects assessed by the LMM are also significant (see Appendix A, Table A.1), suggesting that K_{sat} shows relevant patterns of variation both between locality and within measurement plot. In detail, σ^2loc accounted for 26.3 % and 45.1 % of variability in K_{sat} unexplained by land use at 16 and 23 cm soil depth respectively, while the corresponding values for σ^2plot were 12.3 % and 15.7 %.

Using the mean K_{sat} as a proxy for infiltration and comparing it with the precipitation intensity, the following results were obtained: (i) none of the LCTUs produced surface runoff at a rainfall intensity corresponding to a 5-years return period equivalent to 50 mm/h, (ii) for a 10-years return period (60 mm/h), only PS generate a potential surface runoff of 7 mm/h, (iii) for a 20-years return period (75 mm/h), PS and FT_S yield a potential surface

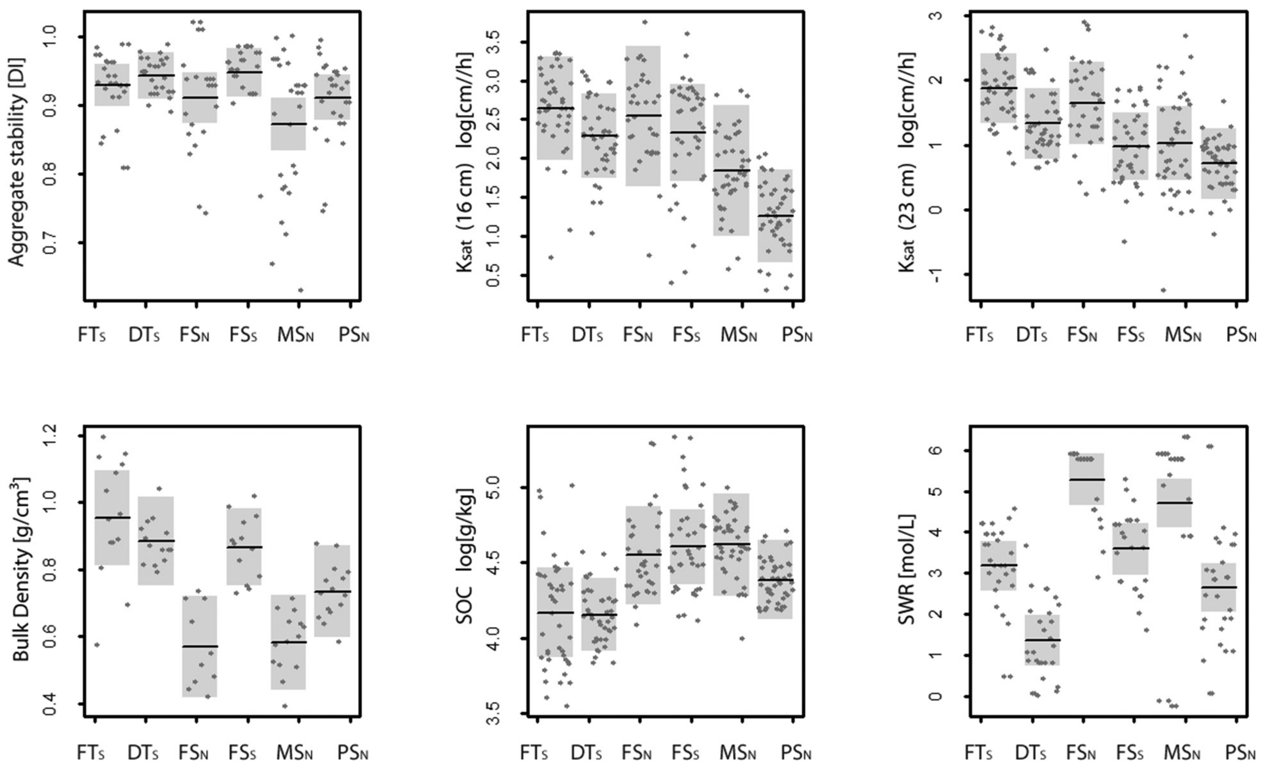


Fig. 5. Linear mixed model (LMM) of the different soil properties.

Table 2
Correlation among the physical and chemical properties of the soil.

	Aggregate stability	K_{sat} (16 cm)	K_{sat} (23 cm)	Bulk density	SOC	SWR
Aggregate stability		0.139	0.151	---	**0.255**	0.007
K_{sat} (16 cm)	0.081		**0.512**	-0.036	-0.074	**0.189**
K_{sat} (23 cm)	0.058	**<0.001**		-0.194	0.060	**0.161**
Bulk density	---	0.754	0.084		**-0.633**	---
SOC	**0.001**	0.255	0.353	**<0.001**		**0.371**
SWR	0.930	**0.018**	**0.043**	---	**<0.001**	

Matrix for the linear correlations among the six physical and chemical properties used to characterize their variability among LCTUs. Upper triangle: spearman correlation coefficients; lower triangle: p-values for the correlation tests. p-Values <0.05 indicate statistical significance. Statistically significant values are reported in bold. — means that soil properties were not comparable because they were not analysed on the exact same samples (but on the same plots).

runoff of 22 and 4 mm/h, (iv) for a 50-years return period (90 mm/h), PS, FT_S, FS_S and MS_N generate a potential surface runoff of 37, 19, 9 and 3 mm/h (v) DT_S produce a potential surface runoff of 6 mm for a 100-years return period (105 mm/h), and (vi) even for a 300-years return period (130 mm/h) FS_N do not generate surface runoff.

