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What makes a soil landscape robust? Assessment of landscape sensitivity in relation to land use changes in a southern Alpine valley (Ticino, Switzerland).

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Abstract

This PhD was carried out in the framework of a three years research project entitled “What makes a soil landscape robust? Landscape sensitivity to land use changes in a southern Alpine valley (Ticino, Switzerland)”, funded by the German Research Foundation. The aim of this work is to investigate the sensitivity towards land use changes of a southern alpine soil landscape located in the Onsernone Valley, Canton Ticino (Switzerland).

This work is organized in the following principal steps: i) assessment of the state of the art regarding the connotation and methods to study and quantify the soil and landscape stability/sensitivity, ii) a detailed characterization of the study area regarding topography, geology, geomorphology as well as land use change history, iii) a preliminary investigation to plan the sampling design and identify the sampling plots, iv) detailed sampling and measurements in the field and in the laboratory, and v) an assessment of the general sensitivity of the area.

The state of art was assessed through a bibliometric analysis based on Scopus and Web of Science peer-reviewed articles. The study shows that the term “landscape stability” is mainly related to quantitatively measurable properties indicating a certain degree of stability. In contrast, the term “landscape sensitivity” is often related to resilience; however, this definition has not substantially changed over time. Even though a large number of quantification methods related to soil and landscape stability and sensitivity were found, these methods are rather ad hoc and not diffused in a more general context.

Following a stratified random sampling design, the following soil key properties were analysed: (i) soil texture, (ii) bulk density, (iii) soil organic carbon, (iv) saturated hydraulic conductivity, (v) aggregate stability, (vi) soil water repellence. In a second step surface dynamics were assessed by measurements of: vii) surface runoff and viii) soil erosion.

The analysis of the effects of land use change on key soil properties were performed through a linear mixed model suitable for the nested structure of the data. While the effect of land use changes on surface dynamics was assessed through notched boxplots due to the low amount of available measurement. 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 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 changes was soil water repellence that is partly influenced by the amount of soil organic carbon and probably by the quality and composition of soil organic matter. Finally, the assessment of surface runoff using a rainfall simulator device indicates a statistically significant variability which seems to be affected particularly by soil water repellence. The latter in turn tend to reduce surface infiltration capacity and favour surface runoff and the generation of preferential flow paths which do not allow a homogeneous wetting of the soil layer. These results suggest a high sensitivity of surface runoff to land use changes that however do not correspond to a high variability in the sensitivity of soil erosion processes. Generally, thanks to the high aggregate stability soils are generally quite stable leading to very low values of sediment transport except for abandoned terrace, which seems to be the only land cover-topography units strongly sensitive and negatively affected by land use change. In conclusion this study emphasizes the importance of a correct land management and application of strategies aiming to limit soil erosion in an alpine environment.

Introduction

Understanding the sensitivity of a landscape to human disturbance is of fundamental importance in times of global change. As stated by the Organization for Economic Cooperation and Development (OECD, 2017) and in the Global Environmental Outlook (GEO-6, 2019), providing a decent life and well-being for nearly 10 billion people by 2050, without further compromising the ecological limits of our planet, is one of the most serious challenges and responsibilities humankind has ever faced ((United Nation, 2015); Organisation for Economic Co-operation and Development (OECD, 2017)). However, over the last few decades, anthropogenic activities, such as human-induced climate change, land use changes (e.g. deforestation, agriculture) and other human impacts on ecosystems, have transformed the Earth's natural systems, exceeding their capacity and disrupting their self-regulatory mechanisms, with often irreversible consequences for global humanity as specified by the Intergovernmental Panel on Climate Change (IPCC, 2014).

Future climate change will impact severely our systems. For Europe for example Jacob et al. (2014) projected the spatio-temporal precipitation pattern (Figure 1) showing a reduction in the precipitation amount of about 15% in southern Europe, but at the same time an increase of heavy rainfall events with the related socio-economic problems (Bruce et al., 1995; Märker et al., 2008; Pelacani et al., 2008; Rasoulzadeh et al., 2019).

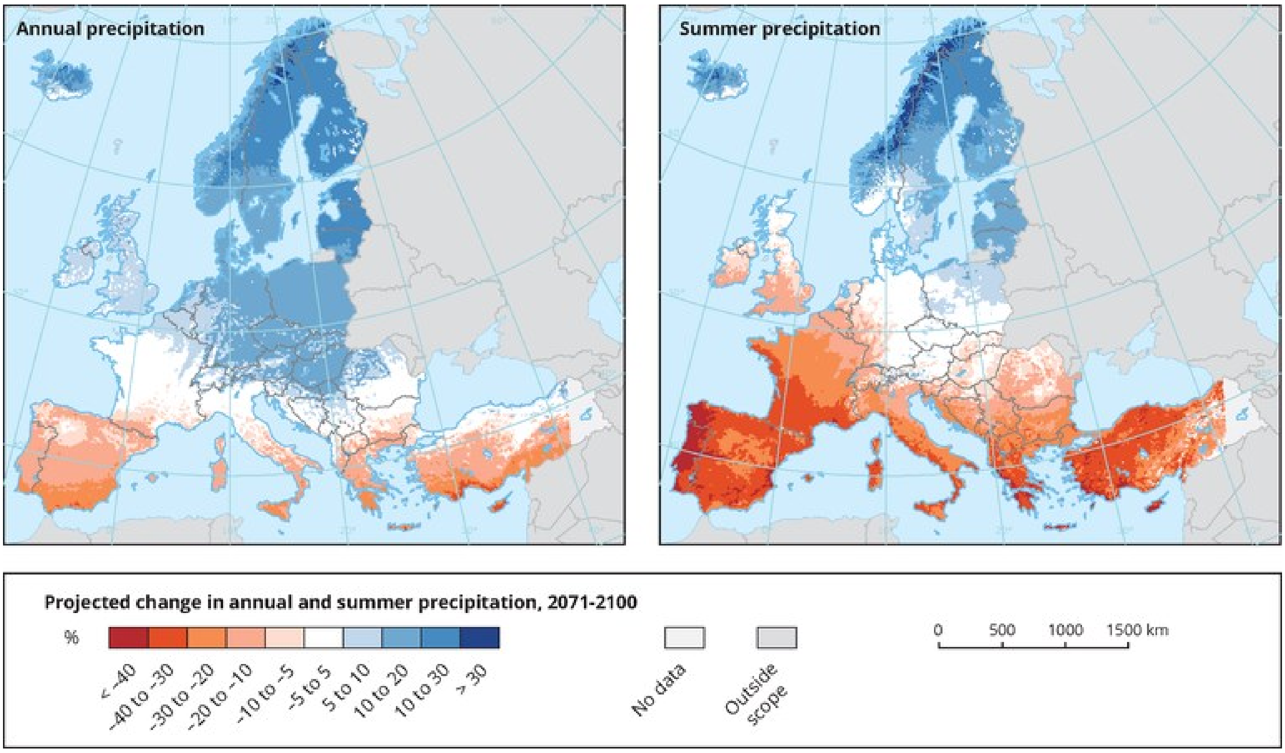


Figure 1. Projected changes in annual (left) and summer (right) precipitation (%) between 1971-2000 and 2071-2100 for the forcing scenario RCP 8.5. Figure taken from Jacob et al. (2014).

A part of climatic changes, also the modification of the landscape itself by human in terms of land use will impact severely our ecosystems. However, the assessment of land use changes in the past might help us to get information about the most sensitive areas in a landscape and may provide useful information towards sustainable management of our landscape in the future. For this reason, we concentrated on the assessment of soil landscape sensitivity in Alpine environments. In fact, Alpine soil landscapes can be considered as particularly sensitive to land use changes because of the combined effects of extreme climatic and topographic conditions as well as intense geomorphologic activity (Gordon et al., 2001). Following the definitions of the term ‘soil landscape’ or ‘soil landscape system’ by Huggett (1975), we consider a three-dimensional body of soil known as a soil landscape system or a “valley basin” that is: (1) bounded by the soil surface, valley watershed and weathering front at the base of the soil; (2) forming part of a more extensive valley basin network; and (3) functioning as an open system.

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). Landscape sensitivity is 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). 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).

Hence, in this thesis I focus on the assessment of soil landscape sensitivity in a southern alpine environment affected by human-induced perturbations in terms of land use changes. The study area is located in the Onsernone Valley, a southern alpine, east-west oriented valley in southern Switzerland, Canton Ticino. This area is suitable to analyse the effects of land use change due to an intense land use change history, which started already in Roman times but was intensified at least since the 13th century (Crivelli, 1943). Moreover, the valley is characterized by a very steep topography (the average steepness of both side of the valley is 36°), a severe climate with annual precipitation of more than 2000 mm per year which can reach 400 mm in a single event (MeteoSwiss, 2020), and finally a constant lithology that are gneiss rich in plagioclase, quartz, biotite, muscovite (Blaser, 1973) and quaternary deposits (Pfeifer et al., 2018). The particular and intense land use change history resulted in the current presence of six different land cover-topography units, which were selected for the analysis (see chapter Material and Methods, Figure 3).

In the last decades numerous studies have been published with the objective to quantify stability and sensitivity of soils and landscapes (e.g. Bayramin et al., 2008; Friedman and Zube, 1992; Tamene et al., 2017; Vojteková and Vojtek, 2019). Nonetheless, an integrated method for investigating and assessing soil landscape sensitivity in Alpine environments is still lacking.

To detect the different connotation and the approach used to describe and quantify soil and landscape stability/sensitivity, a detailed bibliometric analysis was conducted that incorporated different disciplines, such as general environmental sciences, geology, geomorphology, soil science, and ecology, as well as agronomy and other related environmental sectors that deal with the aforementioned terminology on landscape scales. The main objective of this analysis is to contribute and promote a general understanding of the terminology used. Furthermore, all the different approaches that aim to quantify landscape statuses in terms of their sensitivity, stability were reviewed and discussed.

Generally, different soil parameters are reported in literature indicating a certain vulnerability to land use changes and hence, can be utilized as indicators or key properties regarding the sensitivity of a soil landscape. According to the literature, the following soil physical and chemical properties seem to be particularly suitable as key elements of a self-contained causal structure for investigating soil landscape sensitivity: i) Soil organic matter (SOM), ii) Aggregate stability, iii) Saturated hydraulic conductivity (K_{sat}), and related processes like iv) Surface infiltration as well as resulting surface runoff.

Due to the particular characteristics of the Onsernone valley (Zehe et al., 2007), we complemented them by (v) soil water repellence (SWR). In fact soil water repellence is strongly related to soil texture and SOC content and hence can have a large effect on surface runoff generation (Burch et al., 1989; Keizer et al., 2005). SWR is a crucial property controlling infiltration and subsequently surface runoff (Doerr et al., 2003; Lemmnitz et al., 2008; Miyata et al., 2007). As demonstrated by Wang et al. (2000) sandy soils with high SWR are difficult to wet causing very slow infiltration rates, and if wetted by long time rainfall, infiltration occurred mainly through preferential flow paths bypassing larger volumes of the soil.

Infiltration and surface runoff were assessed with a traditional approach to estimate the potential surface runoff characteristics using K_{sat} as a proxy of soil's infiltration capacity as suggested also by different authors (e.g. Miyata et al., 2007). Anyway, using only K_{sat} as proxy of infiltration capacity does not allow for a proper representation of the natural surface conditions and related infiltration processes. In fact, K_{sat} values are measured at certain soil depth. Moreover, K_{sat} measurements are carried out under saturated hydraulic conditions that do not represent the real moisture conditions of the soil. Furthermore, using only K_{sat} as a proxy of soil infiltration capacity does not take into account all other factors that affect surface runoff generation such as the vegetation cover, rainfall characteristics, topography and land management (Buda, 2013; Debolini et al., 2015; Dunne, 1978).

Due to the above mentioned limitation and as already indicated by several authors (e.g. Bayramin et al., 2008; Chen et al., 2019; Diyabalanage et al., 2017; Evans, 1993; Gessesse et al., 2015; Knox, 2001; Kosmas et al., 1997; Simpson et al., 2001; Zhang et al., 2017; Zheng et al., 2019) surface runoff and soil erosion yield valuable information on soil landscape sensitivities that are induced by land use changes.

Aims and objectives of the thesis

The aims and objective of the thesis is to answer the following research questions:

1) When is a landscape sensitive or resilient to climatic and/or socio-economic changes, and how can stability or sensitivity be defined?

   A response to this question is quite complex, since landscapes are assessed from different points of view and different disciplines are involved. Thus, the first aim of the thesis is to: i) screen and identify current knowledge about sensitivity and stability on a landscape scale, (ii) delineate different connotations used in various scientific sectors and determine the most frequently used ones, (iii) identify the articles and fields of research that have had the greatest impact on the topic, (iv) identify the most widely used methods and/or parameters to qualitatively assess or quantify sensitivity and stability on a landscape scale, (v) monitor the changes in the terminology over time, and (vi) identify the different landscape contexts studied. To answer to the above-mentioned questions a bibliometric analysis was done with the aim to systematically collect the available literature in order to deepen our understanding of scientific research in this field and its developments, the results are reported and summarized in Paper 1.

2) Which are the most representative properties to quantify landscape sensitivity in alpine environment affected by land use change?

   We focused on the soil resources since 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 soil’s characteristics. As mentioned in the introduction different chemical and physical soil properties were assessed and the methodology applied are reported in Paper 2 and Paper 3.

3) Is the alpine soil landscape of the Onsernone valley sensitive to land use change? If yes which are the most sensitive land cover-topography units?

   Answering this question requires to identify the differences in the key soil properties from the original conditions of the study area, which are represented by the reference state that is the forested slope in natural condition. To determine whether the study area or a single land cover unit are sensitive to land use change, it is necessary to determine what impact these changes (if any) have on the soil landscape. I summarize the results obtained in the field to answer the research question in papers 2 and 3.

4) Which strategies can be adopted to mitigate or limit the sensitivity of the different land cover-topography units?

   As demonstrated in literature, land use change is one of the main driving factors in the acceleration of soil erosion. The soil is a sustainable resource of fundamental importance, which is affected by soil erosion leading to a reduction of arable land and crop production with the respective socio-economic problems.

   Therefore, preserving this resource is essential e.g. through mitigation strategies that minimize the impact of soil erosion. I tackle this research question in the discussion and outlook.

Material and methods

Study area

The study area is situated in Onsernone Valley, a Swiss alpine valley located in Canton Ticino (Figure 2A). The valley is deeply incised with steep slopes and shows a pronounced East-West orientation (Figure 2B). It 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. The area covers approximately 6 km^2, the altitude ranges from 400 to 1000 m a.s.l. and is characterized by an oceanic (Cfb) climate following the Köppen climate classification (Kottek et al., 2006). Dry winters are followed by rainy springs and autumns with a mean annual precipitation of roughly 2000 mm and a mean annual temperature of about 12° (MeteoSwiss, 2020).

Geologically, 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. Moreover, the Quaternary evolution of the valley was significantly influenced by fluvial, glacial and gravitational processes. The valley presents a typical V-shaped profile indicating fluvial processes as dominant during morphogenesis. However, some evidence of glacial phases can be observed in the field. Other geomorphological evidences are related to the slope evolution showing deposits associated to debris flows as well as rockfalls.

The valley was characterized by an intense land use change history with the first settlements during Roman times (Crivelli, 1943) and an intensification of land use during the Middle Ages initially involving the deforestation of the south-facing slopes. Subsequently, arable land was created by terracing the rather gentle sloping areas that are related to relicts of former valley floors (Canale, 1958; Waehli, 1967). 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. This led to a progressive reforestation accompanied by a partial collapse of the abandoned terraces. Likewise, animal husbandry on the north-facing slopes ceased and resulted in secondary reforestation of former pastures. The abandoned pastures where reforestation has not yet taken place are characterized by meadows that are mowed once or twice a year.

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 (Figure 2C) 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 soil organic matter (SOM), which tend to macroscopically mask the eluvial horizon. Hence these soils have also been classified as Cryptopozsols (Blaser, 1973; Blaser et al., 1999, 1997; Blaser and Klemmedson, 1987). 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).

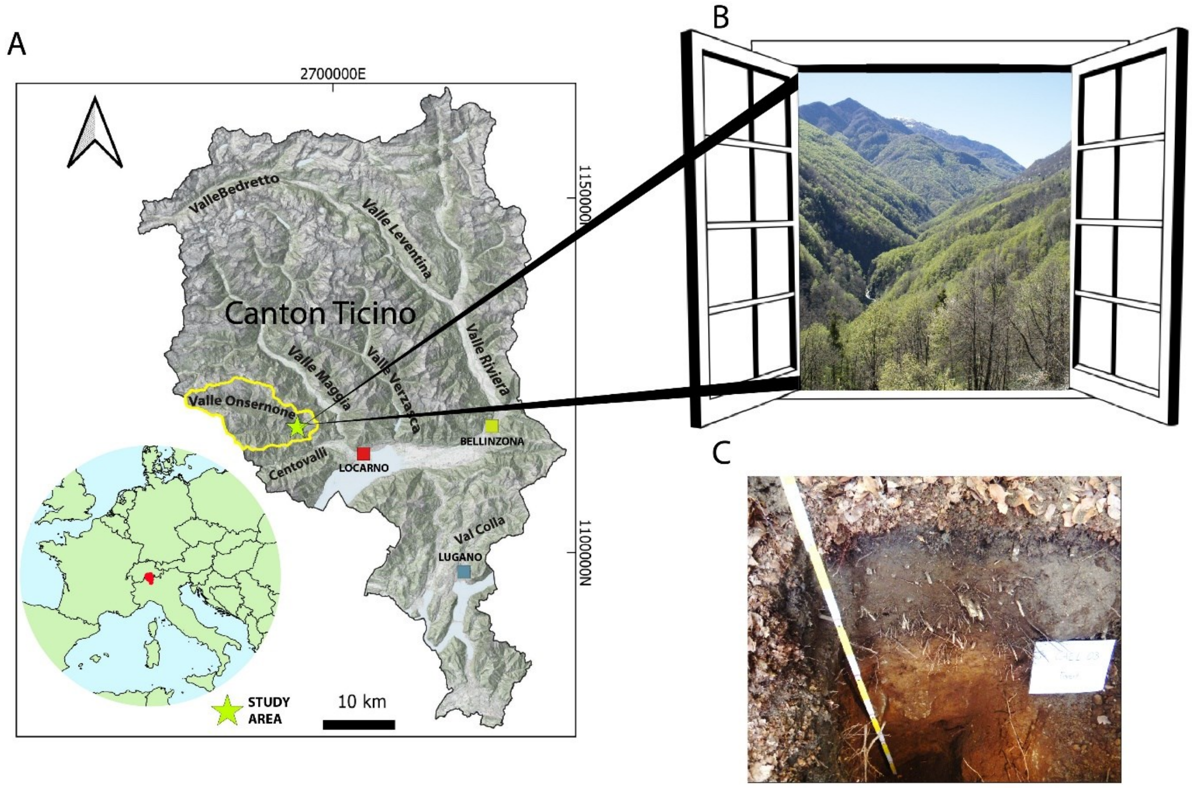


Figure 2. (A) Map of Canton Ticino with the location of the study area (Federal Office of Topography, swisstopo), (B) Images of the Onsernone valley, (C) podzol detected in the Onsernone valley.

Methodology

Research question 1 is the focus of Paper 1 and is based on a systematic literature collection carried out in 2021. The search was based on the bibliographic databases Scopus and Web of Science in order to identify all peer-reviewed publications in English language from the relevant fields of earth science and other related environmental sectors that deal with the terms sensitivity and stability on landscape scale.

All articles identified were screened following a two-stage process. In the first stage, only article titles and abstracts were screened. Any publication identified as not relevant for the purposes of this analysis was excluded from the second stage, where the entire publication was read. Finally, all articles that passed the second stage of screening, according to certain eligibility criteria, were included in the subsequent analysis.

Consequently, two different analyses were carried out:

- A bibliometric analysis was carried out through the bibliometric package (Aria and Cuccurullo, 2017) in the R environment (version 4.0.2, R Core Team, 2021). This analysis allows to identify the most relevant authors, the papers with the greatest impact, scientific productivity, networks and other main indicators of a bibliometric analysis.
- Connotation and quantification methods of stability and sensitivity were collected in different tables chronologically ordered to observe the evolution over time.

To answer research question 2 and 3, different methodological steps are required.

At first, six land cover-topography units that are the result of the particular land use and land cover dynamics in the study area were identified, distinguishing between south- and north-facing slopes (LCTU; Figure 3):

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).

Based on these LCTUs, all analysis with the exception of rainfall simulation were performed in the 18 plots collecting 3 replicates for each LCTU.

For each plot, a grid of 25 cells of 20x20 meters was established. Subsequently, with a simple random sampling algorithm, 15 raster cells were chosen as sampling sites. Due to logistic and accessibility reasons, we changed the above-mentioned scheme for the rainfall simulator experiments. We selected for each of the six LCTUs one single plot in which four replicates were carried out. Every plot is characterized by an extension of 6 x 4 meters, in which at the four extremes of the rectangle the 4 replicates for the rainfall simulation experiments characterized by an extension 1.2 x 1.2 meters were selected.

