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Estimating soil degradation in montane grasslands of North-eastern Italian Alps (Italy)

Loris Torresani [a,*], Jianshuang Wu [b], Roberta Masin [c], Mauro Penasa [c], Paolo Tarolli [a]

[a] Department of Land, Environment, Agriculture and Forestry, University of Padova, Agripolis, Viale dell'Università 16, 35020, Legnaro (PD), Italy
[b] Freie Universität Berlin, Institute of Biology, Biodiversity/Theoretical Ecology, Berlin, 14195, Germany
[c] Department of Agronomy, Food, Natural resources, Animals and Environment, University of Padova, Agripolis, Viale dell'Università 16, 35020, Legnaro (PD), Italy

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ABSTRACT

Grasslands cover a large portion of the terrestrial ecosystems, and are vital for biodiversity conservation, environmental protection and livestock husbandry. However, grasslands are degraded due to unreasonable management worldwide, i.e., soil erosion indirectly due to the damage of overgrazing on vegetation coverage and soil texture. An in-depth investigation is necessary to quantify soil erosion in alpine pastures, in order to manage grasslands more sustainably. In this work, we collected freely available satellite images and carried out intensive field surveys for the whole Autonomous Province of Trento (Northeastern Italian Alps) in 2016. The area (and volume) of soil erosions were then estimated and shown in maps. The average of the depths of soil erosion measured in field was used as a reference for estimating soil erosion of the entire study area. High-resolution DEMs difference in soil surface conditions was also computed in two representative areas between pre- and post-degradation to estimate the volume and the average depth of eroded soils. The degradation of soil in the study areas has been estimated in 144063 m^2 and an estimated volume of 33610 ± 1800 m^3. Results indicate that our procedure can serve as a low-cost approach for a rapid estimation of soil erosion in mountain areas. Mapping soil erosion can improve the sustainability of grazing management system and reduce the risk of pastureland degradation at large spatial scales.

1. Introduction

Grazing lands including pasturelands, rangelands, natural grasslands, shrublands, savannas, and steppes are widespread worldwide (FAO, 2014; Suttie et al., 2005); they cover 33.4 million km^2 of the Earth and accounts for 25% of the emerged lands surface (Excluding Antarctica and Greenland) (FAO, 2014). For example, extensive rangelands and pasturelands are distributed from Mongolia and Himalaya-Kush highlands to Western Europe in Euro-Asia (Suttie et al., 2005; Wu et al., 2014). In the Americas, pasturelands are widespread from the North to the South, with mentions of the Argentinian Pampas, Great Plains, and the Llanos and Cerrados in Patagonia. In the Mediterranean basin, pasturelands are distributed in both arid-semiarid ecosystems like maquis scrubland, and in humid ecosystems like Alps (Suttie et al., 2005). Rangelands are globally distributed and are essential for animal husbandry and biodiversity conservation. The economy and wellbeing of many people, mainly in rural areas, depends on the production of goods and services derived from animal husbandry, such as meat, milk and processed products (Mack et al., 2013; Papanastasis et al., 2017).

However, grazing lands are degrading to some extent due to the ongoing climate change and intensifying human disturbance (Li et al., 2019; Montanarella, 2007; Sivakumar and Stefanski, 2007; Wu et al., 2017). The increase in the number of livestock combined with poor grazing management may lead to a general degradation of pasturelands. At a global scale, the population of the main species of domestic animals has increased over the last decades. For example, buffaloes have risen from 89 million in 1961 to 199 million at the end of 2016, cattle from 940 million to 1474 million, goats from 348 million to 1002 million, and sheep from 994 million to 1117 million (FAO, 2016). Moreover, the number of livestock animals is expected to grow in the near future, mainly due to the increasing demand of animal-derived products, mainly driven by human population growth, which is projected to reach 8.5 billion people by 2030 (United Nations, 2015). Thus, overgrazing becomes a critical driver for grazing-land degradation in both vegetation and soils (Ibáñez et al., 2007; Salvati and Carlucci, 2015; van Oudenhoven et al., 2015; Zucca et al., 2010).

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* Corresponding author.
E-mail address: loris.torresani@phd.unipd.it (L. Torresani).

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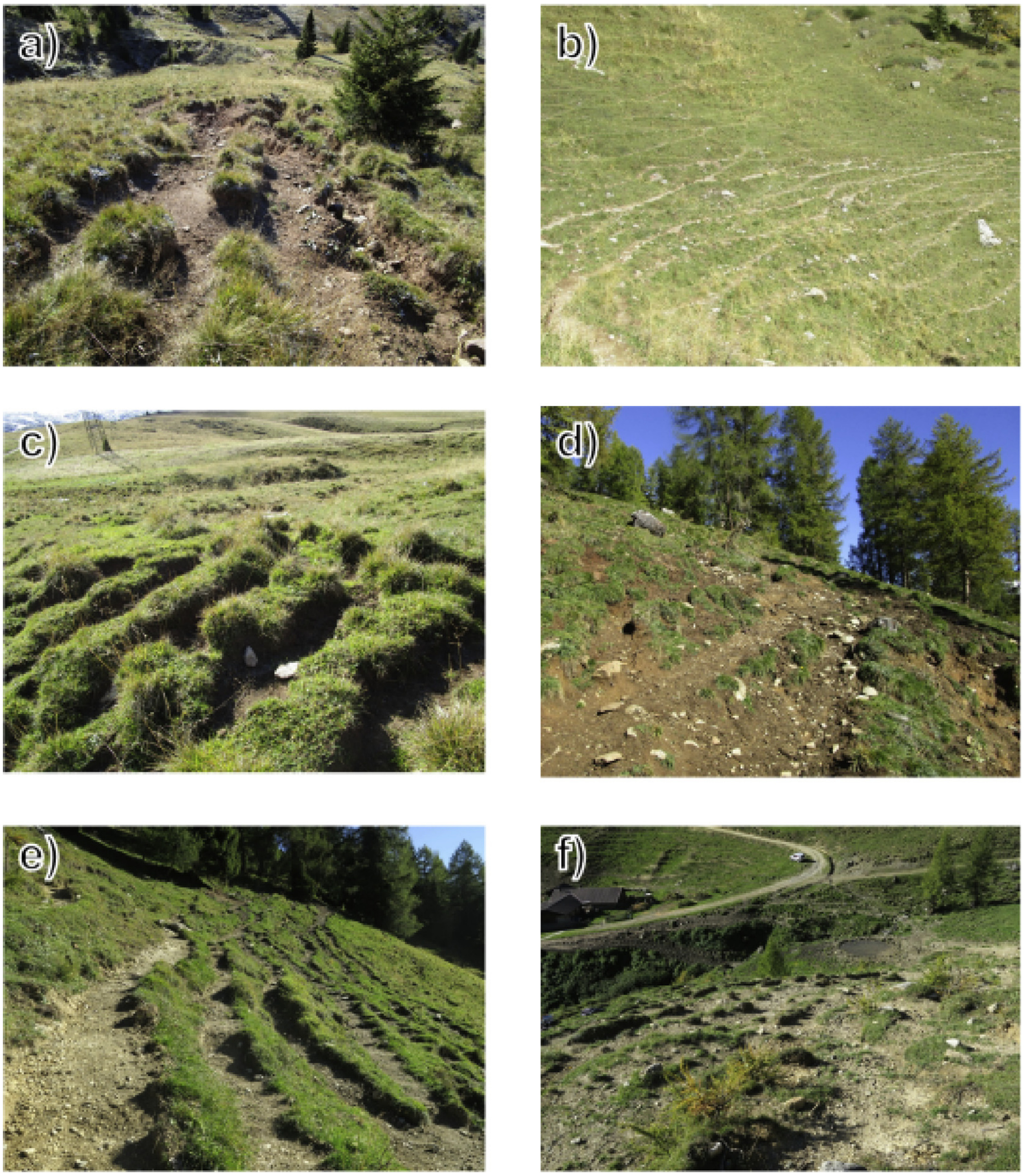

Fig. 1. Examples of areas affected by trampling-induced erosion detected during field surveys along the whole Province. a) Mountain Community of Primiero, b) Mountain Community of Val di Non, c) Mountain Community of Alta Valsugana and Bersntol, d) Mountain Community of Val di Sole, e & f) Mountain Community of Giudicarie.

Soil erosion is defined as the decline of soil quality and especially the weakening of soil structure that can lead to a degenerative trend. Soil erosion can be summarized in three steps: i) soil particles detachment, ii) transport and iii) deposition of soil (Blanco-Canqui et al., 2016).

Such a natural process is mainly caused by the action of various erosive agents like water, ice (or glaciers), wind, snow, plants, animals and humans. So according to these factors, we can divide erosion respectively into water erosion, aeolian or wind erosion, snow erosion, phytogenic erosion, zoogenic erosion and anthropogenic erosion (Zachar, 2011). With regards to zoogenic erosion, several animal species can concur on soil erosion with a large variability of activity. For example, we can have several typologies of erosion induced by grazing animals like deer (Kumbasli et al., 2010), tunnelling activities of mole-rats (Zuri and Terkel, 1997), exposure of soil particle by earthworms (Hazelhoff et al., 1981), erosion in riverbanks by Coypu (*Myocastor coypus*) (Sofia et al., 2017), and soil degradation due to wild boar (*Sus scrofa*) activity (Mauri et al., 2019).