3.5. Aggregate stability

The mean value of aggregate stability observed in all six LCTUs is 0.9 (Table 1). Accordingly, the LMM did not detect any significant land use effect on aggregate stability (Fig. 5, see Appendix A, Table A.1). We found a significant variability of aggregate stability among localities (σ^2loc) independent of LCTU, which account for 18 % of the whole variability in soil stability not explained by the fixed effect. In contrast, the effect of the σ^2plot was not significant (see Appendix A, Table A.1), suggesting that the variability in aggregate stability among measurement plots within a locality is negligible with respect to the variability at sampling site level.

3.6. Soil water repellency

SWR ranged from 0 to 6 mol/L (Table 1). The mean values measured for the different LCTUs fall in the severe SWR class except for DT_S which is classified as moderate. SWR significantly varies among LCTUs (see Appendix A, Table A.1), distinguishing three main groups. Cultivated terraces showed the lowest values of SWR (Fig. 5), which was significantly lower than in all other LCTUs. SWR in abandoned terraces, FSs and PS_N did not significantly differ and are characterized by intermediate values (Fig. 5). Finally, the highest values of SWR were obtained on FS_N and MS_N, which were significantly higher than values recorded on FT_S, FS_S and PS (see Appendix B, Table B.6). In contrast to all previous analyses, the random effects of the locality and the measurement plot within a locality on soil water repellence variability were not significant (see Appendix A, Table A.1). These results suggest that the variability of SWR at site level (σ^2loc) as well as at plot level (σ^2plot) is negligible with respect to the land use-induced variability.

3.7. Correlation analysis

As illustrated in Table 2, aggregate stability shows a significant weak correlation only with soil organic carbon. K_{sat} has a moderate correlation between the two measurement depths as well as weak correlation with SWR, while bulk density is moderately negatively related with SOC. Finally, SOC shows a weak correlation with SWR.

Soil texture was not taken into consideration for the correlation matrix as only a few samples were collected (3 per plot) and since texture is homogeneous over all 6 LCTUs consisting in sandy loam.

4. Discussion

Fig. 6 illustrates the specific interdependencies between land use changes, the analysed key soil properties and soil erosion in the Onsernone valley, which are discussed specifically for each LCTU in the following section.

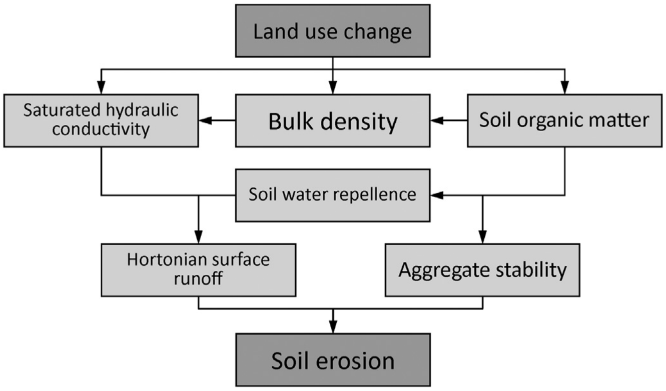


Fig. 6. Specific interdependencies between land use changes, soil properties and soil erosion in the Onsernone valley. Arrows indicate the direction of influence.

4.1. North-facing slopes

4.1.1. Forested slopes (FS_N)

The FS_N as a reference state for negligible anthropogenic influence show the lowest bulk density compared to all other LCTUs characterized by values that are significantly lower than the average of sandy loam soils following Morris and Lowery (1988). This results from the highest SOC contents among all LCTUs establishing a stable soil structure (e.g. Avnimelech et al., 2001; Chaudhari et al., 2013). The very strong accumulation of SOC under forests can be explained by a very slow and fragmentary decomposition of organic material predominantly deriving from European beech (*Fagus sylvatica* L.) (Guo and Gifford, 2002). The K_{sat} is high to very high at 16 and 23 cm depth which is due to a high abundance of macropores generated by tree roots as well as larger stable soil aggregates that promote the formation of preferential flow paths (Toohey et al., 2018). Following Gupta et al. (2021), the K_{sat} values are consistent with the prevalent sandy loam soil texture. Taking K_{sat} as a proxy for the infiltration capacity of the soil and in turn for the potential generation of Hortonian surface runoff, even a 300-years precipitation return period (130 mm/h) does not generate surface runoff indicating rather stable soil conditions. Finally, SWR is classified as severe following the classification of King (1981) reaching the highest value with respect to all other LCTUs. This results from the high amounts of SOC and corresponds to findings of Fu et al. (2021) stating that soils with SOC > 4 % tend to be water repellent.

4.1.2. Pasture on slope (PS_N)

The first land use change on north facing slopes that can be assigned to the cultivation phase was the conversion from forests to pastures (see Fig. 2). This led to significant differences in the studied key soil properties except for bulk density. This is in agreement with the results of De Morares et al. (1996) who studied a chronosequence of pasture establishment from native forests and found only a marginal increase in bulk density in the upper 5 cm of soil with even lower changes detected in deeper soil layers. K_{sat}, on contrary, significantly decreased in both depths with respect to the reference state. This corresponds to e.g., Stewart et al. (2020) who found significant lower K_{sat} values when forest is converted to pastures which they explained by a reduction of macropores as a consequence of soil compaction (Elsenbeer et al., 1999; Głąb et al., 2009). This results in a strong increase in the susceptibility of pastures to generate Hortonian surface runoff already at rainfall intensities of 60 mm/h (10-years return period). The conversion of natural forests to pastures also significantly decreased SWR. Since no significant difference were detected for the amount of SOC, this is probably due to a different SOC quality as documented by Doerr et al. (2000), Lozano et al. (2013), and Fu et al. (2021). However, this was not further analysed in the present study.