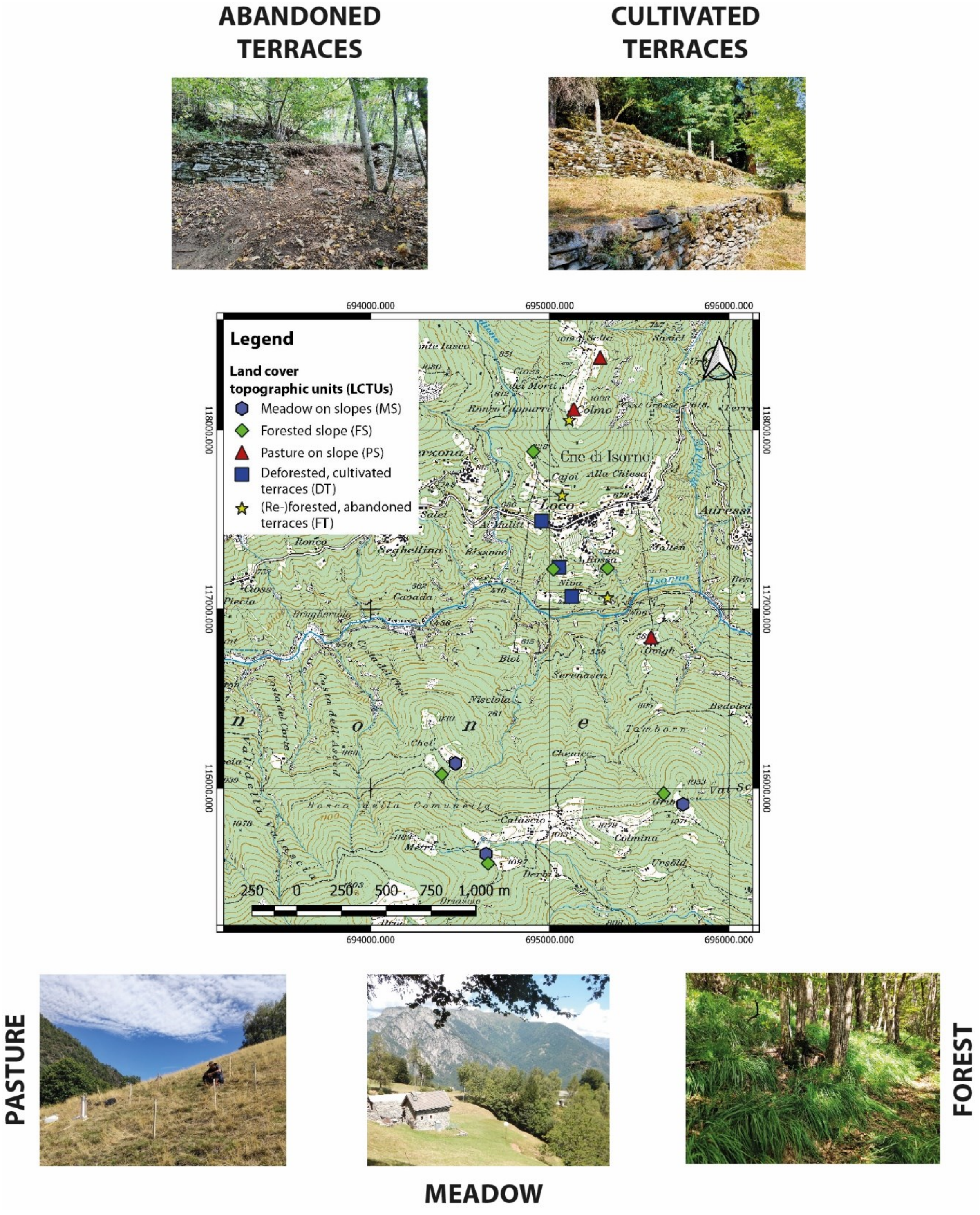


Figure 3. Spatial distribution of LCTU-locations based on Swiss map raster 10 (© swisstopo, reference system CH1903 / LV03 EPSG: 21781). Single images for each of the LCTUs.

The following soil properties were analysed in the field:

(i) Saturated hydraulic conductivity (K_{sat}) was measured in the field using a constant head permeameter (Amoozegar, 1989a) in two different depths of 16 and 23 cm. 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. K_{sat} was calculated in cm/h using the glover solution proposed by Zangar (1953) and adopted by (Amoozegar, 1989b).

(ii) Surface runoff and soil erosion were analysed using a portable automated rainfall simulator device (RSD) (Ritschard, 2000). The sprinkling experiments were carried out for 30 min and hence, long enough to obtain constant runoff values. On forested slopes additionally simulations were done with and without the litter layer. We analysed these two different conditions to verify the effect of the litter layer on runoff generation and sediment transport. Sprinkling experiments were carried out in dry and most hydrophobic soil conditions as well as in wet starting conditions at the same position. Initial and final soil moisture was measured using a time domain reflectometry (TDR) device. An artificial rainfall with an intensity of 50 mm/h was applied, corresponding to a return period of 5 years. The single measurement plot had a size of 1 m^2. Surface runoff was measured every minute and reported in mm per hour. Furthermore, soil loss through soil erosion was quantified by sampling one minute of runoff every 5 min during the runoff period to establish the eroded and transported soil material. A total number of 64 rainfall simulations were carried out.

(iii) To obtain detailed information on the specific soil type of the plot, a profile was dug for each of the 18 plots.

In addition, various laboratory analyses were carried out on the samples collected during the campaign such as:

(i) 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).

(ii) 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).

(iii) Soil organic carbon was analysed 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).

(iv) Potential SWR was assessed in the laboratory on 180 samples 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 and analysed from each sampling cell, at the same position where the samples for aggregate stability were taken.

(v) The bulk density of the upper soil was analysed on undisturbed samples collected by using a ring cylinder of 100 cm^3 following the methodology described in Blake (1965).

The effects of land use changes on the measured soil properties of the six LCTUs were assessed through random intercept linear mixed models (LMM). Pairwise comparisons between the LCTUs were conducted for each key soil property for the fixed effect of land use as predicted by the LMM. To identify linear correlations of the physical and chemical properties among LCTUs, a Spearman correlation matrix was created reporting the coefficients and the p-values for the correlation tests.

Due to the low amount of measurement plots of rainfall simulation, the difference between LCTUs is reported in form of notched box plots. Notched boxplot surrounding the median are useful since the length of notches are indicating the 95% confidence interval providing a measure of the statistical significance of the difference between two medians (Mcgill et al., 1978).

A more detailed description of the methodology is given in the respective articles.

Chapter 1: Bibliometric analysis (PAPER 1)

Bettoni Manuele, Michael Maerker, Alberto Bosino, Calogero Schillaci, Sebastian Vogel
(2022)
Bibliometric Analysis of Soil and Landscape Stability, Sensitivity and Resistivity.
Land. 11, 1328.

Abstract

In times of global change, it is of fundamental importance to understand the sensitivity, stability and resistivity of a landscape or ecosystem to human disturbance. Landscapes and eco-systems have internal thresholds, giving them the ability to resist such disturbance. When these thresholds are quantified, the development of countermeasures can help prevent irreversible changes and support adaptations to the negative effects of global change. The main objective of this analysis is to address the lack of recent studies defining terms like sensitivity, resistivity and stability in reference to landscapes and ecosystems through a Bibliometric analysis based on Scopus and Web of Science peer-reviewed articles. The present research also aims to quantify landscape statuses in terms of their sensitivity, stability and resistivity. The term “landscape stability” is mainly related to quantitatively measurable properties indicating a certain degree of stability. In contrast, the term “landscape sensitivity” is often related to resilience; however, this definition has not substantially changed over time. Even though a large number of quantification methods related to soil and landscape stability and sensitivity were found, these methods are rather ad hoc. This study stresses the importance of interdisciplinary studies and work groups.

1. Introduction

As stated by the Organization for Economic Cooperation and Development (OECD, 2017) and in the Global Environmental Outlook (GEO-6, 2019), providing a decent life and wellbeing for nearly 10 billion people by 2050, without further compromising the ecological limits of our planet, is one of the most serious challenges and responsibilities humankind has ever faced (United Nation, 2015); Organisation for Economic Co-operation and

Development (OECD, 2017). Over the last few decades, anthropogenic activities have caused several changes, including climate change and land use changes (e.g., deforestation, agriculture). Human activities have also had other impacts on ecosystems, transforming the Earth’s natural system, exceeding its resource capacity and disrupting its self-regulatory mechanisms, often with irreversible consequences for the global population, as noted by the Intergovernmental Panel on Climate Change (IPCC, 2014). Human interventions have reached a point where the ecological foundations of natural systems that support other species and provide invaluable ecosystem services are in great danger (Millenium Ecosystem Assesment, 2005).

To tackle the problems listed above, it is imperative to understand the sensitivity, stability and resistance of both landscapes and ecosystems to human disturbance. Ecosystems are highly complex (May, 1973; Stuart Chapin et al., 2012), as they cover different spatio-temporal scales, from microbial to continental, or from short life cycles to geologic timescales. Consequently, to correctly compare ecosystems, spatio-temporal scales must be defined. In light of global, regional and local policies to fight, prevent or cope with the negative effects of global change, it is often easier to make use of the landscape scale. To have an objective criterion for the comparison of ecosystems, choosing a specific scale becomes crucial, e.g., to apply specific measures to cope with the negative effects of specific an-thropogenic interferences, such as climate and land use changes or to appropriately distribute subsidies for agriculture. The ecological status of a landscape needs to be characterized in order to answer questions like the following:

- Is a landscape sensitive or resilient to climatic and/or socio-economic changes, and how can stability, sensitivity or resistivity be quantified?
- At what degree of sensitivity can a landscape be considered stable or unstable?
- At what land use intensity are threshold conditions reached, i.e., where a land-scape switches from stable to unstable conditions?

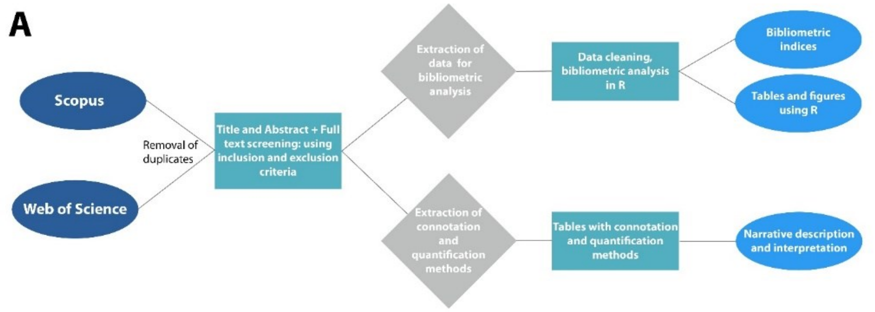
The answers to these questions are quite complex, since landscapes are assessed from different points of view, and different disciplines are involved. Even though many studies have been published in recent decades investigating the effects of global change on landscape sensitivity and stability (McGlade et al., 2008; Thomas, 2004; Lamoureux and Lafreniere, 2015; Smith et al., 2016), a systematic review of the connotation of the terms is still missing. The main objective of this analysis is to contribute and promote a general understanding of the terminology used. Different approaches are reviewed that aim to quantify landscape statuses in terms of their sensitivity, stability and resistivity. A detailed bibliometric analysis was conducted that incorporated different disciplines, such as general environmental sciences, geology, geomorphology, soil science, and ecology, as well as agronomy and other related environmental sectors that deal with the aforementioned terminology on landscape scales. Bibliometric analyses are becoming increasingly popular in the geosciences and environmental academic fields (Bezak et al., 2021); they evaluate the distribution models of publications using mathematical and statistical techniques (Pritchard, 1969), making it possible to perform comprehensive science mapping analyses. Their general purpose is to systematically collect the available literature in order to deepen our understanding of scientific research and its developments (e.g., trends in specific topics, number of papers, journals, authors, countries and research consortia). As highlighted in recent syntheses on, for example, landslides (Bu et al., 2015) and erosion modelling (Bezak et al., 2021), bibliometric analyses are revealing increasing cooperation in research networking (Wagner et al., 2015) and are providing a deeper understanding of research topics (Tang et al., 2020). The methods and parameters adopted by various authors to quantify the sensitivity, stability and resistivity of landscapes will be identified.

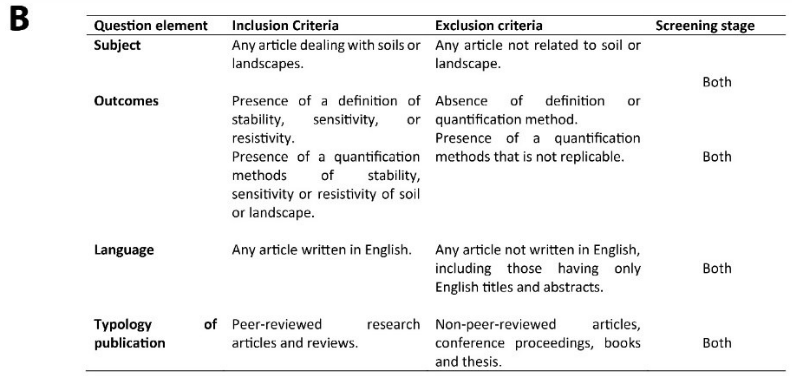
The goal of our applied process is to: (i) screen and identify current knowledge about sensitivity, stability and resistivity on a landscape scale, (ii) delineate different connotations used in various scientific sectors and determine the most frequently used ones, (iii) identify the articles and fields of research that have had the greatest impact on the topic, (iv) identify the most widely used methods and/or parameters to qualitatively assess or quantify sensitivity, stability and resistivity on a landscape scale, (v) monitor the changes in the terminology over time, and (vi) identify the different landscape contexts studied.

2. Materials and Methods

This study is based on a systematic literature collection that was carried out in March 2021 and updated at the end of December 2021. It aims to identify all peer-reviewed publications from several earth science fields such as soil science, geo-morphology, geology, agricultural sciences, ecology and other related environmental sectors that deal with the terms sensitivity, stability and resilience on a landscape scale.

The search was without timespan restriction and, hence, comprised publications from 1958 to the present day (December 2021). The workflow is illustrated in Figure 1A.





Question element	Inclusion Criteria	Exclusion criteria	Screening stage
Subject	Any article dealing with soils or landscapes.	Any article not related to soil or landscape.	Both
Outcomes	Presence of a definition of stability, sensitivity, or resistivity. Presence of a quantification methods of stability, sensitivity or resistivity of soil or landscape.	Absence of definition or quantification method. Presence of a quantification methods that is not replicable.	Both
Language	Any article written in English.	Any article not written in English, including those having only English titles and abstracts.	Both
Typology of publication	Peer-reviewed research articles and reviews.	Non-peer-reviewed articles, conference proceedings, books and thesis.	Both

Figure 1. (A) General Workflow. (B) Inclusion and exclusion criteria used during the screening process.

2.1. Data Sources

The research was carried out on the two most widely used bibliographic online databases: (i) “Scopus” (Elsevier), and (ii) “Web of Science Core Collection” on the Web of Science

(WoS) platform (Clarivate). The latter also covers SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI and CCREXPANDED. While Web of Science covers a period from 1945 to the present and Scopus starts only from 1970, the latter has a larger number of journals in its database (Chadegani et al., 2013). Both databases include English publications as well as papers in other languages, but only if an English abstract is present. Scopus and Web of Science are equipped with a citation analysis system, but generally, the numbers of citations are higher in Scopus (Levine-Clark and Gil, 2008). Both searches were conducted covering the entire time spans of the two databases. This procedure allowed us to cover most publications available to the scientific community and, notably, to identify the most relevant ones. Other databases, such as Google scholar, were purposely excluded due to their lack of proper meta data. Finally, another intention was to consider only articles that had been published in renowned peer-reviewed journals, and thus, to follow the quality standards of good scientific practice. Grey literature (books, unpublished masters and doctoral theses) were deliberately excluded, as they cannot be considered as generally accepted by the scientific community.

2.2. Search for Articles

The search was performed only for scientific articles written in English. This ensured that the publications had significant relevance to the international scientific community and have been globally disseminated and recognized. To carry out the search, the Boolean operator OR was used, allowing us to combine several terms within a single search string.

Since the keyword terms were made up of several words, quotation marks were used to combine multiple words within the same term to specifically identify publications in which these terms were used completely and written in the correct order.

For this study, the following keywords in association with the Boolean operator term “OR” were identified: “Landscape Stability” OR “Landscape Sensitivity” OR “Landscape Resistivity” OR “Geomorphological Stability” OR “Geomorphological Sensitivity” OR

“Geomorphological Resistivity” OR “Geomorphic Stability” OR “Geomorphic Sensitivity” OR “Geomorphic Resistivity” OR “Soil Stability” OR “Soil Sensitivity” OR “Soil Resistivity”.

Since the two bibliographic databases do not allow users to enter the same search parameters in terms of the categories, we defined categories separately for each database. In Scopus, the search was limited to article titles, abstracts and keywords, and was subsequently refined to the scientific sectors of “Earth and Planetary Sciences”, “Environmental Sciences” and “Agricultural and Biological Sciences”. Finally, articles were filtered by including only those belonging to journals pertaining to the research fields of the review.

In contrast to Scopus, in Web of Science, the search was done using field tags “TS”, which limit the search by topic. Additionally, in this case, we refined the search to the most relevant categories, i.e., “Geosciences multidisciplinary”, “Environmental sciences”, “Soil science”, “Geography physical”, ”Agricultural engineering”, “Ecology”, “Water resources”, “Plant sciences”, “Agriculture dairy animal science”, “Engineering geological”, ”Agricultural economics policy”, “Agronomy”, ”Multidisciplinary sciences”, “Engineering environmental”, “Forestry”, “Geology”, “Biodiversity conservation”, “Agriculture multidisciplinary”, “Environmental studies”, “Geography”, “Remote sensing” and “Biology”.

For both searches, only research articles and reviews were included, thereby excluding all other types of publications, such as conference proceedings, books, abstracts, etc. The results of the two searches were imported to the Mendeley library free reference manager. First, the software automatically removes duplicates. After that, all articles are exported in table format, allowing us to proceed to the screening process.

2.3. Article Screening and Study Eligibility Criteria

For the screening process, relevant information, such as authors’ names, journal name, title, DOI, year of publication and type of article, were added to a spreadsheet.

All articles identified in the search procedure and entered into the table were screened following a two-stage process (Figure 1B). In the first stage, only article titles and abstracts were screened. Any publication identified as not relevant for the purposes of this analysis was excluded from the second stage, where the entire publication was read. Finally, all articles that passed the second stage of screening, according to the eligibility criteria, were subsequently subject to bibliometric analysis.

A first selection was conducted in which titles and abstracts were read in order to exclude all articles related to a scientific sector other than those defined above.

The exclusion criteria used during the screening process were as follows:

1. absence of a definition of the search terms (stability, sensitivity, resistivity), or
2. absence of quantification methods of the search terms, and
3. articles belonging to a different field of research,
4. articles where only the title and abstract are reported in English, but the rest of the text is in another language. Generally, it was not possible to exclude these articles earlier using the filter options in Scopus and Web of Science.

2.4. Data Collection

From all publications that passed the different steps of the screening process, various data were extracted, including bibliographic information (authors' names and countries, publication title, affiliation, keywords, journal, year, references, citations, abstract, DOI), as were connotations of stability, sensitivity, and resistivity as well as the methods and parameters of their quantification. For each article, the field or fields of research were identified.

These data were recorded in two types of documents:

1. For the bibliometric analysis, a bibtext file (readable by the R package bibliometrix (Aria and Cuccurullo, 2017)) was prepared with all the articles that passed the screening process. The bibtext file was automatically extracted from Scopus with all the relevant

information for the bibliometric analysis. To avoid formatting conflicts, the data extracted from Web of Science were entered manually in the same bibtext file. Due to the fact that articles were sometimes present in both databases with different citation statistics, we decided to use the Scopus, since it generally presents higher numbers of citations than Web of Science.

2. For further analysis and interpretation, another table was set up including the outcomes of the analysis in terms of the specific definitions of stability, sensitivity and resistivity, as well as the respective quantification methods.

2.5. Bibliometric Analysis

Data extracted in the bibtext format were loaded into the R software environment for statistical computing and graphics (version 4.0.2, (R Core Team, 2021)) and subsequently, a bibliometric analysis was carried out using the bibliometrix package (Aria and Cuccurullo, 2017). Before starting the analyses, a thorough check of the database for errors was performed.

The papers that passed the screening process were analysed to identify the most relevant ones, as well as the relevant authors, i.e., those that produced the highest number of articles. Therefore, the author dominance ranking, as proposed by Kumar and Kumar (2008), was applied. Moreover, each author's productivity over time, as well as the respective trend line, was analysed. The general scientific productivity observed in terms of the frequency of publications of a specific author in a given field of study was compared with the theoretical frequency based on Lotka's coefficient (Lotka, 1926). With the Lotka function of the bibliometrix package, the beta coefficient of the bibliographic database was determined in order to statistically compare the similarity between the observed and the theoretical distribution. Lotka's law describes the frequency of publications by a given author in a particular field of study using the inverse square law, where there is a fixed relationship between the number of authors who publish a certain number of articles and the number of authors who have published only a single article. We hypothesized that the theoretical beta coefficient of Lotka's law would be equal to 2 (Lotka, 1926). Through the biblioNetwork function in bibliometrix, an in-depth citation analysis was conducted based on a co-citation network network (White and Griffith, 1981; White and McCain, 1998). Two articles are co-cited when both are cited in a third article. This type of analysis traces the intellectual structures of science (Bayer et al., 1990); it quantitatively identifies the relationships among scientific ideas (Cawkell and Newton, 1976) and subject similarities (Small, 1973). If two articles are highly co-cited, this is evidence that these articles are significant and related to each other (Cawkell and Newton, 1976). The results are illustrated using the networkPlot function, where nodes are research papers and links are co-citations.

NetworkPlot can also analyse scientific collaboration networks (Glänzel, 2001; Peters and Van Raan, 1991), which we investigated in detail and reported as a map, where the nodes are authors and the links reflect co-authorships.

Finally, keyword co-occurrences were analysed to study the knowledge components and structure of a field of research through the detection of clusters of the most common keywords in the literature (Radhakrishnan et al., 2017; Su and Lee, 2010).

2.6. Connotation and Quantification Methods

The various connotations of the search terms were collected in a table in chrono-logical order so that the evolution of their definitions over time could be assessed.

Regarding the quantification methods and parameters, a table describing the different approaches applied to the different fields of research was generated. The evolution of the quantification methodologies over time is also reported by arranging the relevant data in chronological order.

3. Results

3.1. Literature Search and Screening

A literature search was carried out in December 2021; 1082 articles were obtained, i.e., 433 articles from Web of Sciences and 619 from Scopus. As no time restrictions were set, this included papers from 1958 to 2022. After removing duplicates, the total number of publications was 859.

After a double-stage screening process, only 147 articles were considered useful for the research, coming from 64 difference sources (Journals) and dating from 1976 to 2022 (Table 1). The overlap between the two abstract and citation databases was 20.47%. The average number of citations per document was 36.15, as identified by Scopus and Web of Sciences.

Table 1. Key information about the obtained data after the double-stage screening process.

Main Information about Data	Results
Timespan	1976–2022
Sources (Journals)	64
Documents	147
Average years from publication	10.7
Average citations per documents	36.15
Average citations per year per doc	2.65
References	8169
Overlap	20.47
Article	143
Review	4

The identified publications mostly consisted of research articles (97.3%, n = 143), followed by reviews (2.7%, n = 4). Considering the whole period, the Annual Growth Rate of publications was found to be 2.19%.

Figure 2 shows the number of articles published for each year from 1976 to 2022. Publication activity started at a rather low value, with only slight annual increase, including years without and relevant publications, up to 1998. However, in the following years, activity increased exponentially. The highest number of relevant publications was registered for 2019, with 18 articles published.