This paper focuses on the effects of integrative erosion, which is the combined erosion caused by two factors, animals (Zoogenic erosion) and humans (Anthropogenic erosion).

More in details, we introduce the term Anthropo-zoogenic erosion (see also Apollo et al., 2018), which is (in this case), the adverse effect on soil due to trampling of livestock introduced by humans on alpine areas.

The zoogenic erosion (in this case caused by trampling) is composed of two complementary effects. The first one is the soil compaction caused by animals weight distributed vertically through the hoof area (Kumbasli et al., 2010). This determines a reduced water infiltration capacity and thus an increase in potentially erosive overland flow. The second effect is a soil shear caused by animal movements, during which tangential stress is applied when a hoof is lifted for a subsequent step (Guretzky et al., 2005). This causes a detachment of soil particles that can be spatially redistributed by other erosive factors (see above). Generally, eroded areas caused by grazing animals are linear features along the common pathways (Fig. 1a) or following the hydrologic lines in “rill” and “gullies”

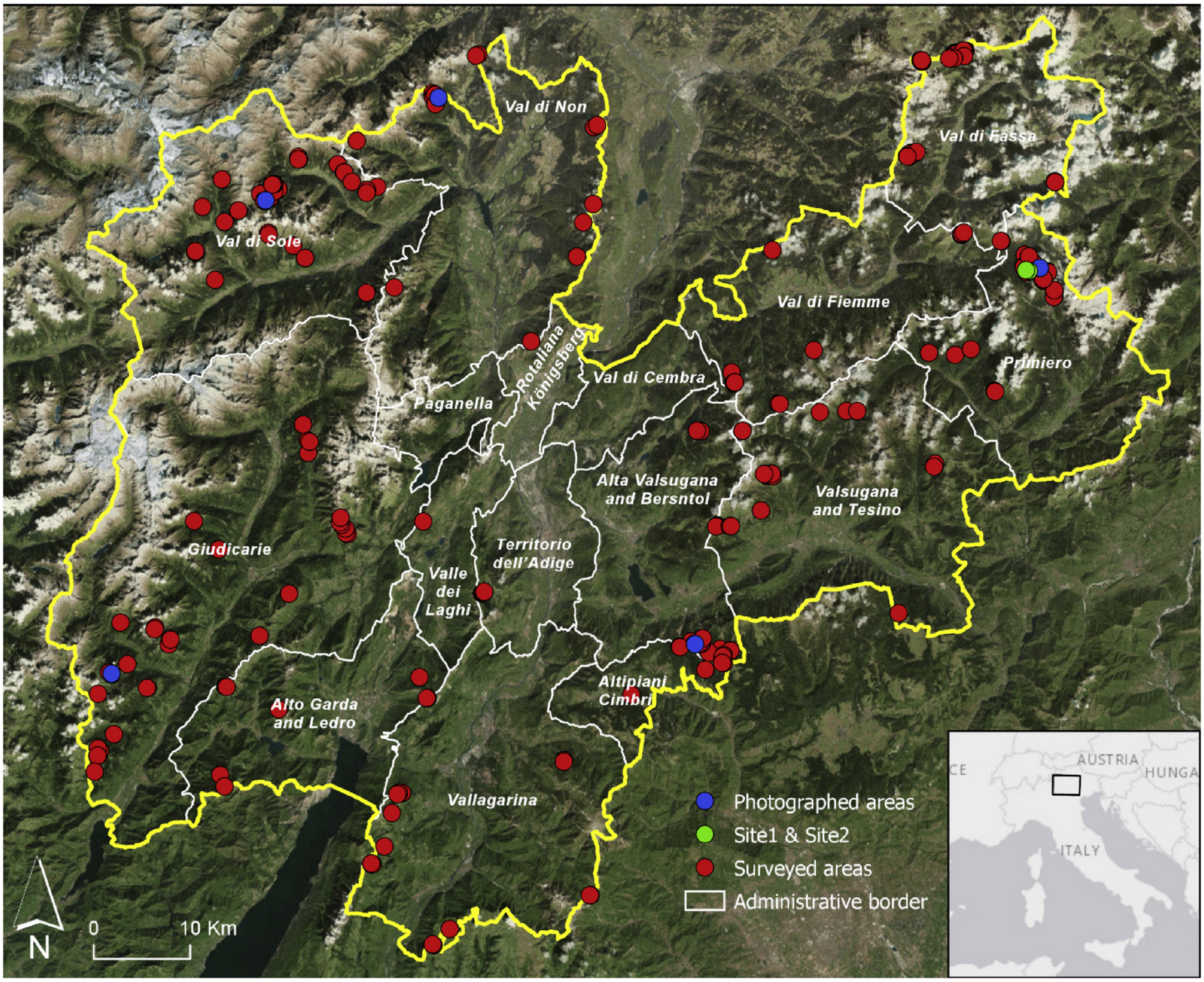

Fig. 2. Map of the Autonomous Province of Trento with trampling-induced eroded areas identified using freely available images services (Google Maps and Bing Maps). In yellow the administrative border of the Autonomous Province of Trento, and white, the administrative borders of the Mountain Communities.

morphologies (Fig. 1b) (Evans, 1997). The gully erosion due to the trampling of livestock animals has been found to be one of the largest sediment contributors in grazing areas (Wilkinson et al., 2018). In addition, soil erosion induced by livestock overgrazing can also result in losses of vegetation cover, productivity and biodiversity, and in soil compaction and desertification (Ibáñez et al., 2007; Oztas et al., 2003; Thornes, 2007; Zhao et al., 2005). Consequently, overgrazing may lead to a reduction of grassland productivity that can reflect on the number of animals that can be feed. This, of course, will affect the availability of animal-derived products and thereby affects human welfare and livelihood (Mather, 1992). Therefore, it is necessary to improve management practices to prevent pastureland degradation (Chen et al., 2014; Department for Environment, 2012; Papanastasis, 2009; Stanchi et al., 2012).

Table 1
Description of the two areas analyzed by Structure from Motion, located in the "Rolle Pass" in the Autonomous Province of Trento (Northeastern Italian Alps).

Site	Location	Elevation (m)	Total surface (m^2)	Eroded surface (m^2)
Site 1	46.29765 N 11.780024 E	1950.8	558.9	211.81
Site 2	46.298765 N 11.776042 E	1913.57	185.91	156.8

Soil erosion is more frequent in grasslands with higher stocking rates (expressed in Livestock Units per hectare land surface), along obligate pathways and near water sources (Hendricks et al., 2005; Zhao et al., 2007). Soil degradation, especially in arid and semi-arid regions can increase the risk of desertification in the rangelands (Ibáñez et al., 2007). A global study indicated that overgrazing could account for 35.9% of soil degradation (Oldeman et al., 1990). In Australia, Mongolia and China, overgrazing affects between 49.2% and 80.2% of all degradation phenomena (Evans, 1998; Oldeman et al., 1991). In Europe, overgrazing degradation represents 22.7% of all soil degradation processes (Warren and Khogali, 1992).

Indeed, worldwide, trampling-induced erosion is a common issue in pastureland, but the information about the eroded volume is still missing or it is available only at a small scale (fenced areas or limited grazing areas). This requires quickly identifying and clearly mapping analyses of soil erosion at both small and large scales. Many studies have been conducted to assess the degradation occurring in grasslands using different methods. Grassland degradation has been assessed using GIS data, and the Universal Soil Loss Equation and the Revised Universal Soil Loss Equation (Ficuț et al., 2017; Ligonja and Shrestha, 2015). The

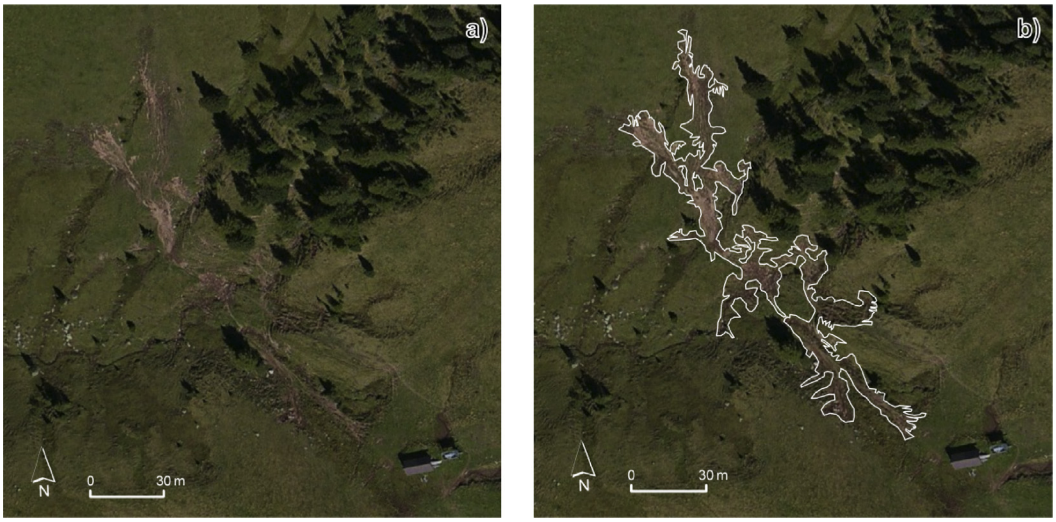

Fig. 3. Example of a mapping operation of an eroded area through the use of freely available orthophoto service (Bing Maps). a) non mapped land, b) mapped eroded area.