4.1.3. Meadow on slope (MS_N)

After the cultivation phase, the second land use change on north-facing slopes was the extensification of animal farming that resulted in the conversion of pastures into meadows. No significant differences in the key soil properties were found with the exception of a significant increase of SWR. This considerable similarity between PS_N and MS_N may be explained by the fact that in the past both were used for grazing, which is visible by a similar vegetation cover and composition. Thus, it can be concluded that the significant differences in the key soil properties between natural forests and pastures are predominantly the result of the land use-induced vegetation change rather than grazing.

4.2. South-facing slopes

4.2.1. Forested slopes (FS_S)

The reference state on $FS_{S\ shows}$ a bulk density that is significantly higher with respect to FS_N. This may be because the FS_S dominated by European chestnut (*Castanea sativa* Mill.) was intensively used in the past and, due to the development of settlements solely on south-facing slopes, anthropic influence is still higher today compared to the FS_N. As a consequence, the soil may have experienced compaction and hence, an increase in bulk density. Similar to the FS_N, the K_{sat} values of FS_S are also high to very high at both depths due to a high macro pore presence generated by tree roots. However, surface runoff can be produced on FS_S already for rainfall intensities of a 100-years return period (105 mm/h), whereas for FS_N instead only the 300-years return period (130 mm/h) produce runoff. Likewise, as a result of the low biodegradability of SOM (Guo and Gifford, 2002) we found very high SOC values. In contrast, SWR shows significantly lower values compared to FS_N, which again cannot be explained by the amount of SOC. Hence, it may be due to a different composition and quality of SOM produced by the different predominant tree species.

4.2.2. Deforested cultivated terraces (DT_S)

On south-facing slopes, the initial land use changes in the cultivation phase were towards deforested cultivated terraces DT_S. It leads to a strong decrease in SOC resulting in the lowest amounts of all LCTUs. This was also observed by Vogel and Conedera (2020) in the same study area and can be explained by the clearance of forest vegetation producing organic material of reduced biodegradability. This eventually results in the formation of an organic surface layer and a SOC-rich upper soil layer. A second reason may be the utilization of the terraces for agriculture. A decrease in SOC can arise from regular tillage of the terraces leading to a better ventilation and aggregate destruction and hence to a higher SOM mineralisation rate (Rehfuess, 1990; see also Guo and Gifford, 2002). However, also SWR shows significantly lower values on DT_S, which is in line with the positive correlation of SWR and SOC stated by Fu et al. (2021). No difference was detected for K_{sat} at a depth of 16 cm. Nevertheless, taking into account the average K_{sat} values, the surface runoff susceptibility increased to a rainfall intensity of 105 mm/h. At a depth of 23 cm, K_{sat} has significantly increased, most likely due to the fact that the soil of the cultivated terraces has been largely disturbed and reworked during terracing destroying the natural soil structure. This may have resulted in a decrease in bulk density in the entire soil profile. In course of settling of the soil and terrace cultivation, soil compaction took place leading to a successive increase of bulk density from the surface to the bottom of the soil. Hence, K_{sat} has decreased in the top layer, while the subsoil is characterized by higher K_{sat} values if compared to the natural reference state.

4.2.3. (Re-)forested abandoned terraces (FT_S)

After the phase of cultivation, the terraces were abandoned and a successive reforestation took place. However, no significant difference was detected for bulk density, K_{sat} at 16 cm depth and SOC. In contrast, regarding the mean K_{sat} values, the susceptibility of surface runoff generation further increased and is responding already on rainfall events of 75 mm/h (20-years return period). Despite the renewed presence of trees that should favour a successive re-increase of SOM, no significant increases in SOC were observed by LMM even though the average SOC content of FT_S is much higher compared to DT_S. This is the result of a much higher variability of SOC values in FT_S as expressed by high standard deviations and coefficients of variation. Lower amounts of SOC than expected can be partly explained by soil erosion that took place due to a collapse of terrace walls increasing the slope gradient and favouring soil exposure. Hence, soil erosion preferentially removes the light soil fraction including SOM, which is concentrated at the soil surface (Kimble et al., 2001). In contrast at depth of 16 cm, K_{sat} at 23 cm showed a significant increase. This may be due to the regrowth of trees with cultivation abandonment and root growth in the subsoil generating macropores that create preferential flow paths (Toohey et al., 2018). Finally, also for SWR a significant increase was detected. Since this is again not accompanied by an increase in SOC, it may be the result of a different SOM composition supplied by the forest trees compared to that of the formerly cultivated crops.

4.3. Discussion synthesis

As mentioned above, no difference in aggregate stability was detected among the LCTUs, which can be explained by the very homogenous soil texture in the study area. Hence, irrespective of the described land use changes in the Onsernone valley, the amount of stable aggregates is very high, pointing to a very low soil erodibility. This can be attributed to the generally high amounts of SOM (Haynes and Swift, 1990; Le Bissonnais and Arrouays, 1997; Smith et al., 2015), so that, regardless of different SOC amounts between the different LCTUs, the critical threshold value of SOC content is not reached that might result in a distinct reduction of aggregate stability. This insensitivity of soil aggregate stability to land use changes in the study area is remarkable, since it was repeatedly used in the past as an indicator for soil's stability and low soil erosion potential (e.g., Ali et al., 2017; Pohl et al., 2009; Fultz et al., 2013). In contrast, SWR was detected to be highly influenced by land use changes and thus possibly controlling soil landscape stability in the Onsernone valley. In fact, significant variations in SWR were identified due to land use changes on both slopes of the valley. This high sensitivity of SWR to land use changes is further demonstrated by the fact that only the fixed effects revealed by the LMM are significant and not the random effects. These land use-induced variations in SWR are only partially explained by the amount of SOC, which can be seen in the low correlation shown in Table 2. However, this is in contrast to the literature (e.g. Liu et al., 2005; Chaplot and Cooper, 2015). Further, and more detailed investigations are required in that context as well as on the effects of SOM quality and composition or anthropogenic disturbances like forest fires on SWR.