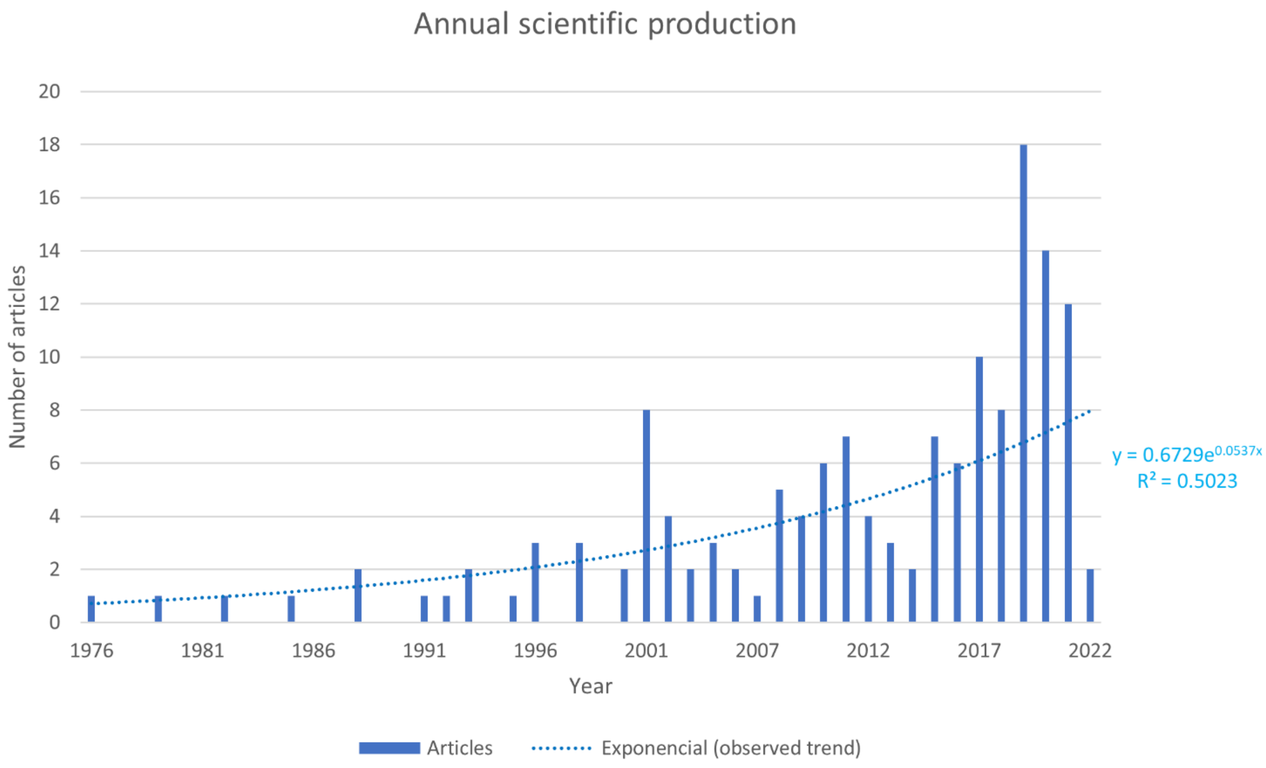


Figure 2. Annual production of articles during the period 1976–2022.

Authors' countries were assessed using the postal addresses reported in the articles. As shown in Table 2, the top 10 most productive countries contributed 96 articles, corresponding to 65.3% of the total outcome. The United States of America was the most productive country, with 27 published articles. Four articles were written in collaboration with other countries. The USA was followed by the United Kingdom, with 16 published articles, five of which were written in collaboration with other countries. China was in third position, with 14 published articles, 3 of which were in collaboration with other countries.

The most cited articles came from the United States, with 1661 citations and an average citation rate of 62 for each of the 27 articles, followed by United Kingdom, with 1132 citations and an average citation rate of 71 for the 16 articles. In third position, New Zealand showed 292 citations for only 2 articles and an average citation rate of 146.

The average number of article citations was consistent with the number of articles published per countries, except for China (5.36), which had the lowest average article citation value among the top 10 of the most productive countries.

Table 2. Number of publications and citations of the 10 most productive countries in the period 1976–2022. SCP: Number of publications by country; MCP: Number of articles for the country, written in col-laboration with other countries; TC: Total number of citations.

Country	Time Interval	Articles	SCP	MCP	TC	TC/Articles
USA	2022–1988	27	23	4	1661	61.52
United Kingdom	2022–1976	16	11	5	1132	70.75
China	2022–2002	14	11	3	75	5.36
Australia	2020–2985	10	8	2	162	16.20
Germany	2021–2010	8	5	3	138	17.25
Iran	2022–2006	8	4	4	179	22.38
France	2019–2004	4	3	1	108	27.00
Canada	2014–1996	3	2	1	102	34.00
India	2021–2012	3	3	0	25	8.33
Italy	2021–2016	3	1	2	57	19.00

As shown in Figure 3, in addition to the number of articles produced by individual authors, we determined the relevance of the corresponding articles by counting the average number of citations (within the database used for the bibliometric analysis), accounting for the period in which the authors worked on a given topic. Jayne Belnap and Matthew A. Bowker can be considered the most productive authors, with 5 articles published each. Both authors focused on soil ecology. Jayne Belnap has received 243 citations (TC), corresponding to an average of 49. In contrast, Matthew A. Bowker has received 277 citations (TC) with an average article citation of 55. All other contributing authors produced up to 3 articles each and focused on different fields of re-search, ranging from fluvial geomorphology to the assessment of soil properties and soil quality through soil indicators and other studies in the field of ecology.

Altogether, the top 10 authors produced 31 articles, or 21.1% of all articles that passed the screening process.

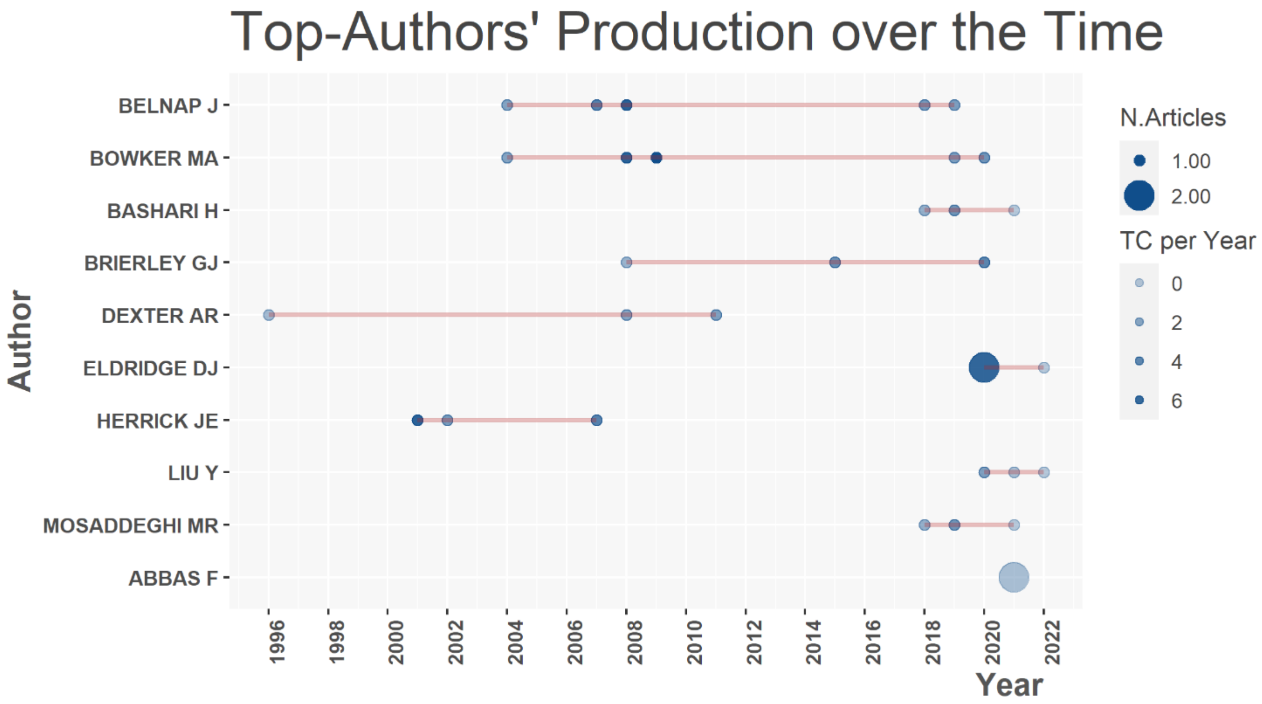


Figure 3. Production of top authors over time. TC: Average citations per year.

In order to assess the quality of publications as well as the general productivity, we used as indicators including the total number of global citations, i.e., total number of citations identified in the Scopus and Web of Sciences databases, and local citations, i.e., the total number of citations that an article received from other publications with-in our database of 147 articles.

Table 3 shows the ranking of the most relevant papers in terms of citations. Top on the list is Brunsden and Thornes (1979) with 472 citations. This paper was the first to attempt to define the term landscape sensitivity for research in the field of geomorphology. It was followed by Six et al. (2000) with 327 citations; those authors focused on soil aggregate distribution and soil stability as quality indicators. In third position was Orwin et al. (2004), with 272 citations; those authors proposed new indices with which to quantify the stability (i.e., resistance and resilience) of soil biota to exogenous disturbances.

Regarding local citations, Brunsden and Thornes (1979) were in first position, with 21 citations in other articles included in our database, followed by Harvey (2001), with 9 citations. The latter paper was included in a Special Issue of Catena from 2001 on landscape sensitivity, focusing on the sensitivity of fluvial systems. Brunsden (2001), in third place, provided an assessment of landscape sensitivity in geomorphology ranging.

Table 3. Total and local citation analysis of the 10 most relevant documents in the present dataset. TC: Total number of citations, LC: Local number of citations.

Document	DOI	TC	TC/YEAR	LC
Brunsden and Thornes, 1979	10.2307/622210	472	10.7273	21
Six et al., 2000	10.2136/sssaj2000.6431042x	327	14.2174	3
Orwin and Wardle, 2004	10.1016/j.soilbio.2004.04.036	272	14.3158	2
Harvey, 2001	10.1016/S0341-8162(00)00139-9	261	11.8636	9
Lal, 1993	10.1016/0167-1987(93)90059-X	189	6.3	0
North, 1976	10.1111/j.1365-2389.1976.tb02014.x	185	3.9362	3
Brunsden, 2001	10.1016/S0341-8162(00)00134-X	181	8.2273	7
Knox, 2001	10.1016/S0341-8162(00)00138-7	166	7.5455	5
Thomas, 2001	10.1016/S0341-8162(00)00138-7	166	7.5455	5
Bullard and McTainsh, 2003	10.1016/S0341-8162(00)00133-8	164	7.4545	4

The Lotka function can be used to determine the coefficients of scientific productivity (Lotka, 1926). As illustrated in Figure 4, the theoretical distribution was very similar to the distribution derived for our bibliographic dataset. The observed frequency of authors who published only one article was 91%, i.e., close to the theoretical frequency of 81%. From more than one article, the frequency of authors drastically decreased, i.e., to 6.9 for two papers, 1.2% for three papers and 0.3% for more than three papers. Although for observed productivity, the curves switched to higher theoretical and lower observed values, the two curves showed similar trends.

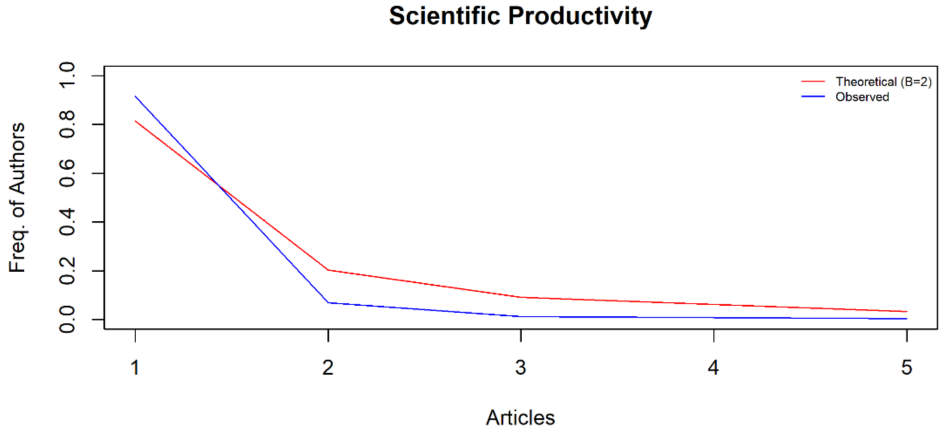


Figure 4. Lotka's law of scientific productivity.

A journal analysis was carried out by measuring the productivity and impact of the articles present in the respective journals. In Table 4, the numbers of publications and total citations of the five most relevant journals are shown.

This analysis identified five journals which represent 29% of all articles, i.e., 44 articles published. Of those five journals, ‘Catena’ was the most productive, with 16 articles. These articles also received the most citations, with an average of 67 per paper. The first article included in the database was published in 2001, concurrently with the publication of the special issue on landscape sensitivity. The second most productive journal was ‘Science of the total Environment’ with 6 articles, but with fewer total citations than the other four journals, i.e., an average citation rate per article of 14. In third place was ‘Geomorphology’, with 7 articles and an average number of citations per paper of 24. The numbers of citations were consistent with the number of publications, except for Science of the Total Environment.

Regarding the growth rate of journal articles, the first journal to publish a paper on landscape stability, sensitivity or resistivity was ‘Soil Science Society of America’, in 1982. This was followed by ‘Soil and tillage research’ in 1991. With the publication of the “landscape sensitivity” special issue in 2001, ‘Catena’ was the most productive journal up to 2014. From 2014 to today, the most productive journal has been ‘Science of the Total Environment’.

Table 4. The 5 most relevant Journal ordered by number of papers. TC: Total number of citations; PY start: year of the first publication of this journal included into database.

Journal	Articles	TC	PY start
Catena	16	1079	2001
Science of the Total Environment	8	109	2014
Geomorphology	7	167	2006
Soil and Tillage Research	7	320	1991
Soil Science Society of America Journal	6	420	1982

An in-depth citation analysis was carried out to identify connections within the bibliographic dataset. As documented in Figure 5, three clusters, coloured red, blue and green, can be seen. The blue cluster shows the publication of Brunsden and Thornes (1979) who have the highest number of co-citations. This is a cluster in which the main topic is geomorphology and landscape sensitivity; different topics were sometimes treated, but research was always related to the macro area of geomorphology. The green cluster, in which the dominant topic was fluvial geomorphology and sediment connectivity, comprised 14 papers. The blue and green clusters are heavily interlinked with each other. In contrast, the minor but independent red cluster had soil structure and soil stability as its main topic, and comprised only four papers.

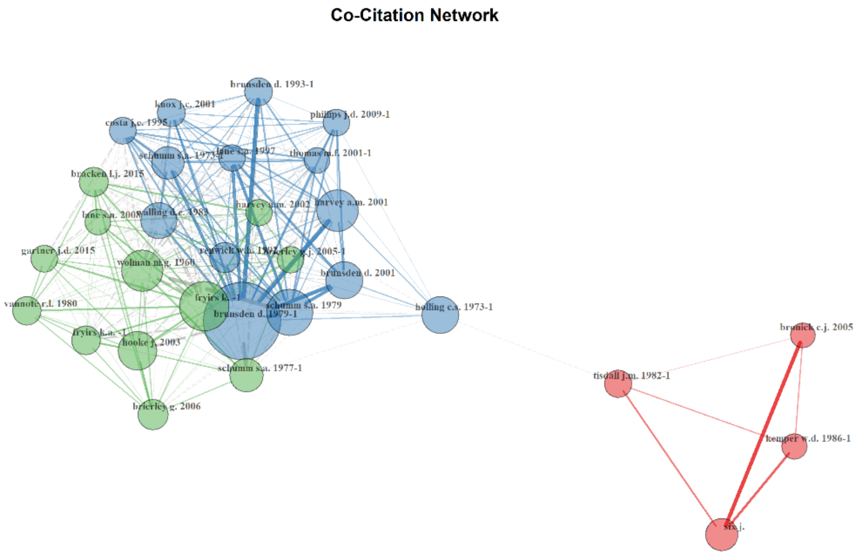


Figure 5. Co-Citation Network.

An author collaboration network is defined as a network where the nodes are authors and the links between them represent co-authorships. The size of the nodes indicates the number of articles authored by a given scholar.

As illustrated in Figure 6, 12 clusters were present. The individual clusters included a limited number of authors, indicating that collaboration is limited to a few authors for the topics covered in this bibliometric analysis. The larger clusters covered topics including soil stability, soil biology, soil structure and ecology. Minor clusters covered topics like aggregate stability, fluvial geomorphology, soil stability, soil properties and soil degradation.

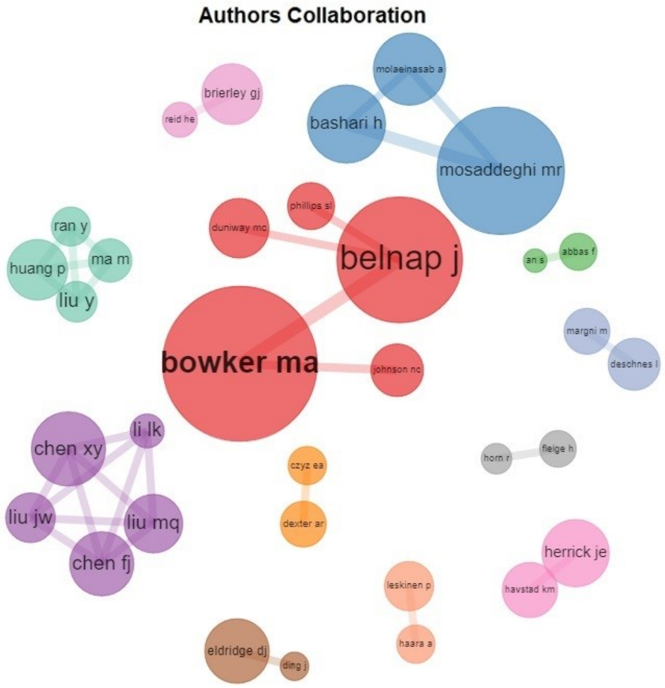


Figure 6. Author collaboration network.

Based on our analysis of keyword co-occurrences, Figure 7 shows that there were three clusters. One cluster (blue) was related to soil, in which the most important keywords were soils, soil stability, soil property, soil structure and soil stabilization. An-other (green), which was closely related to sensitivity, had the following keywords: soils, sensitivity analysis, ecosystem and climate change. A third cluster (green) was dedicated to erosion and was associated with keywords including soil erosion, erosion, soil stability, soil aggregates, soil structure, land use and sediment transport.

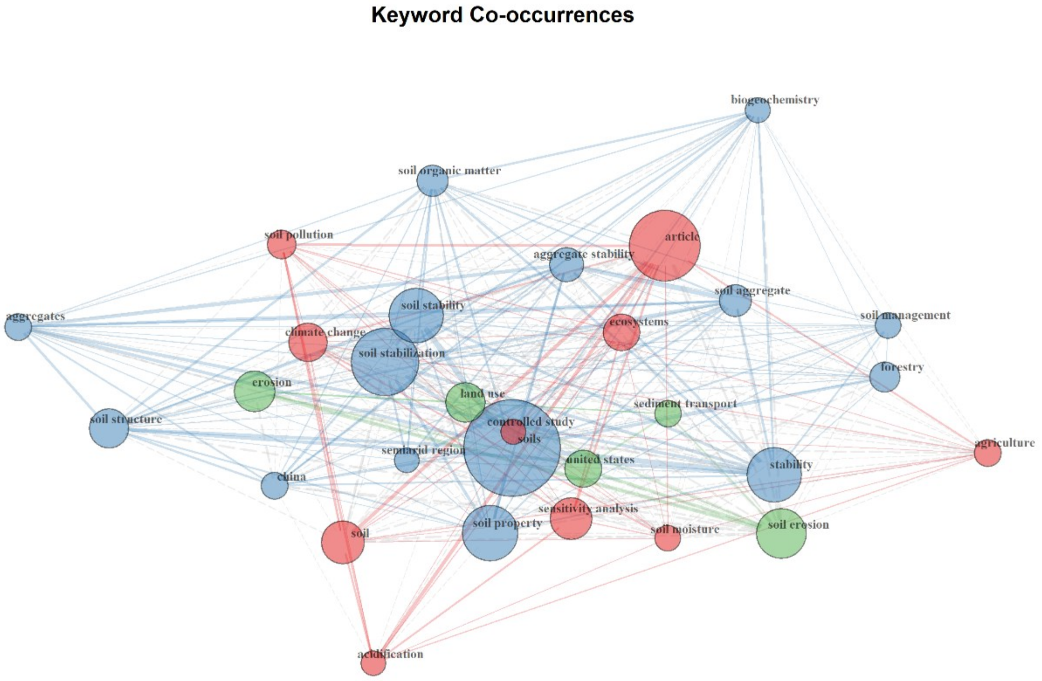


Figure 7. Keyword co-occurrences.

3.2. Identification of Connotation

Following the study eligibility criteria, all articles including a connotation regarding soil, landscape and geomorphological stability, sensitivity and resistivity which is considered to be related to sensitivity were identified.

All connotations identified during the screening process are reported in the fol-lowing tables. Regarding sensitivity, 34 different connotations were identified, starting with Brunsden and Thrones (1979), who proposed the initial connotation of the term “landscape sensitivity” in a geomorphological sense: “The sensitivity of a landscape to change is expressed as the likelihood that a given change in the controls of a system will produce a sensible, recognizable and persistent response. The issue involves two aspects: the propensity for change and the capacity of the system to absorb the change”. This can be considered a basic definition of the term “landscape sensitivity”.

We observed two peaks in publication activity: one in 1993, corresponding to the appearance of a collection of publications entitled ‘Landscape Sensitivity’, edited by D.S.G

Thomas and R.J. Allison, and the other in 2001, corresponding to the release of the 'Landscape Sensitivity' special issue, published in Catena.

The various connotations listed in Table 5 cover different fields of research, such as ecology, geomorphology, fluvial geomorphology, soil erosion, soil pollution, hydrology, land use change and soil structure.

Table 5. Connotations of "soil and landscape sensitivity", reverse chronologically ordered.