Table 2a
Results of the identification of grazing-induced areas in the Autonomous Province of Trento. For each Mountain Community, the number of eroded areas and the extension (m^2) are reported.

Mountain community	number	Extension (m^2)
Val di Fassa	54	12037.7
Alta Valsugana and Bersntol	17	10121.9
Alto Garda and Ledro	11	3051.8
Val di Non	16	7091.1
Val di Sole	42	24572.1
Vallagarina	17	19874.8
Valle dei Laghi	1	1498.5
Val di Cembra	0	0
Giudicarie	33	26390
Primiero	34	24435.6
Val di Fiemme	16	4144.9
Paganella	0	0
Valsugana and Tesino	24	5900.8
Altipiani Cimbri	6	2408.3
Rotaliana-Königsberg	0	0
Territorio dell’Adige	5	2536.2
Total	**276**	**144063.7**

Table 2b
Summary of the collected depth values of trampling-induced erosion. The average value of 23.33 ± 1.25 cm has been used as a reference value for the estimation of volume for the whole Province.

Collected depth (cm)	
Mean	23.33
St. Error	0.58
St. Dev	7.55
Min	3
Max	63
95% Interval	1.25

diffusion of remote sensing technologies allows increasing the availability of high-resolution topographic data from different platforms (e.g. satellites, manned and unmanned airborne vehicles), giving new opportunities of land analysis and understanding of physical processes (Tarolli, 2014). In this study, we used freely available satellite images and Structure from Motion (SfM) photogrammetric technique (Eltner et al., 2016), combined with an onsite survey, to map and analyze soil erosion caused by direct trampling and subsequent erosional processes in pasturelands of North-eastern Italian Alps. In our discussion, we will contribute to filling the existing gap in the literature about the methods for the estimation and quantification of soil erosion induced by trampling (and related processes) during the grazing season.

2. Materials and methods

2.1. Study area

This study was carried out in the Autonomous Province of Trento (Fig. 2), which locates in the North-eastern Italian Alps and covers a surface of 6207 km^2, mostly in mountainous areas (70% over 1000 m asl) and mostly covered by forests (50%). The entire Province is divided into 16 administrative macro-areas called Mountain Communities (Italian: Comunità di Valle), and are composed of a union of municipalities of the same geographic area (valley). In the figures included in the present paper, the border of the Mountain Communities are highlighted with the layer called “Administrative border”.

In 2016, the human population of the Province was 537416 located in 177 municipalities, with a population density of 86.37 people per km^2 (ISTAT, 2016). In 2011 the livestock production was 127.4 million Euro (Statistic Service of Autonomous Province of Trento, 2014). Grazing practices at high altitude are typically seasonal (May–June to September) and are yearly supported by averagely 300 temporary alpine summer farm (Dipartimento Agricoltura, 2013). During the summer of 2016, the number of grazing animals in the Autonomous Province of Trento was 19048 over a pastureland surface of 594 km^2 (Dipartimento Agricoltura, 2013; ISTAT, 2010). In the Province, the transhumance of dairy cows onto highland pastures during summer has a long tradition, and it is characterized by a wide variety of milk-derived products. This practice in the Province of Trento is also essential for tourism attraction, thanks to both landscape peculiarity and eno-gastronomic offer. For example, during the summer of 2015, 69% of the tourists declared at least one visit to an alpine summer farms where animal grazing is practised (Provincia Autonoma di Trento, 2015). Due to its importance, grasslands need to be managed more sustainably to avoid soil erosions caused by, for example, inappropriate grazing management that could lead to a loss of landscape perceptions and grass productivity.

For the photogrammetric analysis used to test the suitability of the proposed method in the current study, two areas located on the “Rolle Pass” were selected (Table 1). These two areas were characterized by a diffuse situation of degradation, mainly induced by grazing; this was particularly true in Site 2.

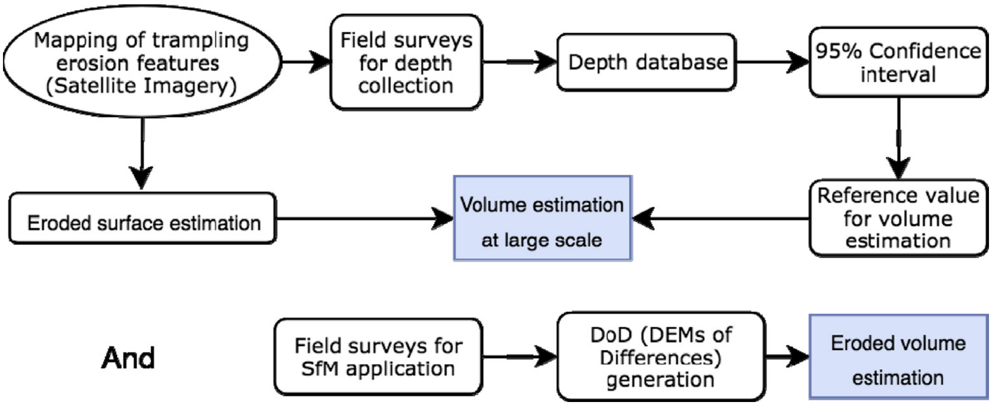

Fig. 4. Flowchart of the proposed procedure to estimate erosion volume, including also SfM technique application.

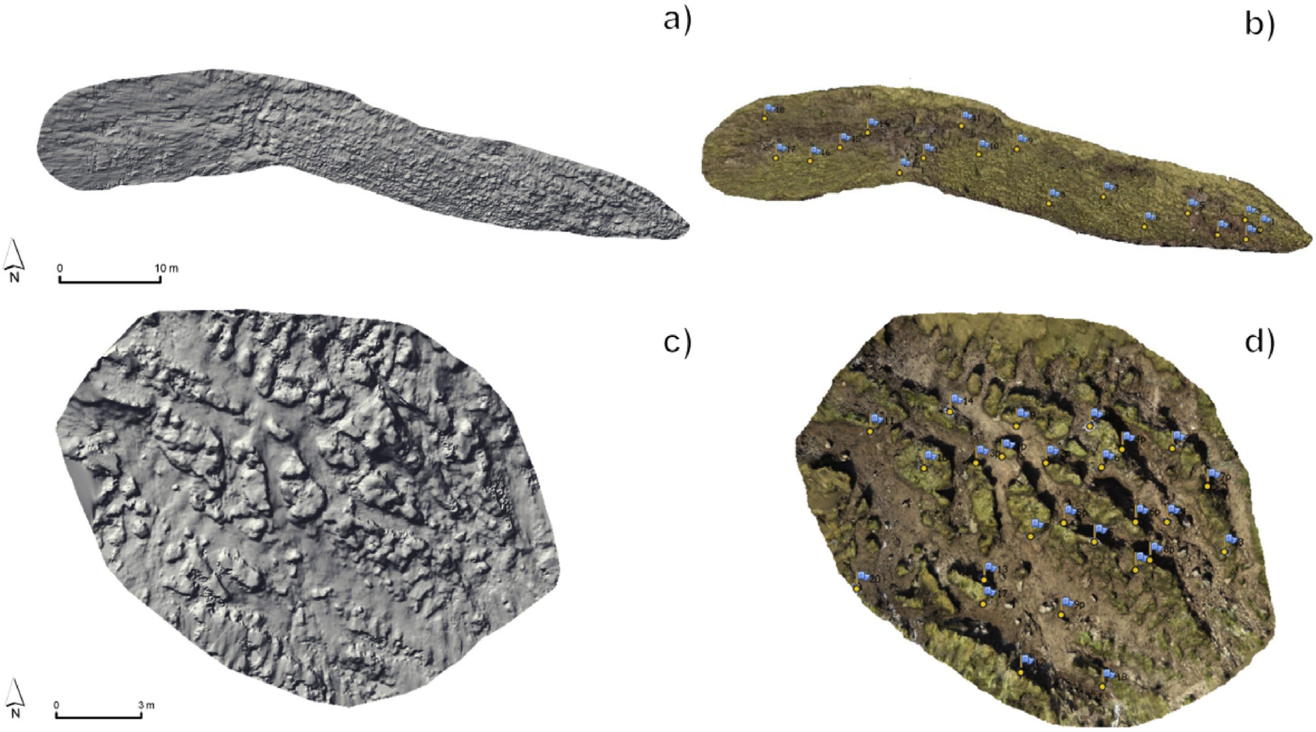

Fig. 5. Examples of the 0.03 m DEM obtained by SfM technique: a) and b) DEM and 3D model of Site 1; c) and d) DEM and 3D model of Site 2, respectively.

Table 3
Summary of point cloud errors on X, Y, Z axes, RMSE and SDE (Standard Deviation of the Error) for both DEMs. Then SDE has been used for minLOD estimation through the application of the equation of Wheaton et al. (2010).