5. Conclusion

Due to extreme topographic and climatic conditions, which are typical for the southern Alps, a general instability of the soil landscape of the Onsernone valley was hypothesized, especially as a result of anthropogenic disturbances. However, aggregate stability, which is commonly used for detecting land use-induced changes in soil erosion susceptibility, was always very high irrespective of the LCTU. This is caused by very high amounts of SOC that reduce soil erodibility and increase landscape stability in the study area. Even though, land use changes affected the amount of SOC, it did not reach the critical threshold value to significantly change the stability of soil aggregates.

In contrast to aggregate stability, SWR turned out to be the most sensitive towards land use changes. Since this can only partly be explained by the amount of SOC, the composition and quality of SOM should be analysed in the future.

Finally, K_{sat} was used as a proxy for the soil's infiltration capacity and, by comparison with the rainfall intensity to assess the susceptibility of a LCTU for surface runoff generation. However, this does not take into account other controlling factors in surface runoff generation. Especially a high SWR causes a reduced infiltration capacity, and thus might increase surface runoff (Doerr et al., 2003; Miyata et al., 2007; Lemmnitz et al., 2008). To further study and quantify surface runoff generation and soil erosion in the different LCTUs, in a next step, rainfall simulation experiments will be carried out. These data can be used to verify the current conclusions drawn and to finally evaluate the sensitivity of the Onsernone valley towards land use changes.

Nonetheless, the Onsernone soil landscape seems to be quite stable in terms of aggregate stability, surface runoff and soil erosion for events up to a 10 years return period. However, it is very likely that in the future these return period thresholds might be higher and droughts may be longer leading to intensified effects related to SWR (see e.g. Jacob et al., 2014). These effects might increase surface runoff and thus, affect soil landscape sensitivities especially in the land uses that are already stronger affected such as FT_s and PS. Thus, our results point to a careful land management that should already now start to think about measures to fight, cope or mitigate negative effects of climate change in order to maintain crucial resources like Alpine soils.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.159779.

Funding

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

Ethical approval

Not required.

CRediT authorship contribution statement

Manuele Bettoni: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing. **Michael Maerker:** Conceptualization, Investigation, Supervision, Writing – review & editing, Project administration. **Roberto Sacchi:** Formal analysis, Writing – review & editing. **Alberto Bosino:** Investigation, Writing – review & editing. **Marco Conedera:** Writing – review & editing, Funding acquisition. **Laura Simoncelli:** Investigation. **Sebastian Vogel:** Conceptualization, Methodology, Investigation, Writing – review & editing, Supervision, Funding acquisition, Project administration.

Data availability

Data will be made available on request.

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.

Acknowledgments

The authors are thankful for the contribution of Geraldine Quénéhervé and Janusch Bach for their help during the field campaigns. Moreover, we would like to thank the owners and authorities of Onsernone valley for collaboration and support of the fieldwork.

References

Ad-hoc-Arbeitsgruppe-Boden, 2006n. Bodenkundliche Kartieranleitung. KA5. Schweizerbart Science Publishers, Stuttgart, Germany.

Ali, H.E., Reineking, B., Münkemüller, T., 2017. Effects of plant functional traits on soil stability: intraspecific variability matters. Plant Soil 411, 359–375. https://doi.org/10.1007/s11104-016-3036-5.

American Society for Testing Materials, 1988. Annual book of ASTM standards. American Society for Testing and Materials, Philadelphia.

Amoozegar, A., 1989a. A compact constant-head permeameter for measuring saturated hydraulic conductivity of the vadose zone. Soil Sci. Soc. Am. J. 53, 1356–1361. https://doi.org/10.2136/SSSAJ1989.03615995005300050009X.

Amoozegar, A., 1989b. Comparison of the glover solution with the simultaneous-equations approach for measuring hydraulic conductivity. Soil Sci. Soc. Am. J. 53, 1362–1367. https://doi.org/10.2136/SSSAJ1989.03615995005300050010X.

Angers, D.A., Eriksen-Hamel, N.S., 2008. Full-inversion tillage and organic carbon distribution in soil profiles: a meta-analysis. Soil Sci. Soc. Am. J. 72, 1370–1374. https://doi.org/10.2136/sssaj2007.0342.

Avnimelech, Y., Ritvo, G., Meijer, L.E., Kochba, M., 2001. Water content, organic carbon and dry bulk density in flooded sediments. Aquac. Eng. 25, 25–33. https://doi.org/10.1016/S0144-8609(01)00068-1.

Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Softw. 67, 1–48. https://doi.org/10.18637/jss.v067.i01.

Bayramin, I., Basaran, M., Erpul, G., Canga, M.R., 2008. Assessing the effects of land use changes on soil sensitivity to erosion in a highland ecosystem of semi-arid Turkey. Environ. Monit. Assess. 140, 249–265. https://doi.org/10.1007/s10661-007-9864-2.

Bertogliatti, M., 2013. Indagine preliminare per una ricerca storico-archeologica sui terrazzamenti nel Moesano. Ricerca svolta nell'ambito del programma Moesano: Cultura e Natura. Report of the Centro culturale di circolo Mesocco Soazza Lostallo.

Blake, G.R., 1965. Bulk Density. Methods Soil Anal., Agronomy Monographs. https://doi.org/10.2134/agronmonogr9.1.c30.

Blaser, P., 1973. Die bodenbildung auf silikatgestein im südlichen Tessin. Mitteilungen der schweizerischen anstalt für das forstl. Versuchswes. 49, 253–340.