Article	Connotations of Soil and Landscape Sensitivity
(Song et al., 2021)	Soil resistance refers to the capacity of soil to retain stability upon exposure to stress. Soil resilience means the ability of soil to resist degradation and recover to its pre-perturbation status within an appropriate time scale.
(Manolaki et al., 2020)	The term landscape sensitivity can imply both resistance to change and resilience, i.e., the ability to recover from a change. Landscape sensitivity was defined as the ratio of the change in a system to the change in a landscape component; the larger the ratio, the greater the sensitivity.
(Mirzaee et al., 2020)	Resistance of soil particles to erosive forces such as rainfall and runoff is defined as soil sensitivity to erosion.
(Song et al., 2020)	Soil resistance (the capacity of soil to maintain its stability upon exposure to of stress) and soil resilience (the ability of soil to resist degradation and return to its pre-perturbation status).
(Llena et al., 2019)	The geomorphic sensitivity of the landscape: the response of the system to environmental change or disturbance and its recovery.
(Brogan et al., 2019)	Sensitivity is defined as "the propensity of a system to respond to a minor external change". Sensitivity also can vary across landscapes and over time, depending on other, previous perturbations.
(Wohl, 2018)	Earlier descriptions of resilience include landscape sensitivity and transient and persistent landforms. Transience and persistence, which are commonly defined in terms of the duration of a specific landform relative to the frequency of the process creating that landform, also take into account the temporal dimensions of the associated context (i.e., the recurrence interval of disturbances).
(Lizaga et al., 2018)	Geomorphic or landscape sensitivity refers to how geomorphic systems respond to environmental change, that is, the ability of a system faced with external interference to withstand the change.
(Rathburn et al., 2018)	Landscape sensitivity is another way to assess landscape resilience and resistance (i.e., the ability to resist changes in form and process caused by external factors). Sensitivity can thus be considered a function of the spatial and temporal distributions of the resisting properties (e.g., rock strength, resistance to weathering and erosion) and the disturbance forces (e.g., sediment load, high shear stress).
(James, 2018)	Landscape sensitivity, in turn, reflects a large variety of factors such as geology, soil, vegetation cover, antecedent conditions and topography. Legacy sediment is both a response to and a driver of landscape sensitivity and change.
(Anthony Stallins and Corenblit, 2018)	Like resilience theory, landscape sensitivity encompasses the propensities of a geomorphic system to recover from disturbance, as well as the tendency to change in state.
(Haara et al., 2017)	Landscape sensitivity describes the tolerance of landscape to change, which affects visibility, recreation and ecological sustainability. Landscape sensitivity varies both spatially and temporally.
(Fryirs, 2017)	Sensitivity is a system response characteristic that describes the severity of a response to a disturbance relative to the magnitude of the disturbance force.
(Phillips and Van Dyke, 2016)	Resilience is the ability of a system to return to its previous state after a perturbation. The landscape sensitivity concept in geomorphology incorporates resilience as well as resistance.
(Store et al., 2015)	The term "landscape sensitivity" has been used to indicate geomorphic sensitivity, which means how geomorphic systems respond to environmental changes such as erosion, increasing temperature, winds and storms and human activity. It can imply both resilience to change and the ability to recover from change. It can be defined as the likelihood that implementing certain forestry practices or other activities will evoke criticism and concern from the public.
(Roy et al., 2014)	Soil sensitivity represents receptor changes (if any) in soil properties over a certain area due to deposition in a single fraction.
(Zhang et al., 2013)	Soil erosion sensitivity is defined as the possibility of soil erosion occurrence and the identification of areas which are susceptible to erosion due to natural factors.
(Falconer et al., 2013)	Landscape sensitivity is measured to assess the degree to which a landscape can accommodate the type of change being predicted.
(Jain et al., 2012)	The sensitivity of a system is defined by the system specifications that describe its propensity for change and its ability to absorb any disturbing forces. The sensitivity dictates the landform response to external change.

(Phillips, 2009)	The landscape sensitivity concept encompasses the probability that a given change in the boundary conditions or forcings of a geomorphic system will ‘produce a recognizable and persistent response’.
(Gregory et al., 2008)	Regarding rivers, disturbance responses reflect the sensitivity to change or capacity for adjustment of any given reach.
(Kheir et al., 2006)	Landscape sensitivity is assumed to be inversely proportional to vegetal cover but directly proportional to slope and drainage density.
(Bullard and McTainsh, 2003)	Landscape sensitivity is the capacity of systems to absorb, resist or respond to changes in controlling factors such as moisture availability, sediment availability or transport capacity. The sensitivity of a given landscape is largely determined by its internal connectivity, i.e., the density and strength of the links between different parts of a geomorphic system.
(Tao et al., 2002)	Sensitivity, in this context, refers to the degree to which a system will respond to acid deposition. Thus, the term emphasizes the risk of an increase in the rate of change of the soil chemistry (the acidification rate).
(Usher, 2001)	Landscape sensitivity is expressed as the ratio of the change in a system to the change in a landscape component; the larger the ratio, the greater the sensitivity.
(Miles et al., 2001)	Landscape sensitivity indicates the likelihood of change, i.e., of instability versus stability.
(Harvey, 2001)	Sensitivity can be expressed by the ratio between the mean relaxation time of the system and the mean recurrence time between effective events. It distinguishes between robust landscapes, where the effects of disturbances are minimized, and sensitive landscapes, where the effects of disturbances may persist, i.e., landscapes which are transient in nature.
(Thomas, 2001)	The concept of landscape sensitivity, therefore, implies conditional instability within a system, with the possibility of the occurrence of rapid and irreversible change due to perturbations in the controlling environmental processes.
(Brunsden, 2001)	The landscape sensitivity concept describes the likelihood that a given change in a system or in the forces applied to that system will produce a recognizable and persistent response. Sensitivity refers to the propensity of a system to respond to minor external changes. Beyond a certain threshold, a significant adjustment occurs in the system. The system is considered to be sensitive if it is near such a threshold and will respond to an external influence.
(Thomas and Allison, 1993)	The question of sensitivity thus focuses on the potential and likely magnitude of change within a physical system and the ability of that system to resist change A cause/effect relationship can be identified where external processes control, influence and dictate change.
(Evans, 1993)	The sensitivity of a given landscape to erosion depends upon the threshold at which erosional forces are triggered by weather or earthquake shocks, in association with gravity, overcoming the resistance of rock, soil and vegetation.
(Downs and Gregory, 1993)	Sensitivity can be mathematically described as the ratio of two differentials that express the response or induced output change resulting from stimulus or applied input change.
(Schumm, 1991)	Sensitivity refers to the propensity of a system to respond to a minor external change. Changes occur at a threshold, which, when exceeded, results in a significant adjustment. If the system is sensitive, i.e., near the threshold, it will respond to the external influence.
(Brunsden and Thornes, 1979)	The sensitivity of a given landscape is expressed as the likelihood that a change in the controls of the system will produce a recognizable and persistent response. The concept involves two aspects: the propensity for change and the capacity of the system to absorb such a change.

Regarding the connotation of soil and landscape stability, 19 definitions were identified (Table 6). The oldest definition of soil stability was provided by North (1976): “The stability of a soil is indicated by its ability to resist potentially disruptive forces”.

These connotations cover different fields of research, of which the most significant are ecology, followed by soil biology, soil properties, land use change, paleoenvironmental studies, geotechnics and the effects of land use on landscapes.

Table 6. Connotations of soil and landscape stability, ordered reverse chronologically.

Article	Connotations of Soil and Landscape Stability
(Picariello et al., 2021)	Soil stability encompasses both resistance, i.e., the ability to withstand a perturbation or stress, and resilience, i.e., the ability to recover to pre-perturbation levels.
(Eldridge et al., 2020)	The ability of surface soil aggregates to break down in water; stable soil fragments will stay intact upon wetting.
(Vojtekova and Vojtek, 2019)	The term landscape stability refers to the spatial and functional stability in various land-use categories over time. Basically, landscape stability represents the share of stable areas between the first and last years of study. In contrast, landscape structure instability refers to situations when a small change in the environment is enough to divert the system from its oscillating mode around a central state.
(Zhang and Zhang, 2019)	Landscape stability describes a balanced state in the landscape structure and pattern of a fixed size. A landscape pattern describes the response when that landscape is controlled and shaped by climate or human disturbances.
(Menezes et al., 2019)	Periods of landscape stability in which the pedogenesis exceeded the sedimentation rates, resulting in the formation of soil profiles
(Liu et al., 2019)	Landscape stability describes a landscape that has been stable (i.e., when perturbed, it tends to return to an undisturbed state) and which will not undergo significant structural changes in the short term. The term also implies that the natural processes that contribute to the functions and sustainability of that landscape will not be disrupted
(Prokopová et al., 2019)	Ecological (landscape) stability is defined as the ability of a given ecosystem to return to its initial equilibrium state after a disturbance. Additionally, this notion describes the intrinsic ability to maintain ecological functions despite disturbance. The notion is based on three complementary attributes: resilience, adaptability and transformability.
(Xuan et al., 2016)	Landscape stability is an index that is effective at revealing past changes. Landscape stability assessments measure the risk faced by a certain area after a disturbance and analyze the relationship between that disturbance and stability, as well as other relationships between the structure of ecological areas and their stability.
(Guo et al., 2015)	Soil stability indicates the extent of the anti-erosion properties of various soil types,
(DeJong et al., 2010)	the ratio of initial penetration resistance and the remolded resistance.
(Mikheeva, 2010)	Stability describes the ability of soil to retain its properties, regime parameters, phase ratio and structural organization within a set of limits determined by natural variations under different external perturbations (including anthropogenic ones).
(Chaudhary et al., 2009)	Soil stability is the ability of soils to resist erosive forces.
(Derbel et al., 2009)	The stability index provides information about the ability of soil to withstand erosion and to recover after disturbance.
(Orwin and Wardle, 2004)	Stability (resistance and resilience to disturbance) is a key factor influencing the properties and processes of a soil system.
(Brunsden, 2001)	Landscape stability is assessed according to the temporal and spatial distributions of resisting and disturbing forces and is therefore diverse and complex.
(Lal, 1993)	Soil stability refers to the susceptibility of soil to change under natural or anthropogenic perturbations.
(Friedman and Zube, 1992)	The purposes of this article is to present means by which to assess (i) the spatial and temporal changes in land use and land cover at the landscape and vegetation community scales, and (ii) landscape stability. Landscape stability is defined as no change in the extent of each of the relevant components.
(Brunsden and Thornes, 1979)	Landscape stability is a function of the temporal and spatial distributions of resisting and disturbing forces and may be described by the landscape change safety factor, here considered to be the ratio of the magnitude of barriers to change to the magnitude of the disturbing forces.
(North, 1976)	The stability of a soil is indicated by its ability to resist potentially disruptive forces.

Table 7 reports the parameters that are used to quantify soil and landscape stability/sensitivity in reverse chronological order. In total, we identified 104 papers reporting quantification methods. The most important thematic field is the study of soil properties and soil structure, with 40 instances, followed by ecology (19 instances) and soil erosion (11 instances). Other key research fields are soil biology, agriculture, geomorphology and remote sensing.

For quantitative assessments of soil and landscape sensitivity, different methods are applied, depending on the field of research. One of the most commonly used parameters is aggregate stability (e.g., Abbas et al., 2021b; Teixeira et al., 2021; Young et al., 2019), which is measured using the following variables: mean weight diameter (MWD) (Liu et al., 2021), geometric mean diameter (GMD) (Ran et al., 2022), water stable aggregates (Marquez et al., 2004), macro aggregates stability (Marquez et al., 2004), the resistance of a soil sample to slaking (Marquez et al., 2004) and aggregate distribution before and after disruption (Six et al., 2000).

Remote sensing applications are often used to evaluate land use changes, for example, by applying a Landscape Function Analysis (LFA), which is employed to estimate soil resistance to erosion.

Sensitivity to soil erosion is mainly evaluated using qualitative and quantitative methods. Other methods include landscape character assessment s (LCAs) (Daniel J Brogan et al., 2019; Safaei et al., 2019) and analyses of soil sensitivity to acid deposition (Lau and Mainwaring, 1985).

Table 7. Parameters of quantification of stability and sensitivity.

Article	Parameters of Quantification of Soil and Landscape Stability/Sensitivity	Research Field
(Ran et al., 2022)	mean weight diameter (MWD), geometric mean diameter (GMD),	soil properties
(Abbas et al., 2021b)	aggregate stability	soil properties
(Sawicka et al., 2021)	base saturation (BS), aluminum saturation (Alsat),	soil properties
(Liu et al., 2021)	mean weight diameter (MWD)	soil structure
(Ghosh et al., 2021)	mean weight diameter (MWD), geometric mean diameter (MWD), normalized soil stability index (NSSI)	soil erosion
(Mamedov et al., 2021)	modal suction (MS), soil VDP (area under a specific water capacity curve and above the soil shrinkage line)	soil structure
(Abbas et al., 2021a)	relative stability of soil aggregates (RSA)	soil structure
(Jiaguo et al., 2021)	slope class, aspect class, land use class	soil pollution
(Teixeira et al., 2021)	soil aggregate stability	soil structure
(Molaeinasab et al., 2021)	soil cover percentage, litter cover percentage, origin and degree of decomposition, cryptogam cover percentage, crust brokenness, soil erosion type and severity, deposited material, soil surface nature, slake test	soil properties
(Song et al., 2021)	soil resilience, soil resistance	soil structure
(Minhas et al., 2021)	structural index (ratio of volume of drainable pores to modal suction 'peak of water capacity curve')	soil hydrology
(Mirzaee et al., 2020)	baseline inter-rill soil sensitivity to erosion, slope factor, rainfall intensity, runoff rate, inter-rill sediment, detachment capacity, baseline rill soil sensitivity to erosion, flow shear stress, rill detachment threshold parameter or soil baseline critical shear stress	soil erosion
(Manolaki et al., 2020)	ecological sensitivity, cultural sensitivity (integrity and value), visual sensitivity	ecology
(Crawford et al., 2020)	mean weight diameter (MWD) of soil aggregates	soil biology

(Okolo et al., 2020)	mean weight diameter, % of soil organic matter, %silt, %clay	soil structure
(Okolo et al., 2020)	normalized channel steepness index (ksn)	remote sensing
(Brahim et al., 2020)	rainfall and runoff erosivity factor, slope length and steepness factor, soil erodibility factor, vegetation cover, management and cultural practices factor, conservation practice factor.	soil erosion
(Ran et al., 2020)	mean weight diameter (MWD), geometric mean diameter (GMD), fractal dimension (D)	soil restoration
(Oliva et al., 2019)	aerial cover for rain interception, litter cover, origin and degree of incorporation, cryptogram cover, deposited materials, soil crust type and degree to which it was disturbed, surface crust resistance and slake test, time that soil aggregates retain integrity in water	ecology
(Dor et al., 2019)	aggregate durability index (ADI) based on changes in soil particle-size distribution	soil properties
(Durante et al., 2019)	Ca exch, Mg exch, K exch, Ptot and Ntot	ecology
(Karadag and Senik, 2019)	erosion sensitivity, landslide sensitivity, water infiltration sensitivity, habitat sensitivity	ecology
(Farazmand et al., 2019)	geology, soil texture, climate, runoff, topography, vegetation, land use, current erosion, gully erosion	ecology
(Llena et al., 2019)	index of sediment connectivity	geomorphology
(Sepehr et al., 2019)	mean weight diameter of aggregates (MWD), soil aggregate stability (SAS), clay dispersion index (CDI)	soil biology
(Riggert et al., 2019)	precompression stress and bulk density	soil degradation
(Chung et al., 2019)	soil aggregate stability	soil biology
(Young et al., 2019)	soil aggregate stability	soil structure
(Daniell et al., 2019)	soil cover percentage, litter cover percentage, origin and degree of decomposition, cryptogam cover percentage, crust brokenness, soil erosion type and severity, deposited material, soil surface nature, slake test	soil pollution
(Safaei et al., 2019)	soil organic carbon, % silt, % clay	soil structure
(Klopp et al., 2019)	soil swelling	soil structure
(Niewiadomska et al., 2018)	soil resistance under natural conditions over time (t0), resistance of soil subjected to pressure over time	ecology
(Molaeinasab et al., 2018)	soil cover percentage, litter cover percentage, origin and degree of decomposition, cryptogam cover percentage, crust brokenness, soil erosion type and severity, deposited material, soil surface nature, slake test	soil quality
(Lizaga et al., 2018)	Upslope and downslope component, average weighting factor of the upslope contributing area, average slope gradient of the upslope contributing area, upslope contributing area	land use change
(Merante et al., 2017)	clay content, soil organic carbon	soil management
(Cao, 2017)	landscape patch change	remote sensing
(Tamene et al., 2017)	rainfall erosivity, soil erodibility, 3D terrain representation, land use/cover, conservation/management factor.	soil erosion
(Ali et al., 2017)	soil aggregate stability, penetration resistance, soil shear vane strength	ecology
(Berendt et al., 2017)	soil texture	ecology
(Munoz et al., 2017)	water-stable aggregates	agriculture
(Read et al., 2016)	aerial cover for rain interception, litter cover, origin and degree of incorporation, cryptogram cover, deposited materials, soil crust type and degree to which it was disturbed, surface crust resistance and slake test, time that soil aggregates retain integrity in water	ecology
(Xuan et al., 2016)	instability patch area ratio, dispersion, uniformity, uniformity shape coefficient	ecology
(Geraei et al., 2016)	carbon pools in uncultivated and cultivated soils	land use change
(Mirmousavi, 2016)	soil erodibility index of the texture classes, wind condition, vegetation and land cover	soil erosion
(Bast et al., 2015)	mean weight diameter (MWD), aggregate stability coefficient (ASC)	soil structure
(Reid and Brierley, 2015)	river style, potential for adjustment	fluvial geomorphology
(Store et al., 2015)	scenic attractiveness or quality, visibility of landscape, the number and type of viewers	ecology
(Reinhart et al., 2015)	soil aggregate stability	ecology
(Ladanyi et al., 2015)	soil moisture regimes, groundwater resources, biomass production of vegetation, levels of wind erosion hazard.	ecology
(Guo et al., 2015)	type of soil	ecology
(Safeeq et al., 2015)	watershed drainage area, principal component, regression coefficients a, b, c	fluvial geomorphology
(Pulido Moncada et al., 2014)	particle size distribution (%clay and % soil) and soil organic carbon	soil structure
(Fultz et al., 2013)	mean weight diameter (MWD)	agricolture
(Zhang et al., 2013)	rainfall erosivity, soil types, relief, vegetation coverage (%)	soil erosion
(Roy et al., 2012)	base cations to aluminum ratio, aluminum to calcium ratio, pH, and aluminum concentration	soil properties
(Munro et al., 2012)	rain splash protection, perennial vegetation cover, leaf litter, cryptogram cover, crust brokenness, soil erosion, deposited material, soil surface roughness, resistance to disturbance, slake test, soil texture	ecology

(Sharma et al., 2012)	soil depth, soil texture, surface texture, erosion, stoniness, slope, drainage, hydraulic conductivity	landslide
(Schacht et al., 2011)	buffering capacity for inorganic adsorbable pollutants, slaking of the upper soil layers, salinization, buffering capacity for boron, buffering capacity for non-adsorbable substances, soil surface area	agriculture
(Dexter et al., 2011)	clay dispersion from soil	soil structure
(Rozsa and Novak, 2011)	constants of climatic condition (Kc) and relief condition (Kr)	geomorphology
(Nichols and Toro, 2011)	soil aggregate stability	soil properties
(Bhardwaj et al., 2011)	soil aggregate stability	ecology
(DeJong et al., 2010)	undrained shear strength (Su), remolded undrained shear strength (Sur)	geotechnics
(Carpenter and Chong, 2010)	resistance of soil samples to slaking	soil biology
(Washington-Allen et al., 2010)	bands of Landsat MSS data, soil taxonomy	soil erosion
(Zink et al., 2010)	precompression stress	agriculture
(Du et al., 2010)	rate of dispersion of soil aggregates in water	soil erosion
(Chaudhary et al., 2009)	in-field aggregate stability test	soil biology
(Derbel et al., 2009)	rainsplash protection, perennial vegetation cover, leaf litter, cryptogram cover, crust brokenness, soil erosion, deposited material, soil surface roughness, resistance to disturbance, slake test, soil texture	ecology
(Pohl et al., 2009)	stability of soil aggregate	soil structure
(Whicker et al., 2008)	dust flux (HDF)	restoration
(Bayramin et al., 2008)	percentage of silt and sand, percentage organic matter, structure and permeability	soil erosion
(Czyz and Dexter, 2008)	readily dispersible clay	soil properties
(Bowker et al., 2008)	soil aggregate stability	soil erosion
(Belnap et al., 2007)	soil aggregate stability	soil biology
(Rezaei et al., 2006)	individual soil surface features comprising soil cover, litter cover, cryptogam cover, crust brokenness, erosion features, deposited material, microtopography, slake test, and soil surface texture	soil quality
(Kheir et al., 2006)	vegetal cover, drainage density, slopes maps	soil erosion
(Marquez et al., 2004)	mean weight diameter (MWD), water stable aggregates (WSA), stable aggregates (SAI), stable macroaggregates index	soil structure
(Orwin and Wardle, 2004)	resilience and resistance index	soil biology
(Bowker et al., 2004)	soil aggregate stability	soil biology
(Pernes-Debuyser and Tessier, 2004)	soil surface, aggregate stability, soil water dispersion index (DI)	soil treatment
(Koptsik et al., 2003)	soil acidity, cation exchange capacity (CEC), degree of base saturation, base content	soil properties
(Tao et al., 2002)	base saturation (BS), cation exchange capacity (CEC),	soil properties
(Herrick et al., 2002)	soil aggregate stability	ecology
(Barlow and Nash, 2002)	soil water characteristics curves (between 0 and 3 kPa)	soil properties
(Gordon et al., 2002)	vegetation type and strength of the root mat, regolith cohesion and soil properties, topographic position, degree of exposure	ecology
(Herrick et al., 2001)	soil aggregate stability	soil structure
(Six et al., 2000)	aggregate distribution before and after disruption	soil structure
(Martínez-Mena et al., 1998)	aggregate stability RSSI	soil structure
(Hodson et al., 1998)	short-term acid buffering capacity	soil properties
(Dodds and Fey, 1998)	soil score, lithology score, land use score, rainfall score	soil properties
(Curtin et al., 1996)	pH	soil properties
(Hodgkinson and Thorburn, 1996)	total suspended clay and silt as a result of aggregate disruption by mechanical factors	agriculture
(Watts et al., 1996)	turbidity index, tensile strength index	soil structure
(Hornung et al., 1995)	base saturation and pH	soil properties
(Lal, 1993)	rates of new soil formation or soil restoration (Sst), which include organic matter, texture properties, soil biodiversity, and climate, vegetation; susceptibility of soil to degradation (Ssu) based of its parent material, climate, pedogenetic processes	soil properties
(Friedman and Zube, 1992)	land use	landscape dynamics
(Wace and Hignett, 1991)	dispersible clay content at 10Kpa	soil properties

(Gobran and Bosatta, 1988)	cation depletion	soil properties
(Levine and Ciolkosz, 1988)	pH, soil solution Al concentration	soil properties
(Lau and Mainwaring, 1985)	buffer capacity	soil properties
(Cass and Sumner, 1982)	water composition volume element which lies below the threshold concentration plane, total volume of the water composition element.	soil structure
(North, 1976)	energy dispersion	soil properties

4. Discussion

The aim of this study were as follows: to screen and identify current knowledge about sensitivity, stability and resistivity on a landscape scale through a systematic analysis of peer-review articles and fields of research that have had the greatest im-pact on the topic; to identify the different connotations associated with these terms in various scientific sectors; and to identify the most widely used parameters and methods of quantification.