	Site 1	Site 2
X err. (±m)	0.0129	0.0135
Y err. (±m)	0.0146	0.0149
Z err. (±m)	0.0167	0.0265
RMSE (m)	0.0262	0.0333
SDE (m)	0.0268	0.0520

Different sites were visited in the whole Province and different situations of erosion were recorded (Fig. 1).

2.2. *Trampling-induced erosion mapping and land survey*

The first step of this research consisted of identifying and mapping the eroded areas caused by direct trampling and the subsequent combined action of all the eroded factors mentioned in the introduction (Chapter 1). The detection was completed with freely available satellite images (GeoEye, WorldView, Landsat) in web portal (e.g. Google Maps and Bing Maps), which allowed the identification and accurate mapping (in GIS environment) of eroded areas (Fig. 3).

Subsequently, soil erosion depth was measured during an intensive field survey campaign carried out in summer of 2016. Nearly 1500 measures were collected using a simple meter stick. The measuring methodology is simple and is based on multiple depth measurements along transects at a variable distance in order to represent the depth variability of the surveyed area (see also Gudino-Elizondo et al., 2018; Mauri et al., 2019; Salesa et al., 2019 for further details and applications). In order to be more accurate, a metal bar helped to keep the meterstick perpendicular and also to represent the pre-erosion level (when placed across non-eroded spot) of the investigated surface.

These measures were used as the basis to provide a reference value of the mean erosion depth for the entire region. With this value and areas mapped through satellite, we estimated the potential volume (in m^3) of eroded soil for each area.

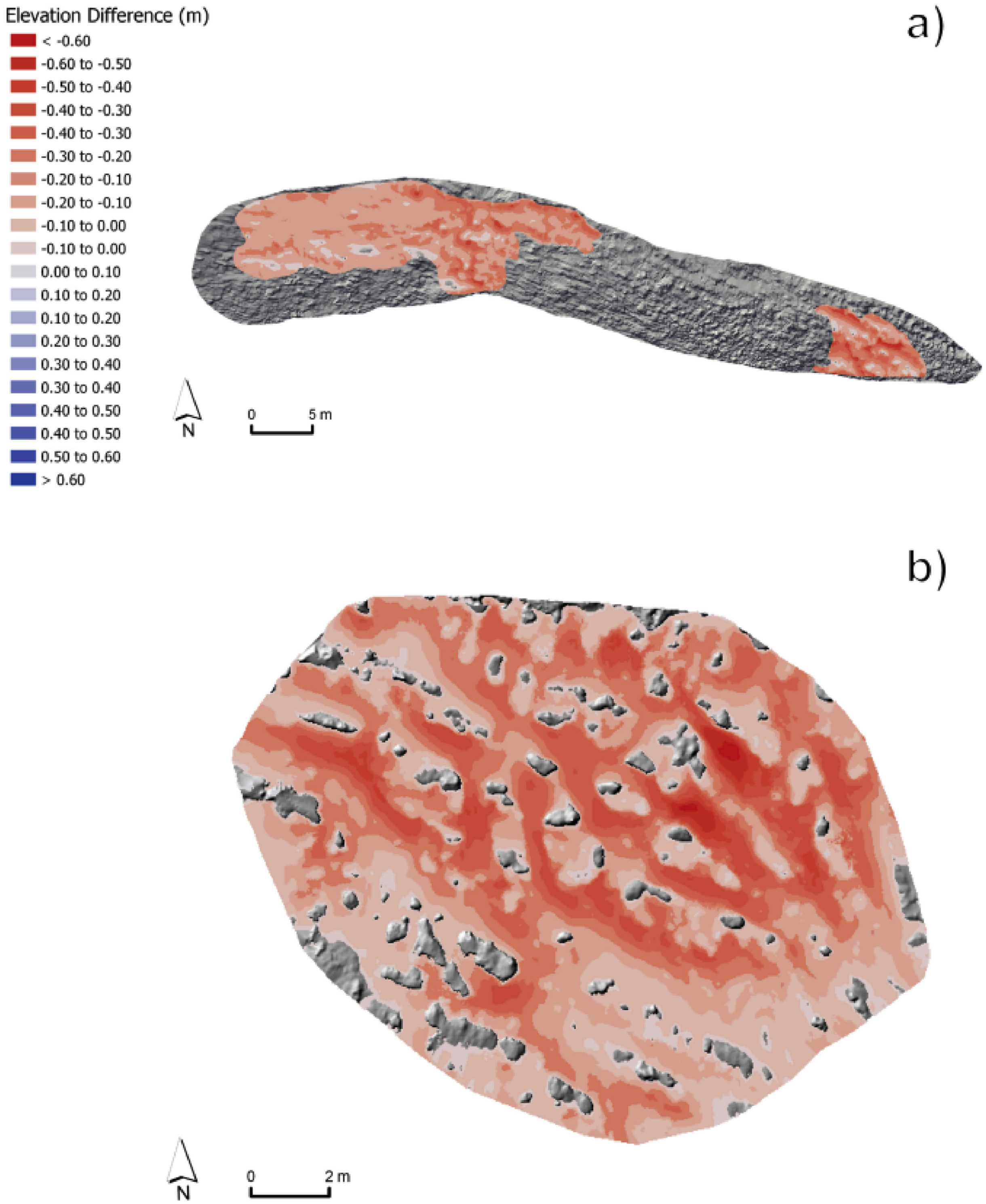

Fig. 6. a) DoD of Site 1, b) DoD of Site 2. For both DoDs erosion is highlighted with a red gradient.

The reference interval for the Autonomous Province of Trento, estimating a 95% confidence interval (CI) with "RStudio" software, was set at 23.33 ± 1.25 cm (mean +/- CI) (Table 2b). The eroded volume was then computed by multiplying the total eroded surface (Table 2a) and the reference depth of erosion (Table 2b).

Such methodology was then tested in two study areas, through SfM photogrammetric technique (now a well-established methodology for the analysis of surface morphology; Eltner et al., 2016; Pijl et al., 2019; Sofia et al., 2017). According to this technique, two Digital Elevation Models (DEMs) were created and then processed to estimate the volume of eroded soil. The flowchart of the proposed procedure is depicted in Fig. 4.

2.3. *Structure from motion and DEM of difference*

In the two areas selected for the application of SfM, several photographs were taken with a standalone digital camera, a Canon G16 with 12 MP set at a focal length of 6 mm. Firstly, 18 targets at "Site 1" and 28 targets at "Site 2" were distributed to geo-reference the digital models.

Table 4
Results of DoD and comparison of on-site data.

	Average depth (cm)		95% Confidence Interval (cm)	Volume (m^3)		95% Confidence Interval (m^3)
On-Site data						
Site 1	22.59	±	1.16	46.16	±	4.63
Site 2	24.58	±	1.64	46.46	±	3.03
SfM (DoD)						
Site 1	20.00	±	4.00	42.13	±	8.37
Site 2	28.00	±	7.00	46.83	±	11.51

Table 5
Summary of volume estimation for each Mountain Community in the Autonomous Province of Trento. Volume data expressed as: value +/- CI.

Eroded areas		
Mountain community	Extension (m^2)	Volume (m^3)
Val di Fassa	12037.7	2808.4 ± 150.4
Alta Valsugana and Bersntol	10121.9	2361.4 ± 126.5
Alto Garda and Ledro	3051.8	712.0 ± 38.1
Val di Non	7091.1	1654.4 ± 88.6
Val di Sole	24572.1	5732.7 ± 307.1
Vallagarina	19874.8	4636.8 ± 248.4
Valle dei Laghi	1498.5	349.6 ± 18.7
Val di Cembra	-	-
Giudicarie	26390	6156.8 ± 329.9
Primiero	24435.6	5700.8 ± 305.4
Val di Fiemme	4144.9	967.0 ± 51.8
Paganella	-	-
Valsugana and Tesino	5900.8	1376.7 ± 73.7
Altipiani Cimbri	2408.3	561.9 ± 30.1
Rotaliana-Königsberg	-	-
Territorio dell'Adige	2536.2	591.7 ± 31.7
Total	**144063.7**	**33610.1 ± 1800**

Secondly, each target position was measured with a Topcon Hiper V dual-constellation (GLONASS & GPS) used in differential mode. Once every position of each target for both areas was collected, SfM technique was applied to obtain a 3D referenced point cloud of the two eroded areas. The photographic dataset acquired was processed with the commercial software Agisoft Photoscan®. The workflow is mostly automatic and consisted of the following steps: image import, image alignment, georeferencing, optimization of image alignment, building geometry and export of the 3D georeferenced point cloud. Finally, such point cloud, cleaned from vegetation using Cloud Compare® software, was interpolated by "natural neighbours" algorithm (Sibson, 1981) for the generation of a 0.03 m resolution DEM, a resolution already proven to be suitable for the analysis of micro-morphology of agricultural surfaces (Tarolli et al., 2019). Overall, two DEMs were created, which described the current situation (post-event DEM) of the eroded areas in Site 1 and Site 2 (Fig. 5).