Blaser, P., Kernebeek, P., Tebbens, L., Van Breemen, N., Luster, J., 1997. Cryptopodzolic soils in Switzerland. Eur. J. Soil Sci. 48, 411–423. https://doi.org/10.1111/j.1365-2389.1997.tb00207.x.

Blaser, P., Klemmedson, J.O., 1987. Die bedeutung von hohen aluminiumgehalten für die humusanreicherung in sauren Waldböden. Z. Pflanzenernähr.Bodenkd. 150, 334–341. https://doi.org/10.1002/jpln.19871500512.

Blaser, P., Zysset, M., Zimmermann, S., Luster, J., 1999. Soil acidification in southern Switzerland between 1987 and 1997: a case study based on the critical load concept. Environ. Sci. Technol. 33, 2383–2389. https://doi.org/10.1021/es9808144.

Boardman, J., Poesen, J., 2006. Soil erosion in Europe: major processes. Soil Eros. Eur., Wiley Online Books, Causes and Consequences. https://doi.org/10.1002/0470859202.ch36.

Bozzini, C., Conedera, M., Krebs, P., 2012. A New monoplotting tool to extract georeferenced vector data and orthorectified raster data from oblique Non-metric photographs. Int, Jour. of Heritage in the Digital Era. 1 (3), 499–518. https://doi.org/10.1260/2047-4970.1.3.499.

Brunsden, D., Thornes, J.B., 1979. Landscape sensitivity and change. Trans. Inst. Br. Geogr. 4, 403–484. https://doi.org/10.2307/622210.

Burch, G.J., Moore, I.D., Burns, J., 1989. Soil hydrophobic effects on infiltration and catchment runoff. Hydrol. Process. 3, 211–222. https://doi.org/10.1002/hyp.3360030302.

Burt, T., 2001. Integrated management of sensitive catchment systems. Catena 42, 275–290. https://doi.org/10.1016/S0341-8162(00)00141-7.

Canale, A., 1958. Geomorphologie der Valle onsernone. Promot.

Carraro, G., Gianoni, P., Kemper, A., 2020. La vegetazione forestale della valle onsernone e le sue tendenze evolutive.

Chaney, K., Swift, R.S., 1984. The influence of organic matter on aggregate stability in some british soils. J. Soil Sci. 35, 223–230. https://doi.org/10.1111/j.1365-2389.1984.tb00278.x.

Chaplot, V., Cooper, M., 2015. Soil aggregate stability to predict organic carbon outputs from soils. Geoderma 243–244, 205–213. https://doi.org/10.1016/j.geoderma.2014.12.013.

Chaudhari, P.R., Ahire, D.V., Ahire, V.D., Chkravarty, M., Maity, S., 2013. Soil bulk density as related to soil texture, organic matter content and available total nutrients of coimbatore soil. Int. J. Sci. Res. Publ. 3, 1–8.

Crivelli, A., 1943. Prehistoric and historical atlas of italian Switzerland. 1st ed. Istituto Editorale Ticinese.

De Morares, J.F.L., Volkoff, B., Cerri, C.C., Bernoux, M., 1996. Soil properties under Amazon forest and changes due to pasture installation in Rondônia, Brazil. Geoderma 70, 63–81. https://doi.org/10.1016/0016-7061(95)00072-0.

Doerr, S.H., Ferreira, A.J.D., Walsh, R.P.D., Shakesby, R.A., Leighton-Boyce, G., Coelho, C.O.A., 2003. Soil water repellency as a potential parameter in rainfall-runoff modelling: experimental evidence at point to catchment scales from Portugal. Hydrol. Process. 17, 363–377. https://doi.org/10.1002/hyp.1129.

Doerr, S.H., Shakesby, R.A., Walsh, R.P.D., 2000. Soil water repellency: its causes, characteristics and hydro-geomorphological significance. Earth-Science Rev. 51, 33–65. https://doi.org/10.1016/S0012-8252(00)00011-8.

Drewry, J.J., Paton, R.J., 2000. Effects of cattle treading and natural amelioration on soil physical properties and pasture under dairy farming in Southland, New Zealand. New Zeal. J. Agric. Res. 43, 377–386. https://doi.org/10.1080/00288233.2000.9513438.

Drewry, J.J., Paton, R.J., Monaghan, R.M., 2004. Soil compaction and recovery cycle on a Southland dairy farm: implications for soil monitoring. Aust. J. Soil Res. 42, 851–856. https://doi.org/10.1071/SR03169.

Elsenbeer, H., Newton, B.E., Dunne, T., de Moraes, J.M., 1999. Soil hydraulic conductivities of latosols under pasture, forest and teak in rondonia. Brazil. Hydrol. Process. 13, 1417–1422. https://doi.org/10.1002/(SICI)1099-1085(19990630)13:9<1417::AID-HYP816>3.0.CO;2-6.

Friedman, S.K., Zube, E.H., 1992. Assessing landscape dynamics in a protected area. Environ. Manag. 16, 363–370. https://doi.org/10.1007/BF02400075.

Fu, Z., Hu, W., Beare, M.H., Müller, K., Wallace, D., Wai Chau, H., 2021. Contributions of soil organic carbon to soil water repellency persistence: characterization and modelling. Geoderma 401, 115312. https://doi.org/10.1016/j.geoderma.2021.115312.

Fultz, L.M., Moore-Kucera, J., Zobeck, T.M., Acosta-Martínez, V., Wester, D.B., Allen, V.G., 2013. Organic carbon dynamics and soil stability in five semiarid agroecosystems. Agric. Ecosyst. Environ. 181, 231–240. https://doi.org/10.1016/j.agee.2013.10.004.

Głąb, T., Kacorzyk, P., Zaleski, T., 2009. Effect of land management in mountainous regions on physical quality of sandy loam haplic cambisol soil. Geoderma 149, 298–304. https://doi.org/10.1016/j.geoderma.2008.12.007.