The annual scientific productivity in these fields was shown to have been in-creasing exponentially since 1976 (Figure 2), highlighting growing interest due to the ever greater importance of environmental issues and sustainability.

Our bibliometric analysis identified the most productive and influential authors in terms of numbers of publications: J. Belnap and Matthew A. Bowker, with five articles, followed by Hossein Bashari, Gary J. Brierley and Anthony R. Dexter, with three. Each of these authors studied soil and landscape stability/sensitivity from a distinct perspective. Jayne Belnap and Matthew A. Bowker, who co-authored some articles, focused their studies on soil biology and stability. Hossein Bashari focused on assessments of soil quality indicators, while Gary J. Brierley studied fluvial geomorphology and Anthony R. Dexter studied soil properties. Thus, different research fields are in-volved which are not always connected with each other. Although these were the most productive authors, the articles that have received the greatest success in terms of citations are attributed to other authors. In particular, Brunsden and Thornes (1979) is the most globally and locally cited paper. Moreover, it was the first to provide a definition and a method of quantification of landscape sensitivity in the context of geomorphology. Six et al. (2000), the second most cited research paper, focused on soil aggregate distribution, which has since received great interest, as it is one of the most widely used methods to assess soil and landscape stability (Table 7). In third position concerning citations is Orwin et al. (2004), who proposed a new method to quantify the stability of soil biota to exogenous disturbance based on the resistance and resilience indexes. As highlighted above, this bibliometric analysis was multidisciplinary, and hence, involved the work of authors whose specializations cover a range of sectors, from ecology to assessments of soil properties.

Our analysis of productivity, as illustrated in Figure 4, indicated that the majority of authors have published only one article (91.4%). Only 7% of authors have published have two articles, and less than 1% have published three or more. This indicates that only a few authors deal with the topic over long periods of time, and suggests that most authors are not specialized in this topic, but rather, encounter it from time to time in respective specific fields of research. One advantage of this is that when many authors from different fields deal with a topic, completely independent and new ideas can arise; however, it also has the disadvantage that less long-term experience is obtained.

Analysing the productivities of different countries, a broad contribution of different countries and continents was observed. This shows that this topic is of great interest around the world, albeit with a slight prevalence of the United States and Europe. It is interesting to note that the two most productive countries were also those with the highest number of citations per article (Table 3), indicating not only a high quantity but also quality of their scientific contributions. In contrast, other countries characterized by a high number of articles had comparatively few citations per article (e.g., China, with, on average, 1235% fewer citations than the United States and United Kingdom). Nonetheless, since most of these papers were published in esteemed journals such as Catena, Geoderma, Science of the Total Environment, Pedosphere, Environmental Earth Science, Ecological Engineering, Environmental Science and Pollution Research and Journal of Soil Science and Plant

Nutrition, the determining factor for the lack of citations cannot be the quality of the articles; rather, it may be explained by the fact that eleven of the fourteen articles were published in the last two years, and thus, have not have enough time to receive large numbers of citations. This also indicates that interest in this subject in China has increased exponentially over the past two years.

Our analysis showed that the journal Catena has published the most papers on the topic, with sixteen articles (including the special issue on ‘landscape sensitivity’), followed by Science of the total Environment, with eight, and Geomorphology, with seven. However, these journals tackle slightly different research fields. Catena is mainly focused on geoecology and landscape evolution, evaluating interdisciplinary aspects of soil science, hydrology and geomorphology. Science of the Total Environment is focused on research concerning the total environment, which interfaces the atmosphere, lithosphere, hydrosphere, biosphere and anthroposphere. Finally, Geomorphology publishes research on a broad range of geomorphological issues.

Our co-citation analysis discovered three main clusters, of which the main topics are (i) the macro-area of geomorphology, (ii) fluvial geomorphology and sediment connectivity, and (iii) the structure and stability of soil. The first two clusters were found to be closely connected. These three main clusters of co-cited papers do not adequately represent all the research fields in which the topic is addressed. Notably, the field of ecology is missing, which points to the fact that few articles related to ecology have been cited by the articles in the database. In fact, the research field of ecology is missing, which points to the fact that there are not many pairs of articles in the eco-logical field that are cited in turn by a third article present in the database.

Author collaborations showed many small clusters, suggesting that such collaborations are limited in number and extent. This also indicates an absence of large re-search groups involving many research institutions from the same or different countries. However, all the main research fields were well represented. In fact, clusters were found regarding the study of various topics like soil stability, soil biology, soil structure, ecology, geomorphology, soil properties, etc.

Our analysis of keyword co-occurrences highlighted a cluster related to soil stability and keywords such as soil, soil aggregates, soil organic matter and biogeochemistry; these terms encompass different aspects of soil stability quantification (Table 7). A cluster of sensitivity analysis was associated with keywords like soil pollution, climate change, acidification, ecosystem and agriculture. Finally, a third cluster was found dealing with soil erosion related to sediment transport, land use, soil aggregates, soil stability and soil structure.

Our assessment of the term “soil and landscape sensitivity” showed 34 connotations in the various articles. The first was associated with Brunsden and Thornes, 1979. In subsequent publications, it was not possible to identify evolution of the definition, although later definitions were associated with different research fields. As evidenced by many articles, depending on the response, the sensitivity of a system can be defined based on its resistance or resilience. Resistance or robustness means the ability of a system to withstand a disturbance, while resilience indicates both the ability to prevent and/or to return the pre-perturbative state in response to a disturbance.

Regarding soil and landscape stability, only 18 definitions were identified, with most referring to resistance and resilience (Orwin and Wardle, 2004; Picariello et al., 2021; Prokopová et al., 2019). This indicates that there is no clear definition of stability, and that it is often used synonymously with sensitivity. However, other connotations of “stability” were observed in relation to specific research fields; some were based on the stability of soil (Chaudhary et al., 2009; Guo et al., 2015; Mikheeva, 2010), while others were based on the stability of landscapes, notably in reference to changes in land use (Vojteková and Vojtek, 2019). Probably, the absence of a clear definition is due to the fact that “stability” may refer to any of the various properties of soils or landscapes, while “sensitivity” does not change depending on the field of study.

A total of 104 papers were identified in which parameters were proposed to quantify stability and/or sensitivity. Forty research articles proposed the use of soil properties for quantification, mainly focusing on assessments of aggregate stability using different methods. Aggregate stability is a soil property that is easily measurable in the field or laboratory. It is a low-cost technique that is highly reproducible, as document-ed for different environments and soil typologies. In contrast, in ecology, stability and sensitivity are quantified in different ways, ranging from the chemical soil characteristics (cation exchange capacity, content of elements) (Durante et al., 2019) to soil properties (Ali et al., 2017; Berendt et al., 2017; Guo et al., 2015; Reinhart et al., 2015) or landscape properties (Karadağ and Şenik, 2019; Munro et al., 2012; Oliva et al., 2019; Read et al., 2016) and even subjective characteristics, such as culture, scenic attractiveness and visibility (Manolaki et al., 2020; Store et al., 2015). Sensitivity to soil erosion is quantified in different ways; traditional methods use empirical modelling approaches, such as the Revised Universal Soil Loss Equation (RUSLE) to obtain a map of sensitivity to erosion (Brahim et al., 2020; Tamene et al., 2017), or take into account soil properties (Bayramin et al., 2008) such as aggregate stability (Bowker et al., 2008; Du et al., 2010) or landscape topography and vegetation. Finally, data coming from remote sensing, such as multi-spectral data, are also used to identify stable areas (Washington-Allen et al., 2010).

Generally, it can be stated that the terms “stability” and “sensitivity” are used in a lot of different research fields, and as such, there are no unique definitions or generally accepted methods to assess them. Often, specific indicator properties are used that vary according to the landscape that is being analysed.

5. Conclusions

A bibliometric analysis was carried out based on peer-reviewed literature obtained from the Web of Science and Scopus bibliographic databases using landscape stability, sensitivity and resistivity as keywords for research fields such as geoscience, geomorphology, soils and agriculture.

The concluding remarks are as follows:

- Our analysis of publication trends shows that the number of relevant, peer-reviewed papers is undergoing exponential growth, with some fluctuations due to, for example, the publication of the special issue of Catena in 2001 on ‘landscape sensitivity’.
- Research on landscape stability, sensitivity and resistivity is widespread globally and is particularly prevalent in the USA and the UK. Authors from these countries were among the first to study the aforementioned topics, while China, which was in third place, has started to study them in recent decades, and as such, still has fewer papers and citations.
- The most popular definition of “landscape sensitivity” was established by Brunsden and Thornes (1979). Those authors applied the term to geomorphological environments. It did not undergo substantial evolution over time. In fact, theirs remains the most widely used definition.
- There is not a clear definition of “landscape stability”, and it is often synonymous with “sensitivity”.
- A large number of methods were identified for the assessment of soil and landscape stability and sensitivity; however, it was not possible to identify a universal method due to the specific characteristics of each study area and the individual focus of each paper. Quantification methods variously encompass analyses of individual soil physical and chemical properties (i.e., aggregate stability, cation ex-change capacity, etc.), of intangible properties (culture, scenic attractiveness and visibility) and of land use change, susceptibility to erosion, etc.

- Quantifications of stability and sensitivity have been carried out in very different landscapes and contexts, ranging from arid and semi-arid environments to agricultural fields, but also fluvial systems, coastal environments, mountain catchments, forests, highland ecosystems and rangelands. Moreover, different spatial scales are covered from very small areas to entire countries.

As demonstrated by Donthu (2021), bibliometric analyses have several limitations, such as errors in bibliographic databases which must be manually corrected. Bibliometric qualitative assertions may be subjective; this is in contrast with the nature of bibliometric analyses, which must be quantitative. Finally, bibliometric studies provide only a short-term overview of a given field of research.

Generally, this study revealed that there is limited collaboration between authors. As such, we stress the necessity to establish international and interdisciplinary research groups to more clearly define the terms landscape stability and sensitivity. The results also indicated a lack of coordination in international interdisciplinary research regarding methods that could be used to assess the terms landscape stability and/or sensitivity. Finally, our study revealed a general need for long-term studies, and hence, the creation of steady research groups that might benefit from long-term experience in this setting.

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Chapter 2: Landscape sensitivity analysis (PAPER 2)

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

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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 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, (iv) saturated hydraulic conductivity, (v) aggregate stability and (vi) soil water repellence. 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. Analysis of the effect of land use change on soil properties were performed through linear mixed model 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 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 to natural 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 as well as 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 is a huge (if not the biggest) threat of 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:

i. 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). Among other things, this is due to mechanical tillage reducing 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).

ii. 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 the topsoil horizons (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).

iii. 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 (K_{sat}) (Ziegler et al., 2004; Hassler et al., 2011).

iv. 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, can finally increase the potential for soil erosion. Due to the irreversible loss of fertile topsoil material 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 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 for investigating and assessing soil landscape sensitivity in Alpine environments is still lacking. 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 because of 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 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) SOM, (ii) aggregate stability, and (iii) K_{sat}, which are generally considered as key sensitivity indicators. We further complemented them by (iv) soil water repellence (SWR), which is a particular characteristic of the soils of the Onsernone valley (Zehe et al., 2007). Soil water repellence is strongly related to soil texture and SOM content and hence can have a large effect on surface runoff generation (Burch et al., 1989; Keizer et al., 2005).

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[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.

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 (Figure 1) and covers approximately 6 km^2 with an altitudinal range going from 400 to 1,000 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 characterised 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 2,000 mm (Swiss average: 1,300 mm/year) with rainfall intensities reaching 400 mm per day and more. The mean annual temperature is 12°C (1991–2020; MeteoSwiss, 2020).

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°. 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. 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. 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 can be detected 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 SOM (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 characterised 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. Another important characteristic of the sandy and SOM-rich soils in the Onsernone valley is their tendency to be water repellent when dry.

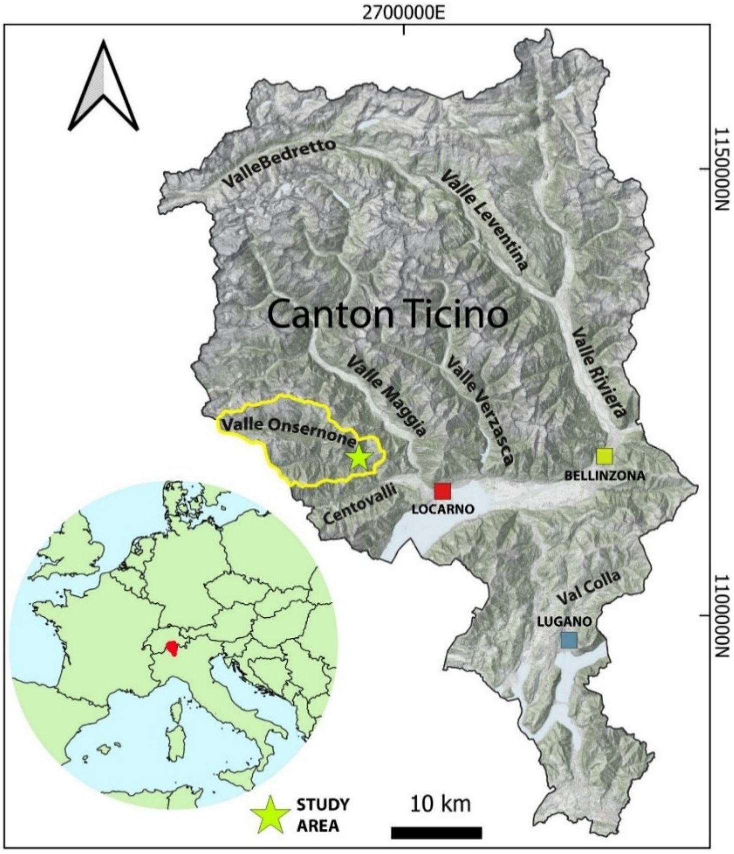

Figure 1. Map of Canton Ticino with the location of the study area (Federal Office of Topography, swisstopo).

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. Likewise, animal husbandry on the north-facing slopes ceased and resulted in secondary reforestation of former pastures. The abandoned pastures where reforestation has not yet taken place are characterized by meadows that are 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; Figure 2):

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

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. 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. Pastures were grazed by cows and goats whereas terraces are predominantly used as vineyards or horticulture. Finally, post-abandonment (re-)forested, abandoned terraces (FT) 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 and display according to the dendrochronological analyses over 40 years old trees.

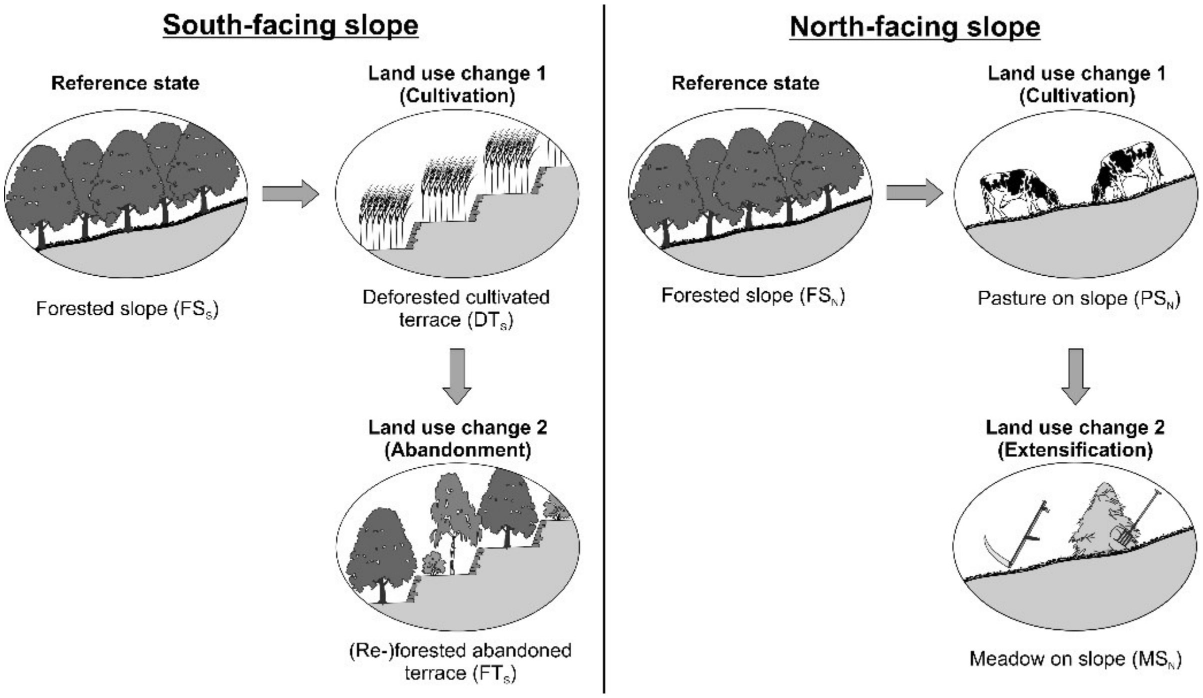

Figure 2. Land use changes in the Onsernone valley.

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

Following soil properties have been analysed:

i. Soil texture:

   The 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.

ii. Bulk density:

   The 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.

iii. Soil Organic Carbon (SOC):

   The Soil Organic Carbon was analysed 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.

iv. Saturated hydraulic conductivity (K_{sat}):

K_{sat} was measured in the field using a constant-head permeameter (Amoozegar, 1989a) in two different depths of 16 and 23 cm. 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.

v. 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 grams 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 Equation 1:

$$AS = \frac{W1}{W1+W2} \qquad \text{(Equation 1)}$$

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

vi. Soil water repellence (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 seconds 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 soil water repellence, 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).

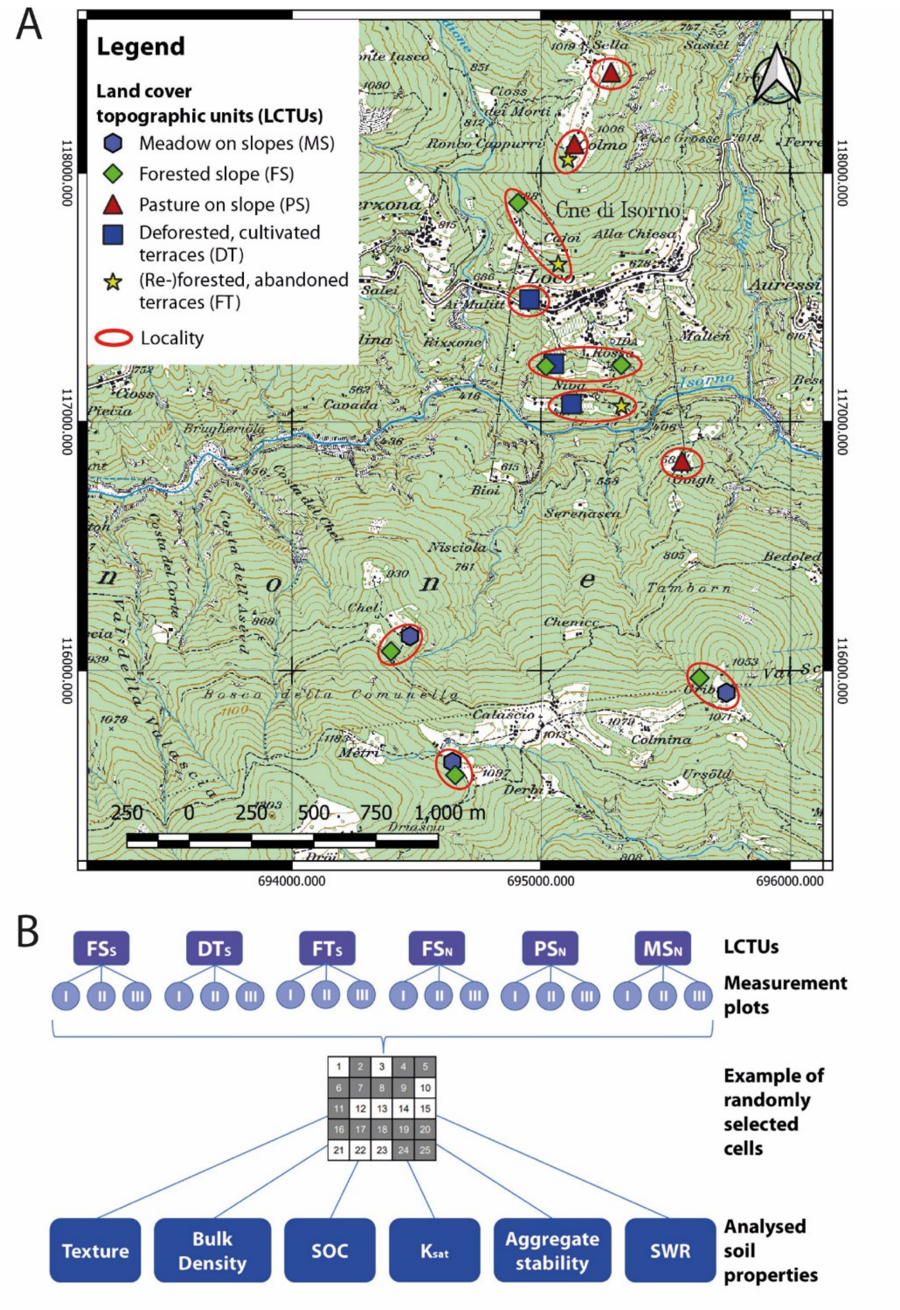

Figure 3. (A) Spatial distribution of LCTU-locations based on Swiss map raster 10 (© swisstopo, reference system CH1903 / LV03 EPSG: 21781), (B) sampling design adopted for the measurement of the soil properties.

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 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 random and fixed effect, 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 (Figure),

(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, pairwise comparisons between the LCTUs were conducted for each key soil property for the fixed effect of land use as predicted by the LMM.

In order to identify linear correlations of the physical and chemical properties among LCTUs, a Spearman correlation matrix was created reporting the coefficients and the p-values for the correlation tests.

3. Results

Table 1 gives a descriptive overview on the results obtained for the five analysed soil physical and chemical key properties of the soil landscape sensitivity, whereas 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).

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.

3.1 Soil texture

Figure 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 less than 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).