The estimation of erosion volume relies on a comparison between multitemporal DEMs. Performing a difference of the two DEMs allows to produce a DEM of difference (DoD) and to estimate the erosion/deposition volume to describe changes over a certain period (Cavalli et al., 2017; Wheaton et al., 2010; Williams, 2012). Accordingly, a DEM showing the pre-erosion situation would have been of great assistance. In the absence of such information, we reconstructed a plausible DEM following the geometry of a non-grazed surface. By comparing the pre- and post-erosion DEMs, we estimated the volume of eroded soils (m^3) by means of the Geomorphic Change Detection 7 (GCD 7), an add-in for ArcGIS that is freely available. The GCD 7 estimates the erosion/deposition multiplying the surface of each cell by the difference in height between the two DEMs (Wheaton et al., 2010).

A further step before the elaboration of the DoDs was the estimation of DEMs uncertainty, in order to set a minimum level of detection (minLOD), which was estimated assuming spatially uniform uncertainties, as reported by Brasington et al. (2003) and Wheaton et al. (2010). Those authors provided evidence that it is possible to set the values of the minLOD threshold for the used dataset, using the following equation:

$$\min LOD = \sqrt{SDE_{post}^2 + SDE_{pre}^2},$$

where SDE is the standard deviation of the error, calculated using the standard deviation of the differences between Ground Control Point GCP altitude measured with DGPS and the GCP altitude extracted from the DEM. Of course, using a synthetic DTM (for reconstructing the pre-degradation status), derived from the post-degradation DTM, the SDE has the same value. The minLOD helps to distinguish real surface changes from noise. Elevation changes below this threshold were discarded, while changes above this threshold were treated as real (Brasington et al., 2003; Lane et al., 2003).

3. Results

3.1. Identification of eroded areas and depth measurements

At the end of the erosion identification phase, a map with eroded areas was created (Fig. 5). Grazing-induced eroded areas are widespread in the whole Autonomous Province of Trento (Fig. 1), in particular in areas where seasonal grazing is a common practice. In total 276 eroded areas with trampling-induced erosion have been found, for an extension of 144063 m^2 (Table 2a).

The average erosion value, at the regional scale, has been estimated analyzing the main statistics of the entire dataset of field-collected depth values.

3.2. DEM analysis and DoD results

In Fig. 5b and d, it is possible to see the 3D reconstruction of erosion of the two areas surveyed with SfM technique, while DTMs of both areas are reported in Fig. 5a and c. For both sites, a table of model errors was created to compare and validate the outcome of DEM generation process (Table 3). All SfM point clouds showed an error comprised between 0.013 m and 0.019 m along X, Y and Z axis at Site 1. The only exception is along the Z axis at Site 2, which was 0.026 m. This is explained by the high morphological complexity of Site 2, where the erosive situation was more dramatic than Site 1. Regarding the errors of the photographic dataset, Table 3 explains the accuracy of the elaboration for both study areas. Generally, the elaboration for Site 1 showed a low Z error (0.0167 m) and a low Root Mean Square Error (RMSE, 0.0262 m). An RMSE of 0.0333 m and a Z error of 0.0268 m was found in Site 2.

DEMs differencing was carried out using the standalone application GCD 7. The outcomes generated by the software are shown in Fig. 6 and consist of two raster files with a chromatic gradient from blue (deposition) to red (erosion). In addition to this map, a table reporting erosion volume (m^3) and depth (cm) have been produced (Table 4), in order to quantify the erosion over the two areas analyzed with SfM. To distinguish real elevation changes from noise, a minLOD of 0.04 m for Site 1 and 0.07 m for Site 2, were introduced. Regarding the amount of sediment eroded, results are reported in Table 4.

At Site 1, the elaboration of DoD gave a volume of 42.13 ± 8.37 m^3 of eroded soil and an average erosion depth of 20 ± 4 cm. Field data of Site 1 resulted in an amount of eroded sediment of 46.16 ± 4.63 m^3 which correspond to an average depth of 22.59 ± 1.16 cm. Comparing field values with those obtained from DoD, the difference in terms of volume was 4.03 m^3. Regarding Site 2, the elaboration of the DoD resulted in an

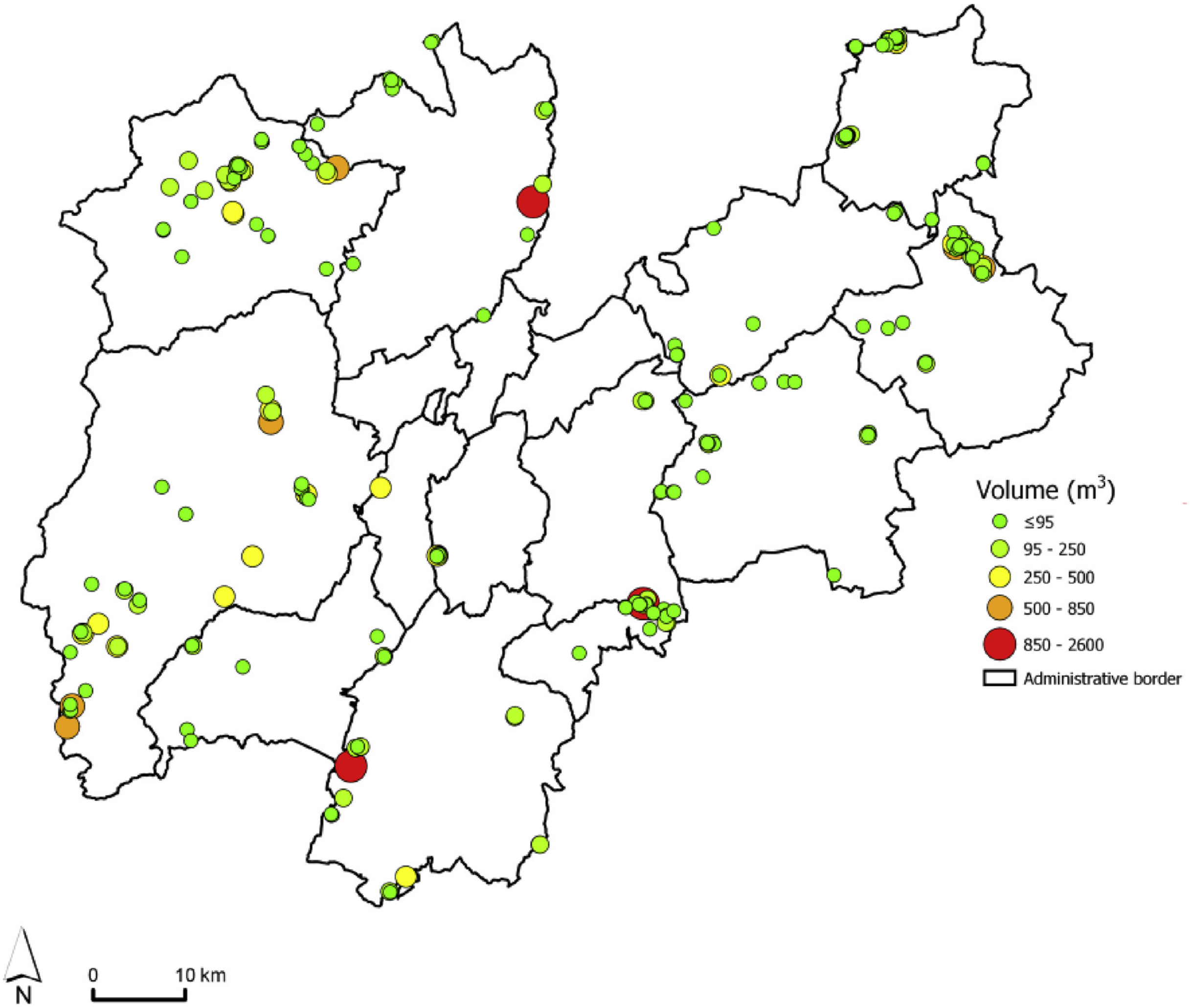

Fig. 7. Trampling-induced eroded areas highlighted with a dimensional and a chromatic gradient.

amount of eroded sediment of 46.83 ± 11.51 m^3 and an average depth of 28 ± 7 cm. Field measured volume was 46.46 ± 3.03 m^3 with an average depth of 24.58 ± 1.64 cm. It is possible to notice that there are some differences between eroded values. In the case of Site 1, we have obtained slightly overestimation of on-site volume and depth values if compared with DoD results. On the other hand, on Site 2, we have obtained a slight underestimation of the two values if compared with DoD results. Moreover, results of DoDs show an error of 8.37 m^3 and 11.51 m^3 in terms of volume estimation of Site 1 and Site 2, respectively. Regarding on-site data, we estimated an error of 4.63 m^3 for Site 1 and 3.03 m^3 for Site 2.

3.3. *Trampling-induced erosion estimation at large scale*

The estimation of trampling-induced erosion volume in the whole Autonomous Province of Trento was carried out by multiplying the erosion surface (144063 m^2) and the average depth (23.33 ± 1.25 cm) estimated for the whole province in section 3.1. The estimated eroded volume at large scale was 33610.1 ± 1800 m^3, which means a sediment production of 0.23 ± 0.0125 m^3/m^2 or 2300 ± 125 m^3/ha. The summary of soil erosion is reported in Table 5, where volume information is reported at both Regional and Mountain Community scale. Moreover, three maps of erosion found over the entire surface of the Autonomous Province of Trento were created (Figs. 7 and 8a, b). From Table 5, Figs. 7 and 9, it is possible to understand where the high value of soil removed was located: Val di Sole, Primiero, Vallagarina and Comunità della Val di Fassa. On the other hand, Mountain Communities with a low value of grazing-induced erosion volume were: Paganella, Val di Cembra, Rotaliana-Königsberg, Valle dei Laghi and Territorio dell'Adige. The same results are displayed at the municipalities scale in Fig. 8a and b.