Gordon, J.E., Brazier, V., Thompson, D.B.A., Horsfield, D., 2001. Geo-ecology and the conservation management of sensitive upland landscapes in Scotland. Catena 42, 323–332. https://doi.org/10.1016/S0341-8162(00)00144-2.

Grieve, I.C., 2001. Human impacts on soil properties and their implications for the sensitivity of soil systems in Scotland. Catena 42, 361–374. https://doi.org/10.1016/S0341-8162(00)00147-8.

Guo, L.B., Gifford, R.M., 2002. Soil carbon stocks and land use change: a meta analysis. Glob. Chang. Biol. 8, 345–360. https://doi.org/10.1046/j.1354-1013.2002.00486.x.

Gupta, S., Lehmann, P., Bonetti, S., Papritz, A., Or, D., 2021. Global prediction of soil saturated hydraulic conductivity using random forest in a covariate-based GeoTransfer Function (CoGTF) framework. J. Adv. Model. Earth Syst. 13, e2020MS002242. https://doi.org/10.1029/2020MS002242.

Hassler, S.K., Zimmermann, B., van Breugel, M., Hall, J.S., Elsenbeer, H., 2011. Recovery of saturated hydraulic conductivity under secondary succession on former pasture in the humid tropics. For. Ecol. Manag. 261, 1634–1642. https://doi.org/10.1016/j.foreco.2010.06.031.

Haynes, R.J., Swift, R.S., 1990. Stability of soil aggregates in relation to organic constituents and soil water content. J. Soil Sci. 41, 73–83. https://doi.org/10.1111/j.1365-2389.1990.tb00046.x.

Hill, A.R., 1987. Ecosystem stability: some recent perspectives. Prog. Phys. Geogr. Earth Environ. 11, 315–333. https://doi.org/10.1177/030913338701100301.

Holling, C.S., 1973. Resilience and stability of ecological systems. Annu. Rev. Ecol. Syst. 4, 1–23. https://doi.org/10.1146/annurev.es.04.110173.000245.

Howard, P.J.A., Howard, D.M., 1990. Use of organic carbon and loss-on-ignition to estimate soil organic matter in different soil types and horizons. Biol Fertil Soils 9, 306–310. https://doi.org/10.1007/BF00634106 (1990).

Huggett, R.J., 1975. Soil landscape systems – model of soil genesis. Geoderma 13, 1–22. https://doi.org/10.1016/0016-7061(75)90035-X.

IUSS Working Group WRB, 2015. World reference base for soil resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O.B., Bouwer, L.M., Braun, A., Colette, A., Déqué, M., Georgievski, G., Georgopoulou, E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hempelmann, N., Jones, C., Keuler, K., Kovats, S., Kröner, N., Kotlarski, S., Kriegsmann, A., Martin, E., van Meijgaard, E., Moseley, C., Pfeifer, S., Preuschmann, S., Radermacher, C., Radtke, K., Rechid, D., Rounsevell, M., Samuelsson, P., Somot, S., Soussana, J.-F., Teichmann, C., Valentini, R., Vautard, R., Weber, B., Yiou, P., 2014. EURO-CORDEX: new high-resolution climate change projections for European impact research. Reg. Environ. Chang. 14, 563–578. https://doi.org/10.1007/s10113-013-0499-2.

Keizer, J.J., Coelho, C.O.A., Shakesby, R.A., Domingues, C.S.P., Malvar, M.C., Perez, I.M.B., Matias, M.J.S., Ferreira, A.J.D., 2005. The role of soil water repellency in overland flow generation in pine and eucalypt forest stands in coastal Portugal. Soil Res. 43, 337–349. https://doi.org/10.1071/SR04085.

Kemper, W.D., Rosenau, R.C., 1986. Aggregate Stability and Size Distribution. Methods Soil Anal. SSSA Book Series. https://doi.org/10.2136/sssabookser5.1.2ed.c17.

Kimble, J.M., Lal, R., Mausbach, M., 2001. Erosion effects on soil organic carbon pool in soils of Iowa. Sustaining the Global Farm. USDA-ARS Washington 472–475.

King, P.M., 1981. Comparison of methods for measuring severity of water repellence of sandy soils and assessment of some factors that affect its measurement. Soil Res. 19, 275–285. https://doi.org/10.1071/SR9810275.

Knox, J.C., 2001. Agricultural influence on landscape sensitivity in the upper Mississippi River valley. Catena 42, 193–224. https://doi.org/10.1016/S0341-8162(00)00138-7.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World map of the Köppen-Geiger climate classification updated. Meteorol. Zeitschrift 15, 259–263. https://doi.org/10.1127/0941-2948/2006/0130.

Le Bissonnais, Y., Arrouays, D., 1997. Aggregate stability and assessment of soil crustability and erodibility: II. Application to humic loamy soils with various organic carbon contents. Eur. J. Soil Sci. 48, 39–48. https://doi.org/10.1111/j.1365-2389.1997.tb00183.x.

Lemmnitz, C., Kuhnert, M., Bens, O., Güntner, A., Merz, B., Hüttl, R.F., 2008. Spatial and temporal variations of actual soil water repellency and their influence on surface runoff. Hydrol. Process. 22, 1976–1984. https://doi.org/10.1002/hyp.6782.

Liu, A., Ma, B.L., Bomke, A.A., 2005. Effects of cover crops on soil aggregate stability, Total organic carbon, and polysaccharides. Soil Sci. Soc. Am. J. 69, 2041–2048. https://doi.org/10.2136/sssaj2005.0032.