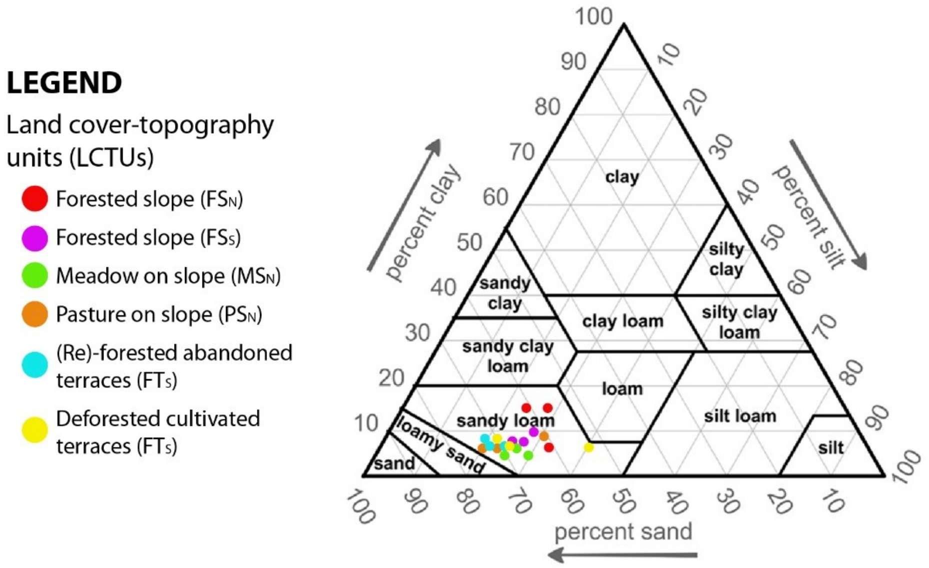

Figure 4. Texture and grain size composition of each LCTU plot reported on ternary diagram with the USDA-based soil texture classes.

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**Errore. L'origine riferimento non è stata trovata.**), but only for two LCTUs (see Figure 5). No significant difference in bulk density emerged among cultivated (DTS), abandoned (FTS) terraces and south-facing forests (FSS), as well as among north-facing forests (FSN), meadows (MSN) and pastures (PSN). In contrast, cultivated and abandoned terraces have significantly higher bulk densities compared to north-facing forests, meadows, and pastures. Furthermore, south-facing forests showed significantly higher values than north-facing forests, meadows, and pastures (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), suggesting that the variability of bulk density among measurement plots within the replicate sites is negligible with respect to the variability among sites.

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 north-facing forests (FS_N) with values > 100 g/kg. Instead, cultivated terraces (DT_S) are characterized by the lowest values amounting to 60 g/kg. The results from the linear mixed models (LMM) confirmed these observations indicating a highly significant effect of the different LCTUs on the amount of SOC. In detail, cultivated (DT_S) and abandoned (FT_S) terraces 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 official 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 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 meadow (MS_N) and pasture (PS_N), in both 16 and 23 cm soil depth (Figure 5). Regarding K_{sat} in 16 cm, no significant difference was detected among cultivated and abandoned terraces, as well as north- and south-facing forested slopes. Nonetheless, all these LCTUs are significantly higher than pastures and meadows (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 meadows, pastures and cultivated terraces, 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, σ²loc 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 σ²plot were 12.3% and 15.7%.

We used the mean K_{sat} as a proxy for infiltration and compared it with the precipitation intensity of the study area in order to assess the potential of surface runoff generation. 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 pastures generate a potential surface runoff of 7 mm/h, (iii) for a 20-years return period (75 mm/h), pastures and abandoned terraces generate a potential surface runoff of 22 and 4 mm/h, (iv) for a 50-years return period (90 mm/h), pastures, abandoned terraces, south-facing forests and meadows generate a potential surface runoff of 37, 19, 9 and 3 mm/h (v) cultivated terraces 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) north-facing forests 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 (Figure 5, see Appendix A, Table A.1). We found a significant variability of aggregate stability among localities (σ²loc) 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 σ²plot 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.

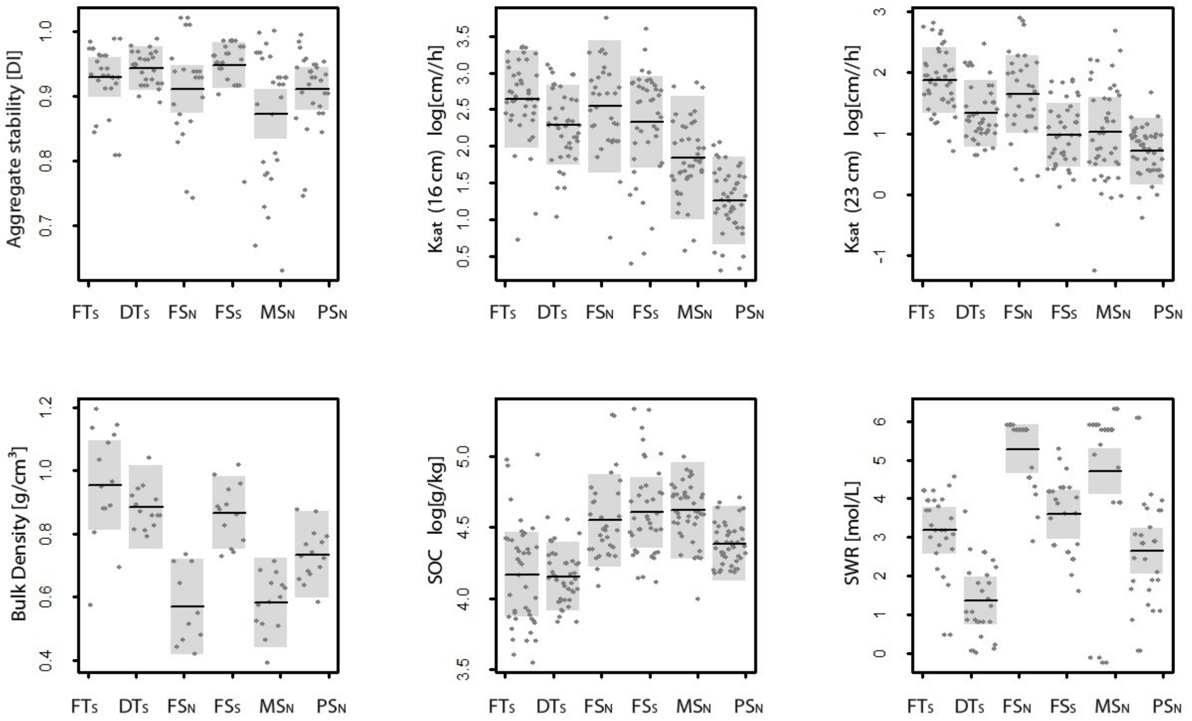

Figure 5. Linear mixed model (LMM) of the different soil properties.

3.6 Soil Water Repellence

Soil water repellence (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 cultivated terraces which is classified as moderate according to the classification of King (1981). SWR significantly varies among LCTUs (see Appendix A, Table A.1), distinguishing three main groups. Cultivated terraces showed the lowest values of SWR (Figure 5), which was significantly lower than in all other LCTUs. SWR in abandoned terraces, south-facing forests (FSs) and pastures (PS_N) did not significantly differ and are characterized by intermediate values (Figure 5). Finally, the highest values of SWR were obtained on north-facing forests and meadows, which were significantly higher than values recorded on abandoned terraces, south-facing forests, and pastures (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 (σ²loc) as well as at plot level (σ²plot) is negligible with respect to the land use-induced variability.

3.7 Linear correlation matrix

As illustrated in Table 2, aggregate stability shows a significant weak correlation only with soil organic carbon. Saturated hydraulic conductivity has a moderate correlation between the two measurement depths as well as weak correlation with soil water repellence, while bulk density is moderately negatively related with soil organic carbon. Finally, soil organic carbon shows a weak correlation with soil water repellence.

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.

Table 2. Matrix of the linear correlation among the physical and chemical properties of the soil.

	Aggregate stability	**K_{sat} (16 cm)**	**K_{sat} (23 cm)**	**Bulk density**	**Soil Organic carbon**	**Soil water repellence**
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**	---
Soil Organic carbon	**0.001**	0.255	0.353	**<0.001**		**0.371**
Soil water repellence	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 same samples.

4. Discussion

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

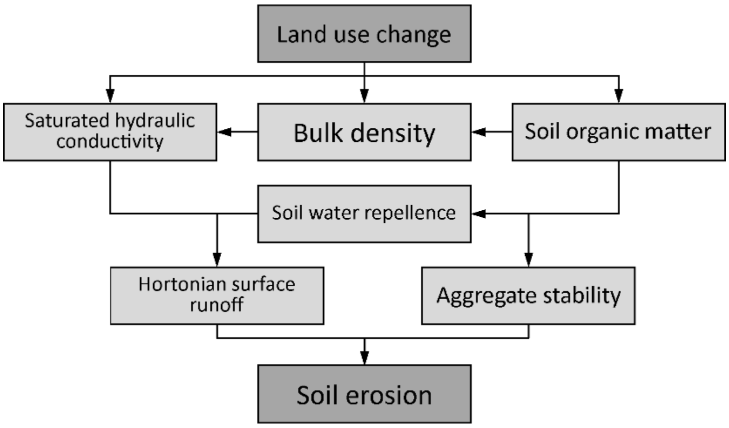

Figure 6. Specific interdependencies between land use changes, soil properties and soil erosion in the Onsernone valley. Arrows indicate the direction of influence.

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 amongst 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 saturated hydraulic conductivity (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, soil water repellence (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 (PS_N) (see Figure 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 Moraes (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 (PS_N) into meadows (MS_N). 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 show a bulk density that is significantly higher with respect to the north-facing forest (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 soil organic matter (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 was 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. 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 soil organic matter (SOM) (Haynes and Swift, 1990; Le Bissonnais and Arrouays, 1997; Smith et al., 2015), so that, irrespective of different amounts of SOC 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, soil water repellence (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 Linear Mixed Models are significant and not the random effects. Those 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. 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 SOM 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. This can only partly be explained by the amount of SOC. It is assumed that composition and quality of SOM are influencing SWR as previously identified in other studies (Doerr et al., 2000; Fu et al., 2021; Lozano et al., 2013).

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. It was found that natural forested slopes show a low susceptibility to produce Hortonian surface runoff confirming the stability of the soil landscape. In contrast, for land use changes to pastures, cultivated terraces and abandoned terraces, the susceptibility to runoff generation significantly increased. 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.

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Chapter 4: Surface runoff and soil erosion (Paper 3)

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

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. The results show a statistically significant increase in surface runoff when the soil gets water repellent and reduces the surface infiltration capacity 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 agricultural terraces. Finally, the abandonment and progressive collapse of terrace walls locally increases 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 resources (Bayramin et al., 2008). Accordingly Panagos et al. (2015) calculated, soil loss rates of more than 5 t ha^{-1} yr^{-1} in the Alps. 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 (Bettoni et al., 2022) concern saturated hydraulic conductivity, aggregate stability (Cantón et al., 2009; Cerdà, 1998) and soil water repellence (Doerr et al., 2003; Lemmnitz et al., 2008; Miyata et al., 2007). Saturated hydraulic conductivity (K_{sat}) is generally higher e.g. in forests where tree roots favour the generation of macropores or where the presence of stable aggregates promote the presence of preferential flow paths (Toohey et al., 2018). In contrast, other land uses such as pasture are characterized by lower K_{sat} values due to compaction and reduction of macropores (Elsenbeer et al., 1999; Głąb et al., 2009). 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 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 organic matter (Doerr et al., 2000; Fu et al., 2021; Lozano et al., 2013) eventually impact the soil water repellence, which may have a large effect on water infiltration 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 (Bettoni et al., 2022). For instance, relating the saturated hydraulic conductivity (K_{sat}) to the precipitation intensity and using it as a proxy of the soil's infiltration capacity do not allow for a proper representation of the natural surface conditions and related infiltration processes. Limiting the K_{sat} measurement at a soil depth of 15 cm and under saturated hydraulic conditions may not be representative for the actual soil moisture conditions (Bettoni et al., 2022). In addition, some soil types such as sandy ones with high SWR are difficult to wet, which results in very low infiltration rates (Wang et al. 2000). Finally, other factors affecting surface runoff generation are usually overlooked, such as vegetation cover, rainfall characteristics, topography, and land management (Buda, 2013; Debolini et al., 2015; Dunne, 1978).

The overall aim of this study is to verify how land use changes may affect surface runoff, soil erosion, and sediment transport and eventually influence the soil landscape sensitivity of a southern Alpine valley. For this purpose, we conducted surface runoff and soil erosion measurements on sites characterized by different land use - topography settings and under controlled and reproducible precipitation conditions using a portable automated rainfall simulator (PARS).

2 Material and methods

2.1 Study Area

The study area extends over an area of approximately 6 km^2 in the Onsernone Valley (Canton Ticino, Southern Switzerland; Figure 1) at altitudes ranging 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 2000 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 (MeteoSwiss, 2020).

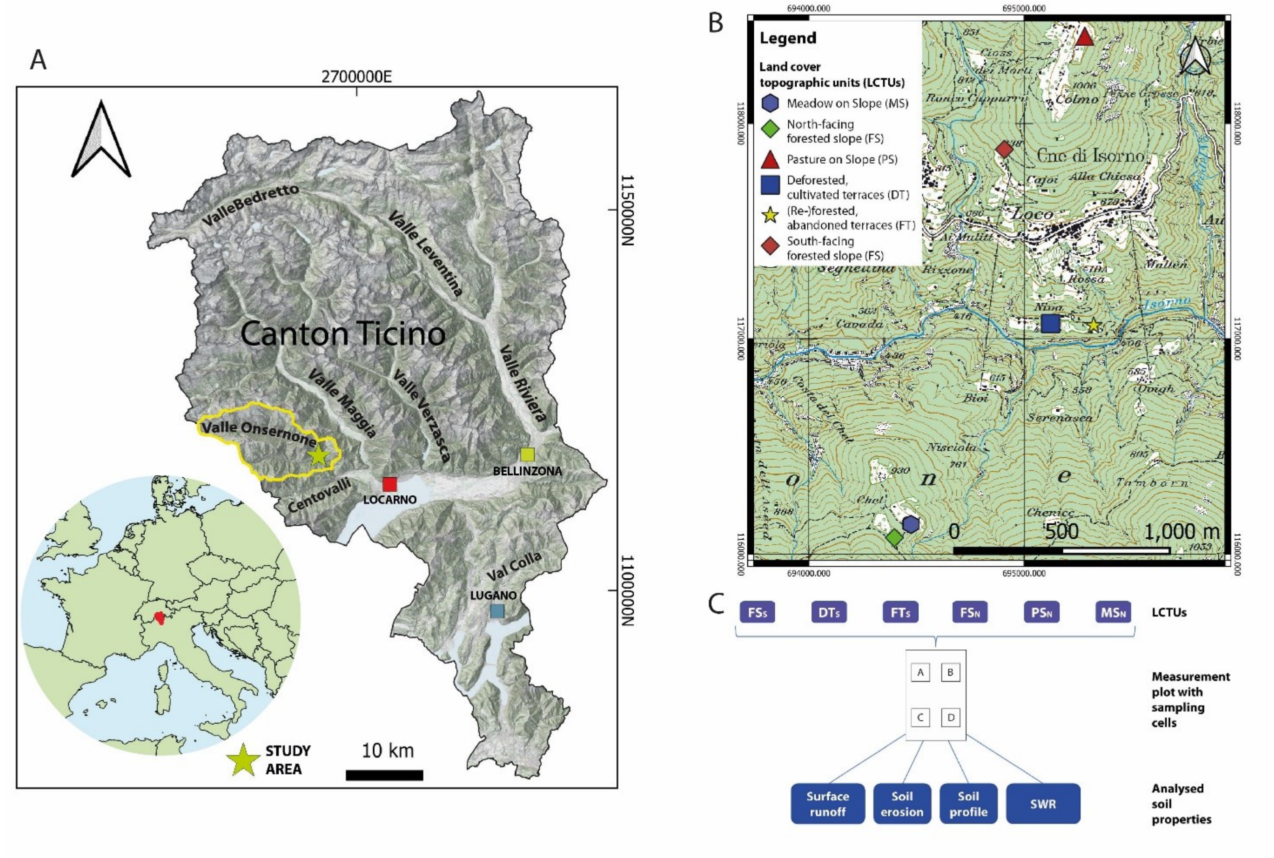


Figure 1. A: Map of Canton Ticino with the location of the study area (Federal Office of Topography, swisstopo). Obtained from Bettoni et al. (2022), B: Land cover-topographic units (LCTUs). Based on Swiss Map Raster 10 (Federal office of Topography, Swisstopo) SR: CH1903/LV03, C: Study design of the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

The valley is E-W oriented with morphological evidences 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 (Figure 2a, d, e). The valley presents a typical V-shaped profile indicating fluvial processes as dominant during morphogenesis (Figure 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 evidences are related to the slope evolution showing deposits associated to debris flows as well as rockfalls (Figure 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 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). In particular, Podzols are characterized by a thick topsoil A horizon, rich in soil organic matter (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 the development of 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 glutionosa* (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). The land use and the related vegetation cover interact with the soils modifying the acidification and the podzolisation processes (Vogel, 2005; Vogel and Conedera, 2020). As a result, Cryptopodzols are prevalent under forest vegetation, while Cambisols are found on deforested sites.

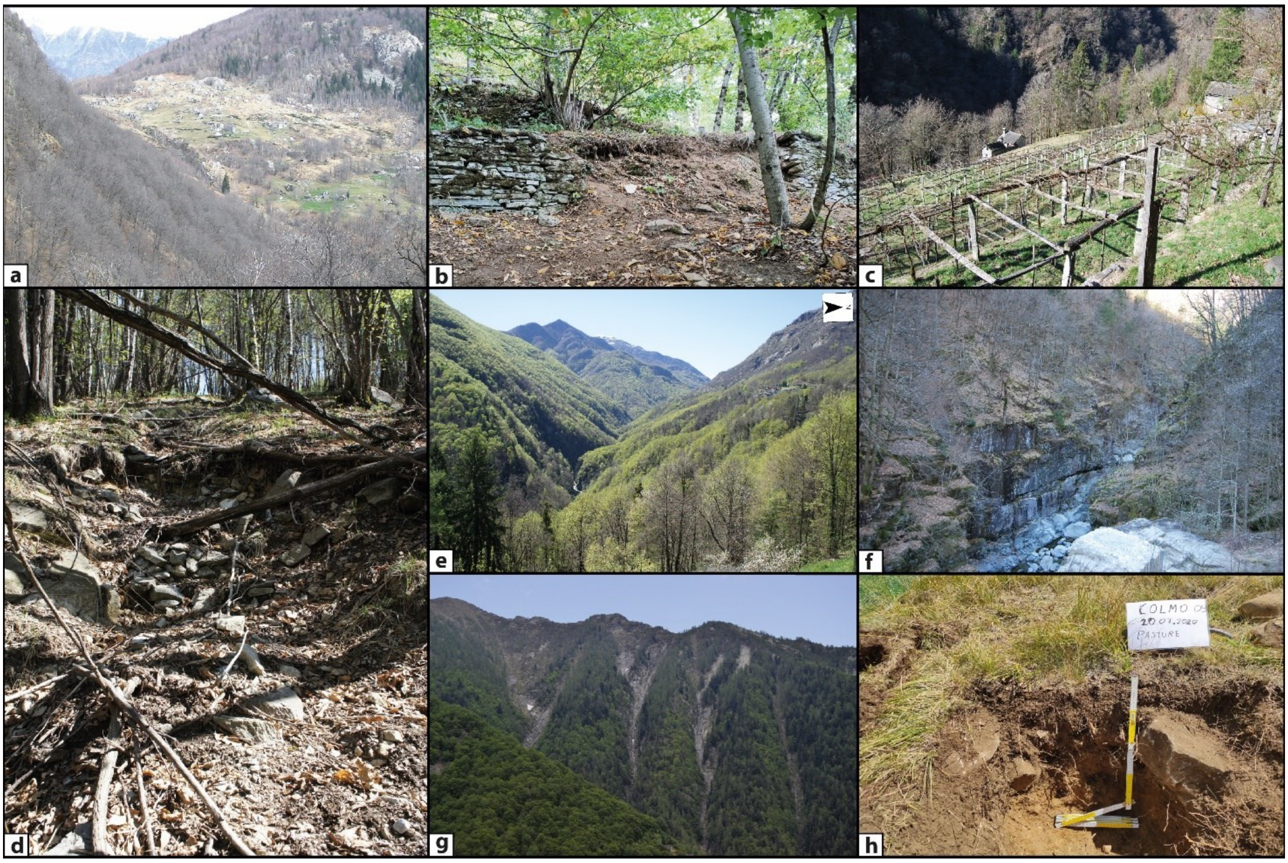


Figure 2. Field evidence in the area: a) transfluence pass b) abandoned agricultural terraces. c) vineyard on the still used terraces. d) debris flow channel and associated deposits e) V-shaped Onsernone valley. f) Isorno stream flowing in the bedrock bed. g) Couloir with debris discharge. h) glacial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

2.2 Land use history

The Onsernone valley is characterized by a long history of land use starting from Roman times (Crivelli, 1943) and intensifying during the Middle Ages. The absence of a recent valley floor leads to a deforestation of the south-facing slopes and a strong anthropic reshaping of the valley related to the construction of agricultural terraces increasing 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 settlements and have been mostly exploited by intense silviculture. In areas of lower steepness, pastoral farming was established.

Starting with the cessation of straw plaiting at the end of the first world war and with the decline of the traditional, marginal Alpine farming in the 1950s, a successive abandonment of land use is documented, which resulted in a progressive reforestation of formerly used sites. As a consequence, nowadays the man-made terraces are poorly maintained and only partially used as vineyards or orchards (Figure 2b and c). Furthermore, pastoral farming is still 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 the following six land cover-topography units (LCTUs), which are heterogeneously represented on south- and north-facing slopes (see Bettoni et al., 2022, Figure 1B):

(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 x 4 m plot was selected paying attention to keep the range of the slope angles similar for all LCTUs, even though slight differences may exist. At the four corners of every plot, four 1.2 x 1.2 m replicates have been subjected to a rainfall simulation experiment (Figure 1C).

** Due to the progressive abandonment of animal husbandry in the study area as well as accessibility problems with the rainfall simulator no pasture was available on north-facing slopes. Consequently, a study site under active pasture was selected on the south-facing slopes. This is valid because pastures on both slopes are characterized by the same conditions in terms of geology, climate and vegetation, exposition is considered of minor importance for soil physics.*

2.3 Soil property assessment

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

i. Surface runoff and infiltration rate

Surface runoff and soil erosion can be analysed under controlled and reproducible conditions using a portable automated rainfall simulator (PARS) (Rasoulzadeh et al., 2019). Iserloh et al. (2013) compared 13 different typologies of PARS and stated that rainfall simulators may differ for the area covered during simulation, the adjustable intensity of precipitation, the dimension of rain drops 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., 2013). PARS allow 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, or soil moisture (Bowyer-Bower and Burt, 1989; Iserloh et al., 2013).

In this study to determine surface runoff generation and soil erosion, sprinkling experiments were carried out using an portable automated rainfall simulator (PARS) (Ritschard, 2000) (Figure 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 x 90 cm plate producing the raindrops. The sprinkling plate is moved by an electric motor and two inversion spindles moving horizontally in perpendicular directions and 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 by a flow meter to up to 60 mm/h. 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 in order to standardize the measurement units to be consistent with the precipitation intensity. Every 5 minutes, 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 in order to obtain constant runoff values. Four replicates were conducted on each of the six LCTUs.