4. Discussion

Effects of animals on landscape evolution have been frequently underestimated and rarely quantified. Moreover, it is not just the effect of one species but the synergy with a number of species and their interaction with climatic and other geomorphic processes to be responsible for landscape degradation. In the present study, we analyzed grazing-induced erosion in an alpine context; it is well known that alpine environment is particularly sensitive to disturbances like erosion once vegetation cover is removed (Hall et al., 1999).

The information on soil erosion induced by grazing at large scale is still missing or available only at a small scale (catchment or limited fenced areas) (Blanco-Canqui et al., 2016; Evans, 1997; Zhao et al., 2005). The phase of erosion mapping using freely available satellite images resulted in the production of Fig. 5 and Table 2a and b. Drawing operations accuracy and image resolution are the two most influencing factors for the estimation of erosion surface and thus eroded volume. However, the use of satellite image services like Google Maps and Bing maps have been proved as effective tools for the recognition and mapping of eroded areas (Boardman, 2016; Desprats et al., 2013; Shruthi et al., 2011).

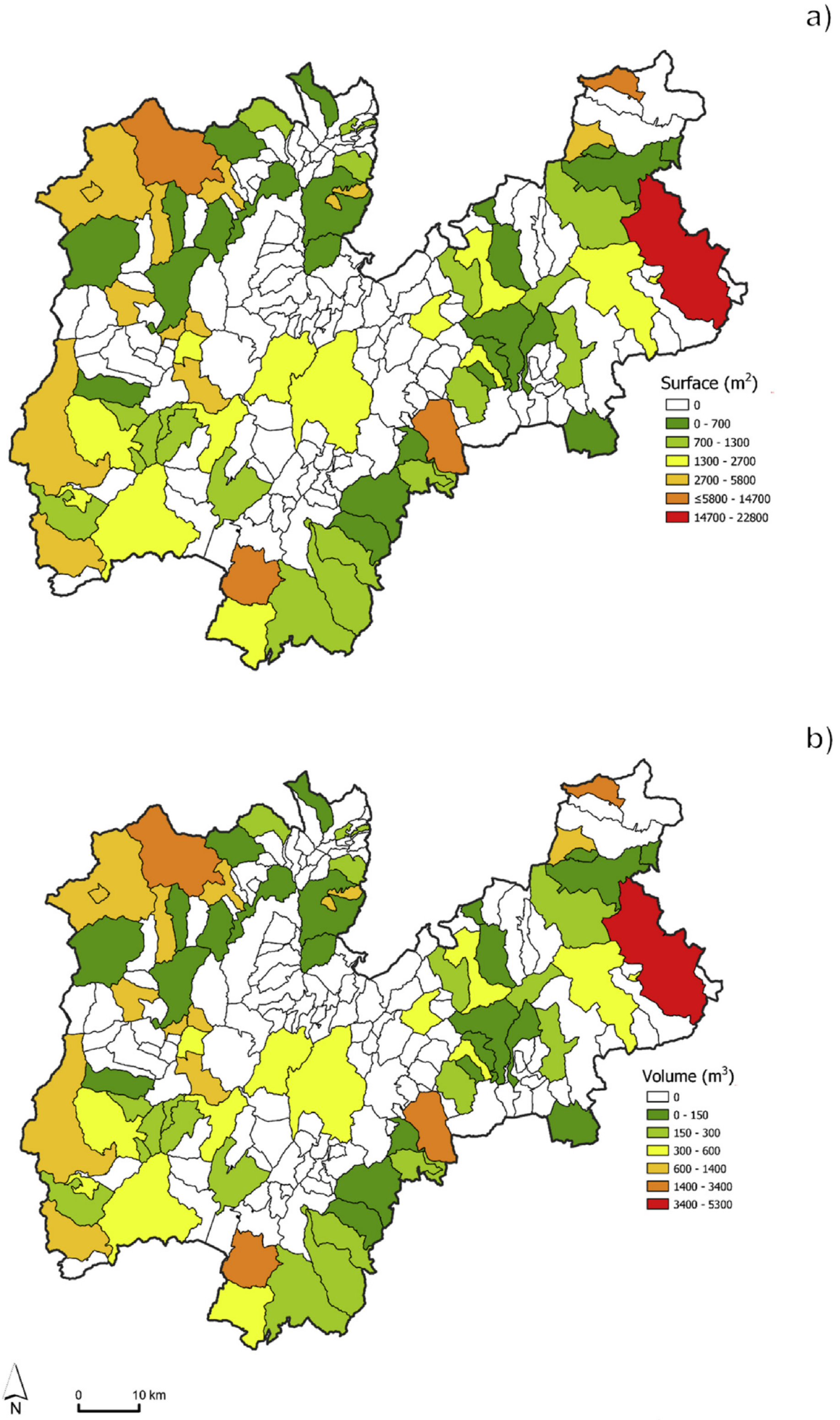

Fig. 8. Map of trampling-induced erosion in the Autonomous Province of Trento: a) erosion surface for each municipality; b) values in terms of m^3 for each municipality highlighted with a chromatic gradient.

Regarding the amount of eroded surface/volume (Table 2a, b and 5), three situations were found:

1) Mountain Communities without grazing-induced erosion (Rotaliana-Königsberg, Val di Cembra and Paganella).
2) Mountain Communities with few degradation (Territorio dell'Adige, Valle dei Laghi, Altipiani Cimbri, Val di Non and Alto Garda e Ledro).
3) Mountain Communities with widespread degradadtion (Val di Sole, Vallagarina, Comunità della Val di Fassa, Alta Valsugana and Bersntol, Valsugana and Tesino, Giudicarie and Primiero).

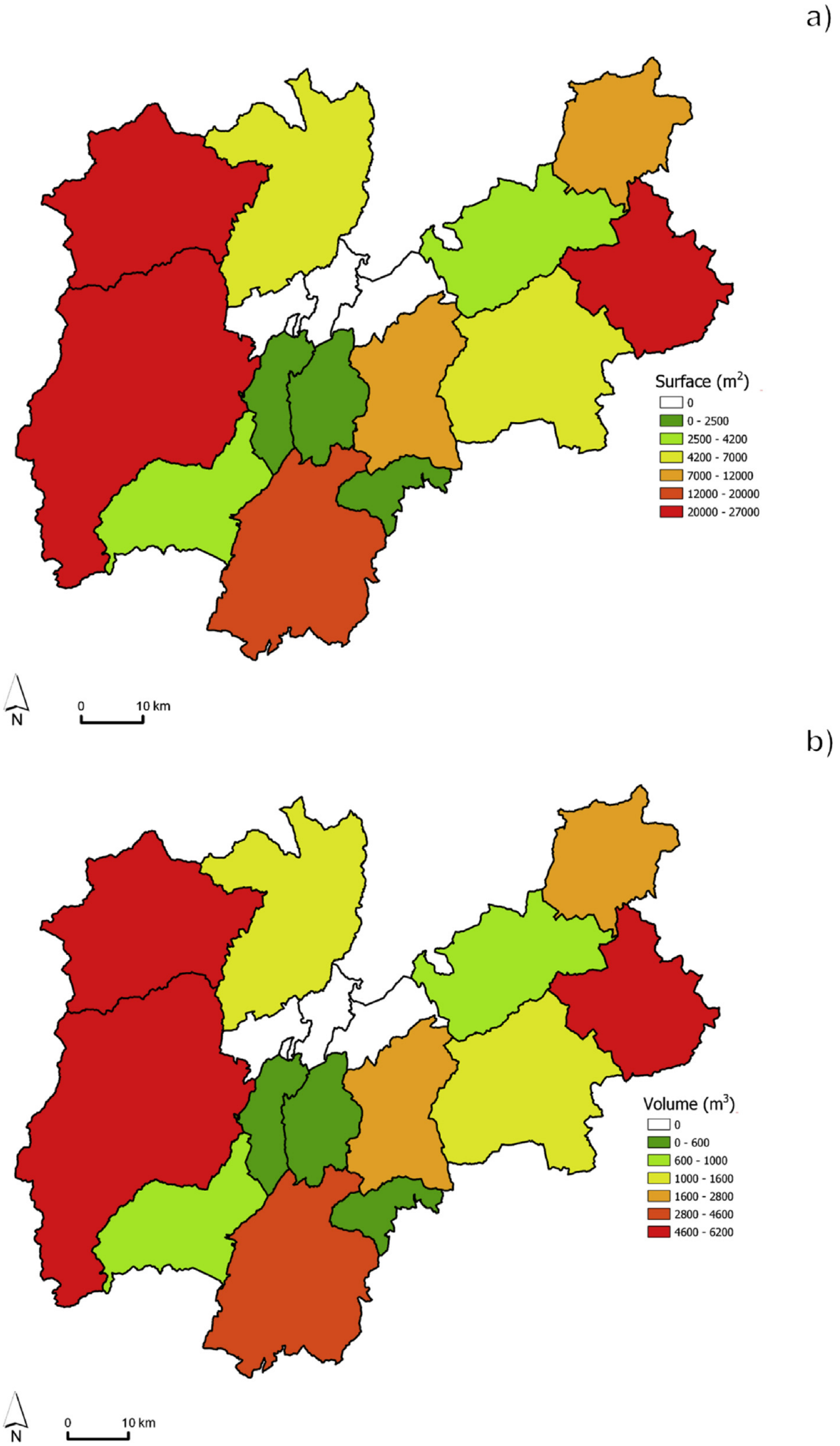

Fig. 9. Maps of trampling-induced areas in the Autonomous Province of Trento: a) erosion surface for each Mountain Community; b) total erosion volume for each Mountain Community, highlighted with a chromatic gradient.