Lozano, E., Jiménez-Pinilla, P., Mataix-Solera, J., Arcenegui, V., Bárcenas, G.M., González-Pérez, J.A., García-Orenes, F., Torres, M.P., Mataix-Beneyto, J., 2013. Biological and chemical factors controlling the patchy distribution of soil water repellency among plant species in a Mediterranean semiarid forest. Geoderma 207–208, 212–220. https://doi.org/10.1016/j.geoderma.2013.05.021.

MeteoSwiss, 2020. Norm value charts in the period 1991 to 2020. https://www.meteoswiss.admin.ch/home/ climate/swiss-climate-in-detail/climate-normals/norm-value-charts.html. (Accessed 4 June 2022).

Miyata, S., Kosugi, K., Gomi, T., Onda, Y., Mizuyama, T., 2007. Surface runoff as affected by soil water repellency in a japanese cypress forest. Hydrol. Process. 21, 2365–2376. https://doi.org/10.1002/hyp.6749.

Morris, L.A., Lowery, R.F., 1988. Influence of site preparation on soil conditions affecting stand establishment and tree growth. South. J. Appl. For. 12, 170–178. https://doi.org/10.1093/sjaf/12.3.170.

Murthy, V.N.S., 2002. Geotechnical engineering: principles and practices of soil mechanics and foundation engineering. CRC Press.

Muster, S., Elsenbeer, H., Conedera, M., 2007. Small-scale effects of historical land use and topography on post-cultural tree species composition in an alpine valley in southern Switzerland. Landsc. Ecol. 22, 1187–1199. https://doi.org/10.1007/s10980-007-9099-1.

Nciizah, A.D., Wakindiki, I.I.C., 2015. Physical indicators of soil erosion, aggregate stability and erodibility. Arch. Agron. Soil Sci. 61, 827–842. https://doi.org/10.1080/03650340.2014.956660.

Oades, J.M., 1984. Soil organic matter and structural stability: mechanisms and implications for management. Plant Soil 76, 319–337. https://doi.org/10.1007/BF02205590.

Oehmichen, J., 2000. Pflanzenernährung und Düngung. In: Entrup, N.L., Oehmichen, J. (Eds.), Lehrbuch Des Pflanzenbaues. Band 1: Grundlagen. Verlag Th. Mann, Gelsenkirchen, pp. 21–56.

Paulino, V.T., Neto, M.S., Teixeira, E., Duarte, K.M.R., Franzluebbers, A.J., 2014. Carbon and nitrogen stocks of a typic acrudox under different land use systems in São Paulo state of Brazil. J. Plant Sci. 2, 192–200. https://doi.org/10.11648/j.jps.20140205.17.

Pekrun, C., Claupein, W., 1998. Forschung zur reduzierten bodenbearbeitung in mitteleuropa: eine literaturübersicht. Pflanzenbauwissenschaften 2, 160–175.

Pfeifer, H.R., Kobe, H., Forster, R., Knup, P., Bächlin, R., Marchon, T., Pozzorini, D., Sartori, I., Schmid, S.M., Walter, P., Steck, A., Tièche, J.C., 2018. Foglio 1312 Locarno. Atlante geol. Svizzera 1: 25 000, Carta 159. Note esplicative. Ufficio federale di topografia Swisstopo.

Pohl, M., Alig, D., Körner, C., Rixen, C., 2009. Higher plant diversity enhances soil stability in disturbed alpine ecosystems. Plant Soil 324, 91–102. https://doi.org/10.1007/s11104-009-9906-3.

Polyakov, V., Lal, R., 2004. Modeling soil organic matter dynamics as affected by soil water erosion. Environ. Int. 30 (4), 547–556. https://doi.org/10.1016/j.envint.2003.10.011.

Team R Core, 2021. R: A Language and Environment for Statistical Computing. R foundation for statystical computing.

Reeves, D.W., 1997. The role of soil organic matter in maintaining soil quality in continuous cropping systems. Soil Tillage Res. 43, 131–167. https://doi.org/10.1016/S0167-1987(97)00038-X.

Rehfuess, K.E., 1990. Waldböden. Entwicklung, Eigenschaften und Nutzung. Schriftenreihe “Pareys Studientexte”. 29. Verlag Paul Parey., Hamburg and Berlin.

Rowell, D.L., 1997. Bodenkunde: Untersuchungsmethoden und ihre anwendungen. Springer-Verlag, Berlin Heidelberg.

Roy, J.L., McGill, W.B., 2002. Assessing soil water repellency using the molarity of ethanol droplet (Med) test. Soil Sci. 167. https://doi.org/10.1097/00010694-200202000-00001.

Scheffer, F., Schachtschabel, P., Thiele-Brune, S., 2010. Lehrbuch der bodenkunde. Spektrum Akademischer Verlag, Heidelberg.

Shapiro, S.S., Wilk, M.B., 1965. An analysis of variance test for normality (complete samples). Biometrika 52, 591–611. https://doi.org/10.1093/biomet/52.3-4.591.

Smith, R., Tongway, D., Tighe, M., Reid, N., 2015. When does organic carbon induce aggregate stability in vertosols? Agric. Ecosyst. Environ. 201, 92–100. https://doi.org/10.1016/j.agee.2014.12.002.

Stewart, A., Coble, A., Contosta, A.R., Orefice, J.N., Smith, R.G., Asbjornsen, H., 2020. Forest conversion to silvopasture and open pasture: effects on soil hydraulic properties. Agrofor. Syst. 94, 869–879. https://doi.org/10.1007/s10457-019-00454-9.

Tabatabai, M.A., 1996. Soil organic matter testing: an overview. In: Magdoff, F.R., Tabatabai, M.A., Hanlon Jr., E.A. (Eds.), Soil Organic Matter: Analysis and Interpretation. vol. 46. Soil Science Society of America, pp. 1–9.