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 minutes 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 in order 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 x 4 replicates and 2x4 replicates of forests slopes without litter) in dry conditions and 32 in moist conditions.

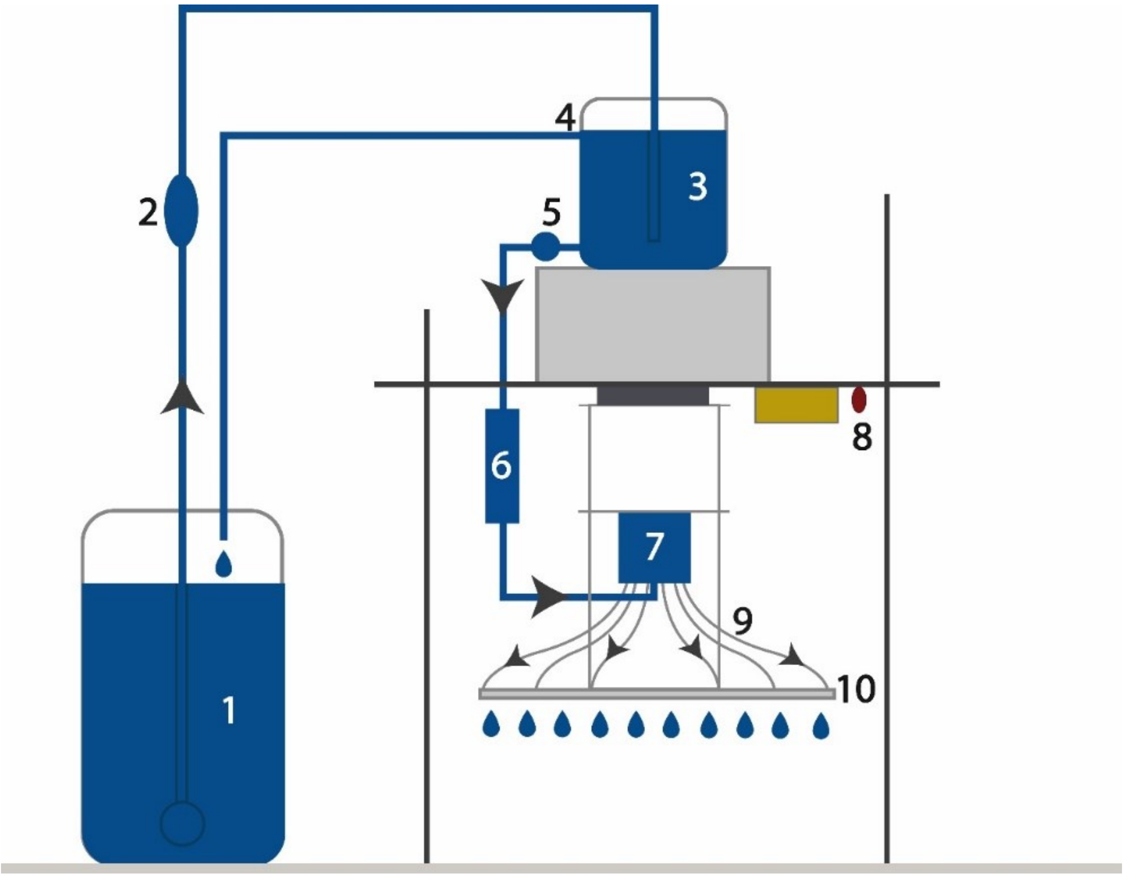


Figure 3. Schematic representation of the rainfall simulator. 1: water tank, 2: water pump, 3: second water tank, 4: overflow drain, 5: water flow regulator, 6 flow meter in cl/min, 7: plexiglass cylinder, 8: regulator of velocity of horizontal movement, 9: connecting pipes to metal plates, 10: metal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

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

$$\mathrm{RLF:}\ \frac{q_{pk}}{t_{pk}} \times \frac{t_{rg}}{t_{pk}} \qquad \textit{(Equation 1)}$$

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 (Figure 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):

$$\mathrm{FLF:}\ \frac{q_{pk}-q_e}{t_e - t_{pk}} \times \frac{t/2\ - t_{pk}}{t_e - t_{pk}} \qquad \textit{(Equation 2)}$$

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.

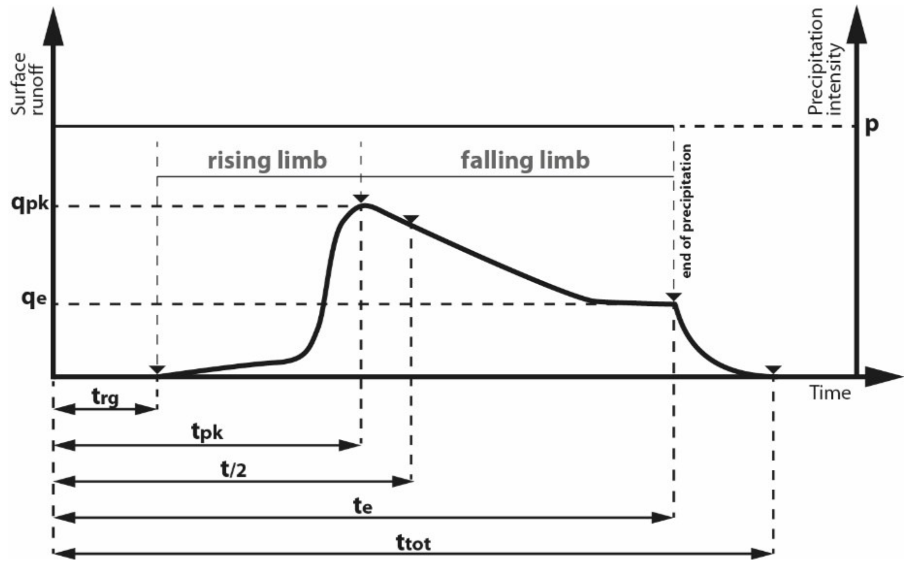


Figure 4. Example of a Hydrograph of surface runoff during a rainfall simulation. qpk: surface runoff peak, trg: time for surface runoff genesis, tpk: time for surface runoff peak. trg: time runoff generation, tpk: time of the peak, t/2: half of the total time of the measurement period, te: time of the end of simulated precipitation, ttot: total time of the measurement period, p: amount of precipitation expressed in mm/hour, qpk: surface runoff intensity of the peak expressed in mm/hour, qe: surface runoff intensity at the end of simulated precipitation expressed in mm/h. Adapted from Ritschard (2000).

ii. Soil water repellence (SWR):

The effective SWR was assessed for each measurement plot in the field using the molarity of ethanol droplet (MED) test (Roy and McGill, 2002). Samples of the uppermost mineral soil horizon were collected and directly measured in the field. 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 seconds time is reported as result in molarity units. Soil water repellence was classified using a scale proposed by King (1981): slight (MED ≤ 1.0 M), moderate (1.0 M < MED < 2.2 M) and severe (MED ≥ 2.2 M) water repellence.

iii. Sediment transport

Using the one-minute surface runoff collected in sampling bottles every 5 minutes 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 the temperature of 70 °C for 24 hours. When 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 liter 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 minutes of surface runoff were calculated.

iv. 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 such as:

i. soil horizon thickness,

ii. soil texture of each soil horizon using lab analysis following the ASTM Standard (American Society for Testing Materials, 1988),

iii. percentage of rock fragments and artefacts (>2 mm) present in each horizon,

iv. soil colour code of each horizon using Munsell colour chart (Munsell Color (Firm), 2010),

v. carbonate content using HCl acid,

vi. field soil pH measured with a portable pH meter,

vii. soil structure types, and

viii. presence and number of roots in a sampling window on 10 square centimetres on each soil horizon.

2.4 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 since the length of notches are indicating 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.

3 Results

3.1 Soil profile description

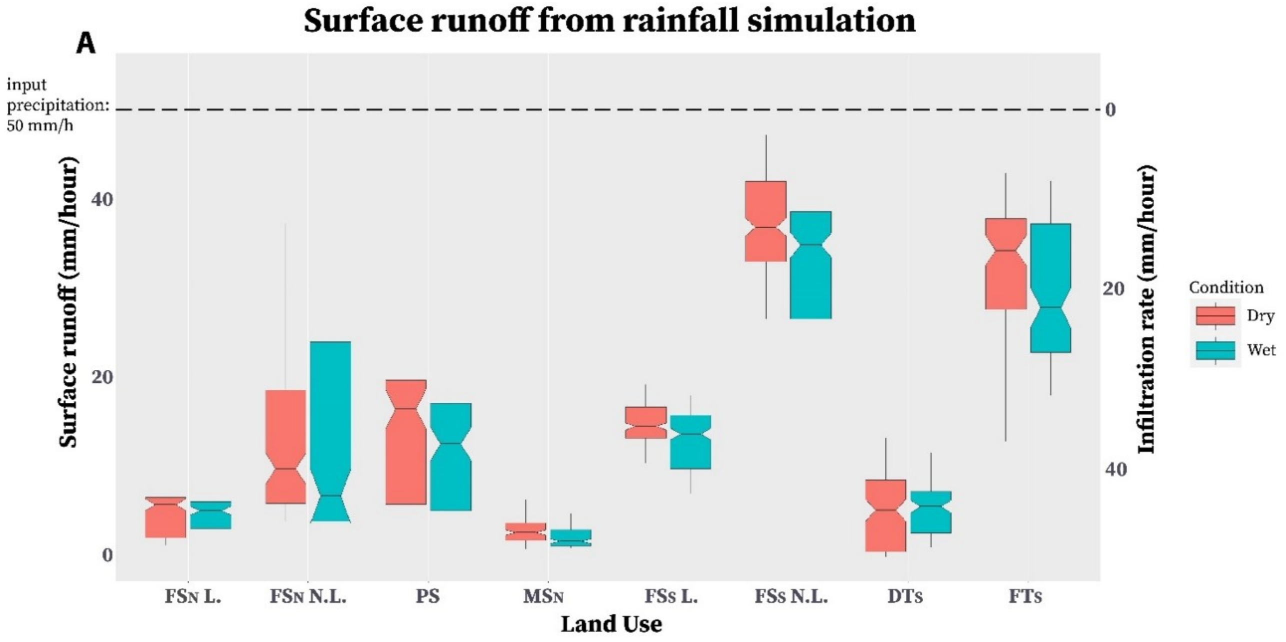
The six soil profiles ranged in depth from 42 cm (FS_S) to 121 cm (FS_N). All soil profiles were characterized by gneiss parent material resulting in high fractions of soil skeleton for most profiles showing boulders and blocks of different dimensions. The skeleton is ranging from a minimum of 2% to a maximum of 30% and is mainly composed by gneissic rock. The soil texture measured by lab analysis was mainly sandy loam following the USDA classes (see Bettoni et al., 2022). However, there are a few exceptions il all LCTUs that are falling in the sand-, loamy sand-, sandy clay- and sandy clay loam-classes. The colour of the horizons is always in the yellow-red (YR) classes with hues ranging from 5YR to 10YR. 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 and a thickness ranging from 5 to 17 cm. Topsoil horizons rich on soil organic matter (SOM) show a granular structure, whereas subsoil horizons reveal a subangular or angular structure.

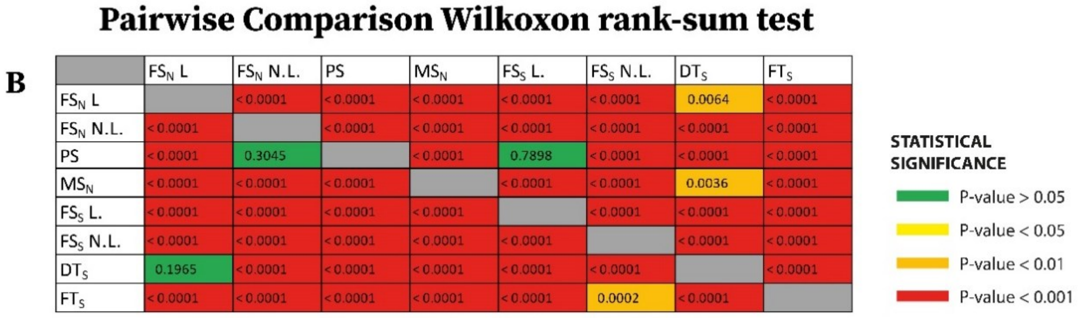
3.2 Surface runoff and infiltration rate

Figure 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 in the forested slopes) under dry and moist conditions.

There are statistically significant differences in surface runoff and infiltration rate between the different LCTUs (Figure 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 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 general lower surface runoff in dry conditions was detected in all LCTUs except for the deforested, cultivated terraces (DT_S). However, the lower values are statistically significant for abandoned terraces (FT_S) and meadows (MS_N) only. Furthermore, on forested slopes, surface runoff has always significantly increased after removal of the organic litter layer, especially on south-facing forests.





	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	

Figure 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. FSN L.: north-facing forested slope with litter layer, FSN N.L.: north-facing forested slope without litter layer, FSS L.: south-facing forested slope with litter layer, FSS N.L.: south-facing forested slope without litter layer, DTS: Deforested cultivated terraces, FTS: re-forested abandoned terraces, PS: pasture on slope, MSN: meadow on slope.

The analysis of the rising limb factor shows lower mean values for dry conditions in all LCTUs except for abandoned terraces (FT$_S$), which are characterized by lower values in the dry setting (Table 1). 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- (FS$_N$) and south-facing forests (FS$_S$) without litter and only a slight higher value on abandoned terraces (FT$_S$).

Table 1. 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

The soil moisture measurements before and after the sprinkling experiments showed no significant difference for most LCTUs (Table 1), except for meadows (MS$_N$) and deforested terraces (DT$_S$), 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 1) was lowest on meadows (MS_N) and cultivated terraces (DT_S) showing 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 (FT_S) with 3 mol/L, pasture (PS) with 4.2 mol/L and north- (FS_N) and south-facing (FS_S) 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 1) never exceeded 0.4 g/L with average values between 0 and 0.2 g/L. The only exception is given by abandoned terraces (FT_S) where maximum values of 5.5 g/L and average values of 2.5 g/L under dry conditions were measured, and maximum values of 3.4 g/L and average values of 1.4 g/L were reached under moist conditions.

4 Discussion

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

4.1 North-facing slope

4.1.1 Forested slope (FS_N)

In the forested north-facing slopes (FS_N), the anthropogenic disturbances have been negligible at least over the last decades, allowing us to consider this LCTU as a kind of 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 cavities and 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 the infiltration rate using the saturated hydraulic conductivity (K_{sat}) as a proxy (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 that 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 volume of the soil 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 high stability of the soil landscape in general.

4.1.2 Pasture on slope (PS_N)

According to the above-mentioned land use change scenarios during the first intensive cultivation phase, the FS_N were partly converted to pastures (PS_N) (see Bettoni et al., 2022). The significant increase in surface runoff induced by such a conversion may be the result of a 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. 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. However, in the particular case of PS, differences exist between SWR measurements in the lab (lower values reported by Bettoni et al. 2022) and in the field (higher values), which may result from pre-treating and air-drying of the samples in the lab. The analysis of the wetting front through TDR measurements showed difficulties in wetting the soil. Hence, the increase in soil moisture never exceed 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 layer (Ritsema et al., 1993; Ritsema and Dekker, 1995; Wang et al., 2000). However, the increase in surface runoff did also 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.

4.1.3 Meadow on slope (MS_N)

The second land use change on north-facing slopes corresponds to the extensification phase caused by the conversion from pasture (PS_N) to meadow (MS_N). 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 caused the increase in the 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. However, it must be considered that this is lower than the potential infiltration capacity obtained using 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 ones of 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 the previous LCTUs (i.e., FS_S and PS). This might be an evidence of a more regular matrix flow within the soil with less influence by preferential flow paths. In turn, it implies a fast 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 is more important than K_{sat} as triggering factor in surface runoff generation dynamics displaying higher values in forests and lower ones on meadows. Finally, meadows also showed a very low sediment transport, highlighting a high stability of MS_N favoured by very low surface runoff and by the dense grass cover that reduces the speed and energy of the water favouring infiltration and limiting the erosive power of surface runoff.

4.2 South-facing slope

4.2.1 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 the slight differences in the slope angles (30° on FS_S and 22° on FS_N) should be also considered. Another reason for higher surface runoff and erosion on FS_S compared to FS_N may be the lower K_{sat} and higher bulk density on FS_S (see Bettoni et al. 2022), which results in lower infiltration rates. This may be explained by the higher soil compaction due to a more intense use of the areas surrounding the settlements on the south-facing slopes. Analysing the rising limb factor, slightly higher values have been registered in $\mathrm{FS_S}$ with respect to $\mathrm{FS_N}$ with litter, although 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 $\mathrm{FS_S}$ without litter. Having a closer look to the vertical wetting dynamics through TDR measurements, a certain delay in the progress of the wetting front for FSs was identified. As mentioned above, this is explained by the genesis of preferential flow paths favouring drainage and maintaining most of the soil profile dry (Ritsema et al., 1993; Ritsema and Dekker, 1995; Wang et al., 2000). Finally, sediment transport by soil erosion is very low highlighting a high stability of $\mathrm{FS_S}$.

4.2.2 Deforested cultivated terrace ($\mathrm{DT_S}$)

During the intensive cultivation phase, south-facing forests ($\mathrm{FS_S}$) were cleared, and slopes were terraced ($\mathrm{DT_S}$) e. This resulted in significantly lower amounts of surface runoff (i.e., 64.2%). This decrease is partially explained by the lower SWR, which switches from severe to moderate values 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 highly 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, which results in a reduced speed and energy of the water flow and higher infiltration rates of 90% (44.8 out of 50 mm/hour). Analysing the rising limb factor of DTs, values similar to PS and higher than $\mathrm{FS_S}$ were obtained, considering that the median surface runoff decreased with respect to $\mathrm{FS_S}$ and PS. The latter is an evidence that $\mathrm{DT_S}$ is quickly reaching its peak surface runoff that in any case has values lower than $\mathrm{FS_S}$ and PS. In contrast, the falling limb factor shows similar values like PS. 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.

4.2.3 (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 (i.e., 15.7 mm/hour in average) with respect to the potential infiltration capacity measured using K_{sat} (i.e., 71 mm/hour). This results in the highest surface runoff values of all LCTUs excluding FS_S without litter, which is however 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 from 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 is lower than on 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 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, and finally strongly increasing 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 situation of the wetting front with an increase in the topsoil moisture of about 5%.

4.3 Synthesis of LCTU characteristics and related dynamics

The present study clearly shows that surface runoff generation in the Onsernone valley is land use-specific (Figure 5). 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 compared to moist conditions except for FT_S. This behaviour may be explained by the SWR characteristics of the soils. Where SWR is high, under dry conditions, the rain drops fall on a semi-impermeable surface favouring a faster generation of surface runoff (Miyata et al., 2007; Ritsema and Dekker, 1994; Witter et al., 1991). In contrast, under moist conditions infiltration increases and the runoff decreases and peaks 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. However, 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 the cavities 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.

It was demonstrated 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. In fact, other soil properties, in our case especially soil water repellence, 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. In fact, 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 paths through unsaturated layers that are bypassed and leaving most of the topsoil layer dry.

SWR is depending on soil organic content and composition but also on the meteorological conditions and hence soil moisture. As documented by MeteoSwiss (2022), especially in the last years there have been exceptionally dry periods, which is in line with the result of Emeis (2021) who showed in the last century a slight increase in the number of dry days in the Alps. 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 might lead to extended water repellent soil conditions.

5 Conclusion

Due to own previous investigations of chemical and physical key soil properties (i.e., very high soil organic 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 abandoned terraces (FT_S). Although, high surface runoff can lead to soil loss as a result of soil erosion, in the Onsernone valley, the different LCTUs show very low soil erosion rates indicating a high stability of the soil landscape. Even though, 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 is (re-)forested abandoned terraces (FT_S) where erosion and hence, sediment transport was significantly increased by one order of magnitude, especially in areas where terrace walls collapsed, and bare soil was exposed. This is the result of lacking terrace maintenance and the regrowth of trees leading to partial collapses of terrace walls and a local increase of the slope steepness. Moreover, the collapse leads to the exposure of bare soil that is in turn subject to the action of atmospheric agents without any protection, thus, facilitating surface runoff and soil erosion leading to a loss of precious and limited soil resources especially in this alpine environment. Consequently, abandoned terraces have to be considered as instable soil landscapes, which is a serious problem due to the enormous spatial extent of terraces in the Onsernone valley. To avoid or mitigate this situation, terrace walls should be maintained limiting the potential of collapses and terraces should be covered by a dense vegetation, thus, providing a natural protection from soil erosion.

Our experiment reveals that surface runoff is higher at higher SWR, which may also increase soil erosion susceptibility especially during exceptional precipitation events. This becomes relevant since 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 5 years return period to assess surface runoff dynamics. As stated above it is very likely that in future the thresholds of these return periods might be higher leading to a change in surface runoff characteristics and soil landscape sensitivities. Thus, the base for planning and dimensioning of measures to cope and fight effects of heavy rainfall events should be adopted in future starting with the most sensitive soil landscape entities. Our study gives clear hints where already today the soil landscape is affected or sensitive like the abandoned terraces. Moreover, we have shown that also properties like SWR must be taken into consideration. The latter are still poorly understood in terms of their dynamics. Hence, taking into account less snow cover and longer dry periods changes in SWR dynamics may become more important. Concluding, we can state that PARS simulations with all their limitations as reported above yield valuable information where in our soil landscapes we should be careful and may implement prevention, coping or mitigation strategies.

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General results and discussion

This thesis is focusing on the definition, identification, assessment, and quantification of the sensitivity of soil landscapes in the Onsernone valley (Canton Ticino, Switzerland) which was identified as being representative for the larger southern-western Swiss alpine valley areas. This work contributes to the identification of the current knowledge about stability and sensitivity on a landscape scale through the delineation of different connotations used in different scientific sectors that deal with environmental sciences. Through this research we identified the most widely used qualitative and quantitative assessment methods of soil and landscape stability/sensitivity. This research proposes an integrated methodology for the assessment of soil landscape sensitivity in the research area.

Initially, the knowledge about stability and sensitivity at landscape scale was identified through a bibliometric analysis of peer-review articles. As demonstrated by the scientific productivity this field of research has grown exponentially. A detailed review of the scientific articles identified in Brunsden and Thornes (1979) the most impacting paper which is the most cited paper. The authors proposed the following definition of landscape sensitivity: “The sensitivity of a given landscape is expressed as the likelihood that a change in the controls of the system will produce a recognizable and persistent response. The concept involves two aspects: the propensity for change and the capacity of the system to absorb such a change.” We document that this definition does not substantially evolve over time. In contrast, a clear definition of soil and landscape stability was not identified, sometimes is erroneously used as synonyms of landscape sensitivity. Only connotation that are referring to specific research fields were identified.