The explanation of these differences between Mountain Communities relies mainly on the economic relevance of animal husbandry. Higher volumes of erosion are more common in rural areas, where animal husbandry is a common practice and relevant for the economy of the local population. Low level of erosion was observed in areas with a high level of urbanization, like industrialized and residential areas (e.g. Territorio dell'Adige), or where fruit cultivation is common (e.g. Rotaliana-Königsberg). Usually, Mountain Communities with widespread erosions are characterized by a high livestock density or poor management, and thus it is necessary to plan and improve sustainable management of the rangelands. Using the approach proposed in the present study to estimate eroded volume at large scale, it is possible to plan effective measures for the protection and recovery of the eroded areas.

The estimated erosion depth (23.33 ± 1.25 cm) used for volume estimation is similar to erosion depth found in the literature. In particular, a value of 0.25 m has been estimated by Zhao et al. (2005), and a value of 0.23 m in Evans (2005). Also, the use of SfM methodology has shown its potential to be used as a fast technique for 3D modelling of livestock-induced erosion. In literature, it is possible to find many applications of this technique for 3D modelling and DTM production of a wide variety of degradation phenomena like landslides, banks erosion, glacier melting and debris flows (Fonstad et al., 2013; Prosdocimi et al., 2015; Sofia et al., 2017).

Considering Mountain Communities with low (2) or no erosions (1) with a maximum eroded volume of 1600 m^3 over the whole area (Fig. 8a), some possible management measures in these specific cases could be:

- continuous monitoring of early stage erosions or sensitive areas;
- grazing rotation, in order to decrease the grazing pressure over these areas;
- adjust grazing intensity and change grazing species over eroded areas.

In the case of Mountain Communities with widespread erosions and high eroded volume (>1600 m^3 globally), more drastic interventions have to be planned in addition to those mentioned above:

- grazing exclusion until recovery dynamics take place;
- earth moving works and grassing over heavily degraded erosions.

All these recovery practices are widely mentioned in the literature (Evans, 2005; Papanastasis, 2009; Quaas et al., 2007), and prove their efficacy in recovering degraded lands in a period of 10–20 years. Once recovery takes place, it is important to introduce sustainable management of grassland, in order to limit the erosion. However, the application of those measures will imply an increase in management costs of pastures and on herding operations. It is thus necessary that the local administration of each Mountain Community or directly the central administration of the Autonomous Province of Trento encourage and subsidize the implementation of such remediation, in order to preserve the landscape quality of the whole Province.

In this study, we illustrated an easy and fast methodology to assess pastureland degradation in an alpine context. With this methodology, the results obtained and the proposed remediations are a starting point to take action and act to achieve the “Land Degradation Neutrality” (LDN) by 2030 in alpine pasturelands (Weigelt et al., 2015).

LDN is the goal n. 15.3 of the 17 goals of the Sustainable Development Goals adopted by the United Nations to address our challenges to achieve a better and more sustainable future, for all. Achieving LDN means a “zero” net erosion rate, which is challenging due to the complexity of land and soil systems and the actual exploitation oriented economy. A holistic approach to achieve LDN, as reported in Keesstra et al., (2018), explain how actions can be inserted in four concepts: i) system thinking, ii) connectivity, iii) nature-based solutions, iv) regenerative economics.

5. Conclusion

This work presents a low-cost methodology for the estimation of the volume of soil eroded directly or indirectly by livestock trampling at a regional scale. The entire surface of the Autonomous Province of Trento (Italy) has been analyzed through the use of freely available satellite images. The proposed methodology has been then tested in two field test sites using SfM photogrammetric technique. Difference of DEM between pre- and post-erosion situation has been used to estimate the volume of eroded soil in the two above-mentioned sites. The estimation of the eroded volume with both SfM and on-site technique is affected by some errors, but both methods are suitable for a fast (and acceptable) estimation of the soil affected by erosion. This study allowed the creation of an up-to-date database of grazing-induced erosions, containing values in terms of Area (m^2) and Volume (m^3) of each feature found along the whole Autonomous Province of Trento. Given such results, we can argue that the on-site volume estimation, even if affected by some uncertainties (but the differences with SfM-DoD methodology are minimal), is a suitable methodology for a quick estimation of the erosion.

The proposed methodology could be a strategic instrument for improving grazing management systems in particular if integrated with information regarding livestock density. Furthermore, providing a value of eroded surface and volume can be considered a first step to attract interests on this kind of land degradation by population, central administrations and rangeland managers.

As a future improvement, the survey needed for SfM application could be performed with the use of Unmanned Aerial Vehicle (UAV). Another idea for future improvements of this methodology and to increase interests on grazing-induced erosions, could be the use of a platform like Open Street Maps to create a collaborative task for grazing-induced erosion mapping.

Improving pastureland management will be a fundamental objective to ensure grass productivity and landscape quality. Putting attention on the integrity of rangeland is becoming an important issue: climate change, extremization of weather conditions, and human activities will increase the risk of degradation and desertification of grazing land.

Declarations

Author contribution statement

Loris Torresani: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Jianshuang Wu, Roberta Masin, Mauro Penasa, Paolo Tarolli: Performed the experiments; Analyzed and interpreted the data.

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Additional information

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References

Apollo, M., Andreychouk, V., Bhattarai, S.S., 2018. Short-term impacts of livestock grazing on vegetation and track formation in a high mountain environment: a case study from the Himalayan Miyar Valley (India). Sustain. Times 10, 951.
Blanco-Canqui, H., Stalker, A.L., Rasby, R., Shaver, T.M., Drewnoski, M.E., van Donk, S., Kibet, L., 2016. Does cattle grazing and baling of corn residue increase water erosion? Soil Sci. Soc. Am. J. 80, 168.
Boardman, J., 2016. The value of Google Earth^{TM} for erosion mapping. Catena 143, 123–127.
Brasington, J., Langham, J., Rumsby, B., 2003. Methodological sensitivity of morphometric estimates of coarse fluvial sediment transport. Geomorphology 53, 299–316.
Cavalli, M., Goldin, B., Comiti, F., Brardinoni, F., Marchi, L., 2017. Assessment of erosion and deposition in steep mountain basins by differencing sequential digital terrain models. Geomorphology 291, 4–16.
Chen, B., Zhang, X., Tao, J., Wu, J., Wang, J., Shi, P., Zhang, Y., Yu, C., 2014. The impact of climate change and anthropogenic activities on alpine grassland over the Qinghai-Tibet Plateau. Agric. Meteorol. 189–190, 11–18.
Department for Environment, F.& R.A.P. of Land management, 2012. Grazing and Pasture: Sustainable Management Schemes. – GOV UK [WWW Document]. URL. https://www.gov.uk/guidance/grazing-and-pasture-sustainable-management-schemes.

Desprats, J.F., Raclot, D., Rousseau, M., Cerdan, O., Garcin, M., Le Bissonnais, Y., Ben Slimane, A., Fouche, J., Monfort-Climent, D., 2013. Mapping linear erosion features using high and very high resolution satellite imagery. Land Degrad. Dev. 24, 22–32.

Dipartimento Agricoltura, Turismo, Commercio e Promozione, 2013. Rapporto Agricoltura 2010 • 2011 • 2012.. http://www.trentinoagricoltura.it/Trentino-Agricoltura/Pubblicazioni2/Monografie/Rapporto-agricoltura-2010-2011-2012.

Eltner, A., Kaiser, A., Castillo, C., Rock, G., Neugirg, F., Abellán, A., 2016. Image-based surface reconstruction in geomorphometry – merits, limits and developments. Earth Surf. Dyn. 4, 359–389.

Evans, R., 2005. Curtailing grazing-induced erosion in a small catchment and its environs, the Peak District, Central England. Appl. Geogr. 25, 81–95.

Evans, R., 1998. The erosional impacts of grazing animals. Prog. Phys. Geogr. 22, 251–268.

Evans, R., 1997. Soil erosion in the UK initiated by grazing animals: a need for a national survey. Appl. Geogr. 17, 127–141.

FAO, 2016. FAO Statistics, Food and Agriculture Organization of the United Nations.

FAO, 2014. FAO Statistics [WWW Document]. Food Agric. Organ. United Nations. http://www.fao.org/faostat/en/?#data/RL.