Tamene, L., Adimassu, Z., Aynekulu, E., Yaekob, T., 2017. Estimating landscape susceptibility to soil erosion using a GIS-based approach in northern ethiopia. Int. Soil Water Conserv. Res. 5, 221–230. https://doi.org/10.1016/j.iswcr.2017.05.002.

Tebrügge, F., Düring, R.-A., 1999. Reducing tillage intensity — a review of results from a long-term study in Germany. Soil Tillage Res. 53, 15–28. https://doi.org/10.1016/S0167-1987(99)00073-2.

Thomas, M.F., 2001. Landscape sensitivity in time and space — an introduction. Catena 42, 83–98. https://doi.org/10.1016/S0341-8162(00)00133-8.

Toohey, R.C., Boll, J., Brooks, E.S., Jones, J.R., 2018. Effects of land use on soil properties and hydrological processes at the point, plot, and catchment scale in volcanic soils near Turrialba, Costa Rica. Geoderma 315, 138–148. https://doi.org/10.1016/j.geoderma.2017.11.044.

Twongyirwe, R., Sheil, D., Majaliwa, J.G.M., Ebanyat, P., Tenywa, M.M., van Heist, M., Kumar, L., 2013. Variability of soil organic carbon stocks under different land uses: a study in an afro-montane landscape in southwestern Uganda. Geoderma 193–194, 282–289. https://doi.org/10.1016/j.geoderma.2012.09.005.

Usher, M.B., 2001. Landscape sensitivity: from theory to practice. Catena 42, 375–383. https://doi.org/10.1016/S0341-8162(00)00148-X.

Vogel, S., 2005. Der einfluss der terrassierung auf die pedogenese am beispiel eines südalpinen Tales. University of Potsdam [Diploma Thesis] Potsdam.

Vogel, S., Conedera, M., 2020. Effects of land use-induced vegetation and topography changes on soil chemistry in the southern Alps (Ticino, Switzerland). Plant Soil Environ. 66, 73–80. https://doi.org/10.17221/633/2019-PSE.

Vojteková, J., Vojtek, M., 2019. GIS-based landscape stability analysis: a comparison of overlay method and fuzzy model for the case study in Slovakia. Prof. Geogr. 71, 631–644. https://doi.org/10.1080/00330124.2019.1611454.

Waehli, G.M., 1967. Centovalli und Pedemonte. Beitrag zur Landeskunde eines Tessiner Tales. Inaugural-Dissertation, Juris Druck und Verlag Zürich., in: Inaugural-Dissertation, Juris Druck Und Verlag Zürich.

Walker, B., Gunderson, L., Kinzig, A., Folke, C., Carpenter, S., Schultz, L., 2006. A handful of heuristics and some propositions for understanding resilience in social-ecological systems. Ecol. Soc. 11. https://doi.org/10.5751/ES-01530-110113.

Wauchope, R.D., Sumner, H.R., Truman, C.C., Johnson, A.W., Dowler, C.C., Hook, J.E., Gascho, G.J., Davis, J.G., Chandler, L.D., 1999. Runoff from a cornfield as affected by tillage and corn canopy: a large-scale simulated-rainfall hydrologic data set for model testing. Water Resour. Res. 35, 2881–2885. https://doi.org/10.1029/1999WR900186.

Werritty, A., Brazier, V., 1994. Geomorphic sensitivity and the conservation of fluvial geomorphology SSSIs. In: Stevens, C., Gordon, J.E., Green, C.P., Macklin, M. (Eds.), Conserving Our Landscape: Evolving Landforms and Ice-Age Heritage. Proceedings of the Conference on Conserving Our Landscape: Evolving Landforms and Ice-Age Heritage, Crewe 1992, pp. 100–106.

Werritty, A., Brazier, V., Gordon, J.E., McManus, J., 1994. The freshwater resources of Scotland: A geomorphological perspective. In: Maitland, P.S., Boon, P.J., McKlusky, D.S. (Eds.), The Freshwaters of Scotland: A National Resource of International Significance. WILEY, Chirchester.

Werritty, A., Leys, K.F., 2001. The sensitivity of scottish rivers and upland valley floors to recent environmental change. Catena 42, 251–273. https://doi.org/10.1016/S0341-8162(00)00140-5.

Zangar, C.N., 1953. Theory and problems of water percolation. Techincal Information Office, Denver.

Zehe, E., Elsenbeer, H., Lindenmaier, F., Schulz, K., Blöschl, G., 2007. Patterns of predictability in hydrological threshold systems. Water Resour. Res. 43. https://doi.org/10.1029/2006WR005589.

Zhang, H., Hartge, K.H., 1992. Zur auswirkung organischer substanz verschiedener humifizierungsgrade auf die Aggregatstabilität durch reduzierung der benetzbarkeit. Z. Pflanzenernähr. Bodenkd. 155, 143–149. https://doi.org/10.1002/jpln.19921550212.

Ziegler, A.D., Giambelluca, T.W., Tran, L.T., Vana, T.T., Nullet, M.A., Fox, J., Vien, T.D., Pinthong, J., Maxwell, J.F., Evett, S., 2004. Hydrological consequences of landscape fragmentation in mountainous northern Vietnam: evidence of accelerated overland flow generation. J. Hydrol. 287, 124–146. https://doi.org/10.1016/j.jhydrol.2003.09.027.

Zimmermann, B., Elsenbeer, H., 2008. Spatial and temporal variability of soil saturated hydraulic conductivity in gradients of disturbance. J. Hydrol. 361, 78–95. https://doi.org/10.1016/j.jhydrol.2008.07.027.

Zoller, H., 1960. Pollenanalytische untersuchungen zur vegetationsgeschichte der insubrischen schweiz. Denkschriften Der Schweizerischen Naturforschenden Gesellschaft, pp. 45–152.