Regarding the quantification methods 104 research articles were identified who proposed the use of soil properties for quantification, mainly focusing on assessments of aggregate stability using different methods. In other research fields such as in ecology, stability and sensitivity are quantified in different ways, ranging from the chemical soil characteristics to soil properties or landscape properties and even subjective characteristics, such as culture, scenic attractiveness, and visibility. Furthermore, sensitivity and in particular sensitivity to soil erosion is quantified in different ways. In general, historical traditional methods use empirical modelling approaches, such as the Universal Soil Loss Equation (USLE) or derivatives of it to obtain qualitative and quantitative information about landscape sensitivity to soil erosion. Especially during the last years, data that are provided through remote and proximal sensing methodologies, such as multi-spectral data, are also used to identify stable areas.

The study was summarised in the Paper 1 highlighting connotation and quantification methods and emphasizing the necessity to establish international and interdisciplinary research groups to more clearly define the terms and methods used for the assessment of landscape stability and sensitivity.

All the information obtained from the bibliometric analysis yield the foundation to assess in detail landscape sensitivity in the Onsernone valley based on a thorough field survey, lab analysis and related statistical analysis.

The lab analyses conducted with the soil samples taken in the different LCTUs show no difference in aggregate stability 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 soil organic matter (SOM) (Haynes and Swift, 1990; Le Bissonnais and Arrouays, 1997; Smith et al., 2015), so that, irrespective of different amounts of SOC between the different LCTUs, the critical threshold value of SOC content is not reached that might result in a distinct reduction of aggregate stability and hence, higher erodibility of the topsoil. 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; Fultz et al., 2013; Pohl et al., 2009). Especially under forest conditions the really high amount of SOC can be explained by a very slow and fragmentary decomposition of organic material (Guo and Gifford, 2002). A significant reduction was detected only in cultivated and abandoned terraces which 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. In contrast, soil water repellence (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. These land use-induced variations in SWR are only partially explained by the amount of SOC, which is expressed by the low correlation between the two soil properties. This is in contrast to the information we found in literature (e.g. Chaplot and Cooper, 2015; Liu et al., 2005). The results show that a more detailed investigation is required in that context as well as on the effects of SOM quality and composition or anthropogenic disturbances like forest fires on SWR. The latter was not included in this study.

Finally, saturated hydraulic conductivity K_{sat} was used as a proxy for the soil's infiltration capacity and, to estimate surface runoff generation for the single LCTU . We found that natural forested slopes show a low susceptibility to produce Hortonian surface runoff confirming the stability of the soil landscape. In contrast, for land use changes to pastures, cultivated terraces and abandoned terraces, the susceptibility to runoff generation significantly increased. However, this does not take into account other important 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; Lemmnitz et al., 2008;

Miyata et al., 2007). This can lead to great disparities between the effective and the potential infiltration capacity of the soil. To further study and quantify surface runoff generation and soil erosion in the different LCTUs we conducted detailed rainfall simulation experiments that are discussed in Paper 3.

The measurements performed with the portable automated rainfall simulation (PARS) provide interesting results. In fact, although high surface runoff can lead to soil loss due to soil erosion, in the Onsernone valley, the different LCTUs show a very high stability of the soil landscape. Even though key soil properties are affected by land use changes soil erosion is almost negligible or at least very limited. The only exception is (re-) forested abandoned terraces (FTs) where sediment transport and hence, erosion is quite high, especially in areas where terrace walls collapsed, and the bare soil is exposed. However, this is a serious problem due to the enormous spatial extent of terraces in the Onsernone valley. Only a proper maintenance of terrace walls might reduce this problematic situation. As demonstrated by Arnáez et al. (2015), soil erosion is directly proportional to the amount of vegetation cover, therefore, the development of vegetation leads to covered bare soils that in turn lead to a reduction of soil erosion phenomena. Our study shows that the Onsernone Valley is characterized by a very high stability among all LCTUs. However, in contrast to what was evidenced by Paper 2, we point out the abandoned terraces (FTs) that are not considered stable and hence yield high amounts of surface runoff with the related soil erosion phenomena.

Taking into account the projection of the spatio-temporal precipitation pattern proposed by Jacob et al. (2014) which predict a reduction in the precipitation of about 15% in southern Europe but an increase of heavy rainfall events our study very likely be subject to an increase in extreme events that might result in an increase of surface runoff especially on abandoned terraces with the related soil erosion phenomena. We observed such an extreme event just recently on 2-3 October 2020 where 372.5 mm in one day were registered.

In this study area, most of the LCTUs are stable and seem to be not sensitive to land use change. Hence, an increase in extreme rainfall events might not lead to a significant increase in soil erosion as demonstrated by the 2-3 October 2020 event where after an inspection we found no significant evidences of severe damages due to soil erosion phenomena. However, we identified the abandoned terraces as highly sensitive in case of extreme events favoured by an increase in the number of collapses exposing bare soil and increasing slope gradients. Consequently, strategies should be developed to maintain or protect the terraces to reduce their susceptibility towards soil erosion.

Conclusion

This study proposes an innovative and integrated methodology for the assessment of soil landscape sensitivity in alpine environments, including a detailed bibliometric analysis, field survey activities and advanced statistical analysis.

From the bibliometric analysis the main remarks are the following:

- The analysis of the publication trends shows that the number of relevant, peer-reviewed papers is undergoing exponential growth.
- The most popular definition of “landscape sensitivity” was established by Brunsden and Thornes (1979). Those authors applied the term to geomorphological environments. It did not underwent substantial evolution over time. In fact, this is the most widely used definition. In contrast, there is not a clear definition of “landscape stability”, that is often used as synonymous of “sensitivity”.
- A large number of methods were identified for the assessment of soil and landscape stability and sensitivity; however, it was not possible to identify a universal method due to the specific characteristics of each study area and the individual focus of each paper. Quantification methods are ranging from (i) the analyses of individual soil physical and chemical properties (i.e., aggregate stability, cation exchange capacity, etc.), (ii) the analyses of intangible properties (culture, scenic attractiveness and visibility) and (iii) the analyses of land use change, susceptibility to erosion, etc.

From the analysis of aggregate stability, which is commonly used for detecting land use-induced changes in soil erosion susceptibility, we obtained very high values irrespective of the LCTU. This is caused by very high amounts of SOC. 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 more sensitive towards land use changes.

Soil water repellence has the most significant effect on surface runoff. Particularly, severe soil water repellence reduces the surface infiltration capacity favouring surface runoff and the generation of preferential paths through unsaturated layers that are bypassed, leaving the topsoil layer almost dry.

If we consider only the selected key soil properties it turned out that the Onsernone valley and the six selected LCTUs represent a stable environment that is quite insensitive to land use changes, nonetheless the fact that SWR is quite sensitive to land use change. However, to confirm the hypothesized stability of the soil landscape also the processes and dynamic related to the soil properties should be taken into account. Therefore, PARS experiments were carried out, revealing a significant variability in surface runoff and hence, a certain sensitivity to land use change. For the applied precipitation corresponding to 5 years return period, generally almost no sediments were detached and transported except for abandoned terraces showing high values of sediment transport. The latter is a consequence of the abandonment of the terraces. The lacking terrace maintenance and the regrowth of trees leads to partial collapses of terrace walls and a local increase of the slope steepness. Moreover, the collapse leads to the exposure of bare soil that is in turn subject to the action of atmospheric agents without any protection, thus, facilitating surface runoff and soil erosion leading to a loss of precious and limited soil resources especially in this alpine environment. This is a serious problem due to the enormous spatial extent of terraces in the Onsernone valley. To avoid or mitigate this situation, terrace walls should be maintained limiting the potential of collapses and terraces should be covered by a dense vegetation, thus, providing a natural protection from soil erosion.

In conclusion, the study area shows a general high stability irrespective to land use change concerning key soil properties, surface runoff and soil erosion for the chosen precipitation magnitude of 50mm/h. The only exception are FTs which seem to be more susceptible to surface runoff and related soil erosion processes.

Outlook

The proposed methodology that was applied in Onsernone valley should be tested also in other areas to further generalize and validate the obtained results for the larger southern alpine environment.

Furthermore, from the analysis carried out in Onsernone valley, interesting result were obtained concerning soil water repellence, this key soil property is the most sensitive to land use change and seems to be one of the triggering factors concerning surface runoff dynamics. As demonstrated in literature (see Paper 2) SWR is not only influenced by the quantity but also by the quality and composition of soil organic matter as well as by the meteorological conditions and hence soil moisture. Consequently, more detailed studies should be carried out regarding soil organic matter which may also include analysis of micro and mesofauna present in the soils. Moreover, SWR is still poorly understood in terms of its temporal dynamics. Hence, taking into account less snow cover and longer dry periods as reported in literature, changes in SWR dynamics may become more important.

Another feature observed during the field campaigns, especially in the most water repellent soils is the heterogeneous wetting of the soil profile. The latter might be based on the generation of preferential flow paths through the unsaturated layer which bypass most of the volume. This behaviour is favouring the drainage of the soil and maintaining dry most of the soil profile. To proof this hypothesis further rainfall simulations are required combined with tracer analysis (brilliant blue).

Moreover, a precious support might be gained by the analysis of remote sensing data.

Additional detailed spatio-temporal information with sufficient detail can be acquired such as snow cover dynamics that play an important role in the slow release of water in spring maintaining the soil wet and less water repellent. The main advantage of remote sensing approaches is that these methodologies are recursive, favouring the collection of time series and allowing the observation of the evolution over time, on very large areas that can hardly be analysed through data obtained from field observation.

Finally, in this study we used 5 years return period to assess surface runoff dynamics, future scenarios with higher values of precipitation in terms of their return periods should be tested to detect land use specific sensitivity thresholds. This will allow more precise management of prevention, coping and mitigation strategies.

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Appendix

List of published and submitted manuscript during the PhD career

2021

Bosino Alberto, Szatten Dawid Aleksander, Omran Adel, Becker Rike, **Bettoni Manuele**, Schillaci Calogero, Maerker Michael (2022). Assessment of suspended sediment dynamics in a small ungauged badland catchment in the Northern Apennines (Italy) using an in-situ laser diffraction method.

Catena. 209, 1.

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2022

Bettoni Manuele, Schillaci Calogero, Vogel Sebastian, Bosino Alberto, Märker Michael, (2022). Bibliometric Analysis of Soil and Landscape Stability, Sensitivity and Resistivity.

Land. 11, 1328.

https://doi.org/10.3390/land11081328

Bettoni Manuele, Maerker Michael, Sacchi Roberto, Bosino Alberto, Conedera Marco, Simoncelli Laura, Vogel Sebastian, What makes soil landscape robust? Landscape sensitivity towards land use changes in a Swiss southern Alpine valley.

Science of the Total Environment. 858 (2).

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Bettoni Manuele, Maerker Michael, Bosino Alberto, Conedera Marco, Simoncelli Laura, Vogel Sebastian. Land use effects on surface runoff and soil erosion in a southern Alpine valley.

Geoderma

Appendix A

Table A.1. Fixed and Random effect in the LMM models.

Variable	**Model**	**F**	**χ^2**	**d.f.**	**P**
Aggregate stability	LCTU (F)	1.76	-	5, 20.7	0.17
	Locality (R)	-	11.11	1	<0.001
	Plot (R)	-	0	1	0.99
Hydraulic Conductivity (16 cm)	LCTU (F)	11.37	-	5, 22.7	<0.001
	Locality (R)	-	49.0	1	<0.001
	Plot (R)	-	13.6	1	<0.001
Hydraulic Conductivity (23 cm)	LCTU (F)	9.3	-	5, 18.1	<0.001
	Locality (R)	-	25.26	1	<0.001
	Plot (R)	-	6.44	1	0.013
Bulk Density	LCTU (F)	3.89	-	5, 19.3	0.01
	Locality (R)	-	25.54	1	<0.001
	Plot (R)	-	0.61	1	0.44
Soil Organic carbon	LCTU (F)	8.19	-	5, 25.4	<0.001
	Locality (R)	-	56.99	1	<0.001
	Plot (R)	-	11.64	1	<0.001
Soil Water Repellence	LCTU (F)	17.59	-	5, 16.3	<0.001
	Locality (R)	-	1.38	1	0.24
	Plot (R)	-	0	1	0.99

Fixed (F) and random (R) effects in the LMM models accounting for the effect of land use change on the five soil properties. F: Fixed effect. χ^2: random effect. d.f.: degree of freedom. P: p-value.

Appendix B

Table B.1: Pairwise comparisons for the fixed effect of land use as predicted by the LMM for the Bulk Density.

comparison	B	SE	d.f.	t	P
FT$_S$ - DT$_S$	0.071	0.064	44.237	1.104	0.276
FT$_S$ - FS$_N$	0.386	0.100	12.100	3.844	0.002
FT$_S$ - FS$_S$	0.087	0.068	24.956	1.282	0.211
FT$_S$ - MS$_N$	0.372	0.102	11.423	3.630	0.004
FT$_S$ – PS$_N$	0.220	0.069	37.589	3.203	0.003
DT$_S$ - FS$_N$	0.315	0.100	11.872	3.144	0.009
DT$_S$ - FS$_S$	0.016	0.057	73.042	0.286	0.775
DT$_S$ - MS$_N$	0.301	0.099	11.107	3.047	0.011
DT$_S$ – PS$_N$	0.149	0.078	42.551	1.921	0.061
FS$_N$ - FS$_S$	-0.298	0.102	13.052	-2.917	0.012
FS$_N$ - MS$_N$	-0.014	0.051	64.951	-0.277	0.782
FS$_N$ – PS$_N$	-0.166	0.101	11.740	-1.642	0.127
FS$_S$ - MS$_N$	0.284	0.100	11.806	2.855	0.015
FS$_S$ – PS$_N$	0.133	0.079	50.144	1.690	0.097
MS$_N$ – PS$_N$	-0.151	0.099	11.086	-1.526	0.155

B: estimated difference, SE: standard error; d.f.: degree of freedom, t: t-value, P: p-value, FSN: north-facing forested slopes, FSS: south-facing forested slopes, DTS: Deforested cultivated terraces, FTS: re-forested abandoned terraces, PSN: pasture on slopes, MSN: meadow on slopes

Table B.2: Pairwise comparisons for the fixed effect of land use as predicted by the LMM for the Soil Organic Carbon.

comparison	B	SE	d.f.	t	P
FT$_S$ - DT$_S$	0.012	0.089	205.206	0.140	0.889
FT$_S$ - FS$_N$	-0.381	0.177	9.651	-2.154	0.058
FT$_S$ - FS$_S$	-0.437	0.100	202.203	-4.367	0.000
FT$_S$ - MS$_N$	-0.450	0.182	10.444	-2.478	0.032
FT$_S$ – PS$_N$	-0.218	0.100	132.008	-2.175	0.031
DT$_S$ - FS$_N$	-0.394	0.177	9.471	-2.226	0.052
DT$_S$ - FS$_S$	-0.449	0.076	234.966	-5.948	0.000
DT$_S$ - MS$_N$	-0.462	0.176	9.248	-2.626	0.027
DT$_S$ – PS$_N$	-0.231	0.112	103.159	-2.056	0.042
FS$_N$ - FS$_S$	-0.056	0.180	10.288	-0.308	0.764
FS$_N$ - MS$_N$	-0.069	0.067	230.274	-1.028	0.305
FS$_N$ – PS$_N$	0.163	0.178	9.610	0.915	0.383
FS$_S$ - MS$_N$	-0.013	0.177	9.511	-0.074	0.943
FS$_S$ – PS$_N$	0.219	0.113	127.986	1.930	0.056
MS$_N$ – PS$_N$	0.232	0.177	9.342	1.310	0.221

B: estimated difference, SE: standard error; d.f.: degree of freedom, t: t-value, P: p-value, FSN: north-facing forested slope, FSS: south-facing forested slope, DTS: Deforested cultivated terraces, FTS: re-forested abandoned terraces, PSN: pasture on slope, MSN: meadow on slope

Table B.3: Pairwise comparisons for the fixed effect of land use as predicted by the LMM for the Saturated Hydraulic Conductivity (16 cm).

comparison	**B**	**SE**	**d.f.**	**t**	**P**
FT_S - DT_S	0.357	0.195	222.786	1.836	0.068
FT_S - FS_N	0.103	0.455	8.022	0.227	0.826
FT_S - FS_S	0.318	0.218	217.209	1.458	0.146
FT_S - MS_N	0.807	0.464	8.560	1.740	0.118
FT_S – PS_N	1.384	0.222	167.178	6.222	0.000
DT_S - FS_N	-0.254	0.455	7.959	-0.558	0.592
DT_S - FS_S	-0.040	0.163	234.158	-0.244	0.808
DT_S - MS_N	0.450	0.454	7.843	0.990	0.352
DT_S – PS_N	1.027	0.251	140.328	4.098	0.000
FS_N - FS_S	0.214	0.461	8.420	0.465	0.654
FS_N - MS_N	0.704	0.144	228.843	4.903	0.000
FS_N – PS_N	1.281	0.459	8.105	2.792	0.023
FS_S - MS_N	0.490	0.455	7.967	1.076	0.314
FS_S – PS_N	1.067	0.252	164.345	4.237	0.000
MS_N – PS_N	0.577	0.456	7.925	1.266	0.241

B: estimated difference, SE: standard error; d.f.: degree of freedom, t: t-value, P: p-value, FSN: north-facing forested slope, FSS: south-facing forested slope, DTS: Deforested cultivated terraces, FTS: re-forested abandoned terraces, PSN: pasture on slope, MSN: meadow on slope

Table B.4: Pairwise comparisons for the fixed effect of land use as predicted by the LMM for the Saturated Hydraulic Conductivity (23 cm).

comparison	**B**	**SE**	**d.f.**	**t**	**P**
FT_S - DT_S	0.546	0.191	147.566	2.854	0.005
FT_S - FS_N	0.227	0.316	8.526	0.720	0.491
FT_S - FS_S	0.897	0.215	144.761	4.168	0.000
FT_S - MS_N	0.851	0.327	9.243	2.607	0.028
FT_S – PS_N	1.166	0.210	71.987	5.563	0.000
DT_S - FS_N	-0.318	0.315	8.217	-1.011	0.341
DT_S - FS_S	0.351	0.165	229.278	2.124	0.035
DT_S - MS_N	0.305	0.312	7.869	0.978	0.357
DT_S – PS_N	0.620	0.232	51.445	2.676	0.010
FS_N - FS_S	0.670	0.324	9.314	2.064	0.068
FS_N - MS_N	0.624	0.147	229.602	4.235	0.000
FS_N – PS_N	0.938	0.318	8.211	2.950	0.018
FS_S - MS_N	-0.046	0.315	8.296	-0.146	0.887
FS_S – PS_N	0.269	0.237	69.096	1.134	0.261
MS_N – PS_N	0.315	0.314	7.907	1.002	0.346

B: estimated difference, SE: standard error; d.f.: degree of freedom, t: t-value, P: p-value, FSN: north-facing forested slope, FSS: south-facing forested slope, DTS: Deforested cultivated terraces, FTS: re-forested abandoned terraces, PSN: pasture on slope, MSN: meadow on slope

Table B.5: Pairwise comparisons for the fixed effect of land use as predicted by the LMM for the Aggregate stability.

comparison	**B**	**SE**	**d.f.**	**t**	**P**
FT_S - DT_S	-0.014	0.022	106.145	-0.641	0.523
FT_S - FS_N	0.018	0.030	13.572	0.593	0.563
FT_S - FS_S	-0.018	0.023	124.079	-0.799	0.426
FT_S - MS_N	0.057	0.029	12.239	1.952	0.074
FT_S – PS_N	0.018	0.023	58.991	0.789	0.433
DT_S - FS_N	0.032	0.031	12.865	1.042	0.316
DT_S - FS_S	-0.004	0.022	139.924	-0.187	0.852
DT_S - MS_N	0.071	0.030	11.651	2.382	0.035
DT_S – PS_N	0.032	0.027	29.231	1.203	0.239
FS_N - FS_S	-0.036	0.032	14.287	-1.134	0.276
FS_N - MS_N	0.039	0.019	146.955	2.046	0.043
FS_N – PS_N	0.000	0.031	12.237	0.011	0.991
FS_S - MS_N	0.075	0.031	13.038	2.426	0.031
FS_S – PS_N	0.036	0.028	34.566	1.304	0.201
MS_N – PS_N	-0.039	0.030	11.089	-1.294	0.222

B: estimated difference, SE: standard error; d.f.: degree of freedom, t: t-value, P: p-value, FSN: north-facing forested slope, FSS: south-facing forested slope, DTS: Deforested cultivated terraces, FTS: re-forested abandoned terraces, PSN: pasture on slope, MSN: meadow on slope

Table B.6: Pairwise comparisons for the fixed effect of land use as predicted by the LMM for the Soil Water Repellence.

comparison	**B**	**SE**	**d.f.**	**t**	**P**
FT_S - DT_S	1.825	0.409	60.823	4.465	0.000
FT_S - FS_N	-2.095	0.462	17.390	-4.535	0.000
FT_S - FS_S	-0.407	0.425	58.168	-0.957	0.343
FT_S - MS_N	-1.523	0.444	15.120	-3.432	0.004
FT_S – PS_N	0.537	0.405	42.105	1.327	0.192
DT_S - FS_N	-3.920	0.467	16.128	-8.394	0.000
DT_S - FS_S	-2.232	0.410	87.421	-5.438	0.000
DT_S - MS_N	-3.348	0.449	14.048	-7.457	0.000
DT_S – PS_N	-1.288	0.436	18.824	-2.953	0.008
FS_N - FS_S	1.688	0.487	15.050	3.465	0.003
FS_N - MS_N	0.572	0.393	148.340	1.455	0.148
FS_N – PS_N	2.632	0.464	14.585	5.678	0.000
FS_S - MS_N	-1.116	0.470	13.248	-2.375	0.033
FS_S – PS_N	0.944	0.457	17.684	2.067	0.054
MS_N – PS_N	2.060	0.445	12.654	4.625	0.001

Appendix C

Table C.1: Mean and standard deviation content expressed in percentage of sand, silt and clay of all the different LCTUs.

	Mean texture [%]			**Standard Deviation [%]**		
LCTU	**Sand**	**Silt**	**Clay**	**Sand**	**Silt**	**Clay**
Forested slope (FS_N)	59.57	28.49	11.94	3.54	5.58	4.46
Forested slope (FS_S)	64.92	26.03	9.04	4.22	3.86	2.70
Meadow on slope (MS_N)	67.84	26.81	5.34	4.86	3.85	2.11
Pasture on slope (PS)	68.39	24.16	7.46	7.69	5.35	3.44
(Re-)forested abandoned terrace (FT_S)	71.06	22.02	6.92	4.17	3.02	2.33
Deforested cultivated terrace (DT_S)	63.50	29.36	7.14	9.98	9.51	2.41