Ficuţ, C.A., Muntean, O.L., Măcicăşan, V., Maloş, C.V., Hartel, T., 2017. A GIS-Based Assessment of Soil Erosion in Wood-pastures of Southern Transylvania. Pro Environ. Promediu. 10 (30).

Fonstad, M.A., Dietrich, J.T., Courville, B.C., Jensen, J.L., Carbonneau, P.E., 2013. Topographic structure from motion: a new development in photogrammetric measurement. Earth Surf. Process. Landforms 38, 421–430.

Gudino-Elizondo, N., Biggs, T.W., Castillo, C., Bingner, R.L., Langendoen, E.J., Taniguchi, K.T., Kretzschmar, T., Yuan, Y., Liden, D., 2018. Measuring ephemeral gully erosion rates and topographical thresholds in an urban watershed using unmanned aerial systems and structure from motion photogrammetric techniques. Land Degrad. Dev. 29, 1896–1905.

Guretzky, J.A., Fehmi, J.S., Anderson, A.B., 2005. Cattle Grazing and Tracked Vehicle Training on Central and Southwest U.S. Army Lands: Potential Consequences for Grassland Ecosystems.

Hall, K., Boelhouwers, J., Driscoll, K., 1999. Animals as erosion agents in the alpine zone: some data and observations from Canada, Lesotho, and Tibet. Arctic Antarct. Alpine Res. 31, 436.

Hazelhoff, L., van Hoof, P., Imeson, A.C., Kwaad, F.J.P.M., 1981. The exposure of forest soil to erosion by earthworms. Earth Surf. Process. Landforms 6, 235–250.

Hendricks, H.H., Bond, W.J., Midgley, J.J., Novellie, P.A., 2005. Plant species richness and composition a long livestock grazing intensity gradients in a Namaqualand (South Africa) protected area. Plant Ecol. 176, 19–33.

Ibáñez, J., Martínez, J., Schnabel, S., 2007. Desertification due to overgrazing in a dynamic commercial livestock-grass-soil system. Ecol. Model. 205, 277–288.

ISTAT, 2016. Bilancio Demografico Nazionale, pp. 1–10. www.istat.it.

ISTAT, 2010. Sixth Agricultural Census – 2010 [WWW Document]. URL. http://dati-censimentoagricoltura.istat.it/Index.aspx?lang=en&SubSessionId=3038517b-8eec-4d1c-bc14-c7f73478581f&themetreeid=-200.

Keesstra, S., Mol, G., de Leeuw, J., Okx, J., Molenaar, C., de Cleen, M., Visser, S., 2018. Soil-related sustainable development goals: four concepts to make land degradation Neutrality and restoration work. Land 7, 133.

Kumbasli, M., İzzet, A., Üniversitesi, B., Makineci, E., Çankırı, M.Ç., Üniversitesi, K., 2010. Long term effects of red deer (Cervus elaphus) grazing on soil in a breeding area. J. Environ. Biol. 31.1, 185.

Lane, S.N., Westaway, R.M., Hicks, D.M., 2003. Estimation of erosion and deposition volumes in a large, gravel-bed, braided river using synoptic remote sensing. Earth Surf. Process. Landforms 28, 249–271.

Li, M., Wu, J., Song, C., He, Y., Niu, B., Fu, G., Tarolli, P., Tietjen, B., Zhang, X., 2019. Temporal variability of precipitation and biomass of alpine grasslands on the northern Tibetan plateau. Rem. Sens. 11, 360.

Ligonja, P.J., Shrestha, R.P., 2015. Soil erosion assessment in kondoa eroded area in Tanzania using universal soil loss equation, geographic information systems and socioeconomic approach. Land Degrad. Dev. 26, 367–379.

Mack, G., Walter, T., Flury, C., 2013. Seasonal alpine grazing trends in Switzerland: economic importance and impact on biotic communities. Environ. Sci. Policy 32, 48–57.

Mather, A.S., 1992. Land use, physical sustainability and conservation in Highland Scotland. Land Use Policy 9, 99–110.

Mauri, L., Sallustio, L., Tarolli, P., 2019. The geomorphologic forcing of wild boars. Earth Surf. Process. Landforms. https://doi.org/10.1002/esp.4623.

Montanarella, L., 2007. Trends in land degradation in Europe. In: Climate and Land Degradation. Springer, Berlin, Heidelberg, pp. 83–104.

Oldeman, L.R., Hakkeling, R.T.A., Sombroek, W.G., 1990. World map of the status of human-induced soil degradation. Geoderma.

Oldeman, L.R., Hakkeling, R.T.A., Sombroek, W.G., 1991. World Map of the Status of Human-Induced Soil Degradation: an Explanatory Note, second revised ed.

Oztas, T., Koc, A., Comakli, B., 2003. Changes in vegetation and soil properties along a slope on overgrazed and eroded rangelands. J. Arid Environ. 55, 93–100.

Papanastasis, V.P., 2009. Restoration of degraded grazing lands through grazing management: can it work? Restor. Ecol. 17, 441–445.

Papanastasis, V.P., Bautista, S., Chouvardas, D., Mantzanas, K., Papadimitriou, M., Mayor, A.G., Koukioumi, P., Papaioannou, A., Vallejo, R.V., 2017. Comparative assessment of goods and services provided by grazing regulation and reforestation in degraded mediterranean rangelands. Land Degrad. Dev. 28, 1178–1187.

Pijl, A., Tosoni, M., Roder, G., Sofia, G., Tarolli, P., Pijl, A., Tosoni, M., Roder, G., Sofia, G., Tarolli, P., 2019. Design of Terrace drainage networks using UAV-based high-resolution topographic data. Water 11, 814.

Prosdocimi, M., Calligaro, S., Sofia, G., Dalla Fontana, G., Tarolli, P., 2015. Bank erosion in agricultural drainage networks: new challenges from structure-from-motion photogrammetry for post-event analysis. Earth Surf. Process. Landforms 40, 1891–1906.

Provincia Autonoma di Trento, 2015. Turismo in Trentino. Rapporto.

Quaas, M.F., Baumgärtner, S., Becker, C., Frank, K., Müller, B., 2007. Uncertainty and sustainability in the management of rangelands. Ecol. Econ. 62, 251–266.

Salesa, D., Terol, E., Cerdà, A., 2019. Soil erosion on the "El portalet" mountain trails in the eastern Iberian peninsula. Sci. Total Environ. 661, 504–513.

Salvati, L., Carlucci, M., 2015. Towards sustainability in agro-forest systems? Grazing intensity, soil degradation and the socioeconomic profile of rural communities in Italy. Ecol. Econ. 112, 1–13.

Shruthi, R.B.V., Kerle, N., Jetten, V., 2011. Object-based gully feature extraction using high spatial resolution imagery. Geomorphology 134, 260–268.

Sibson, R., 1981. A brief description of natural neighbour interpolation. In: Interpreting Multivariate Data, p. 374.

Sivakumar, M., Stefanski, R., 2007. Climate and Land Degradation, Environmental Science and Engineering Subseries.

Sofia, G., Masin, R., Tarolli, P., 2017. Prospects for crowdsourced information on the geomorphic 'engineering' by the invasive Coypu (*Myocastor coypus*). Earth Surf. Process. Landforms 42, 365–377.

Stanchi, S., Freppaz, M., Agnelli, A., Reinsch, T., Zanini, E., 2012. Properties, best management practices and conservation of terraced soils in Southern Europe (from Mediterranean areas to the Alps): a review. Quat. Int. 265, 90–100.

Statistic Service of Autonomous Province of Trento, 2014. Statweb- Livestock Production Trento [WWW Document]. Livest. Prod. 2011. URL. http://www.statweb.provincia.tn.it/PubblicazioniHTML/Settori economici/Agricoltura%2C silvicoltura e pesca/La produzione lorda vendibile 2011/.

Suttie, J.M., Reynolds, S.G., Batello, C., 2005. Grasslands of the World2. Grasslands of the world xxii + 514 pp.

Tarolli, P., 2014. High-resolution topography for understanding Earth surface processes: opportunities and challenges. Geomorphology 216, 295–312.

Tarolli, P., Cavalli, M., Masin, R., 2019. High-resolution morphologic characterization of conservation agriculture. Catena 172, 846–856.

Thornes, J.B., 2007. Modelling soil erosion by grazing: recent developments and new approaches. Geogr. Res. 45, 13–26.

United Nations, 2015. World population prospects: the 2015 revision. United Nations Econ. Soc. Aff. XXXIII, 1–66.

van Oudenhoven, A.P.E., Veerkamp, C.J., Alkemade, R., Leemans, R., 2015. Effects of different management regimes on soil erosion and surface runoff in semi-arid to sub-humid rangelands. J. Arid Environ. 121, 100–111.

Warren, A., Khogali, M., 1992. Assessment of Desertification and Drought in the Sudano-Sahelian Region.

Weigelt, J., Müller, A., Janetschek, H., Töpfer, K., 2015. Land and soil governance towards a transformational post-2015 Development Agenda: an overview. Curr. Opin. Environ. Sustain. 15, 57–65.

Wheaton, J.M., Brasington, J., Darby, S.E., Sear, D.A., 2010. Accounting for uncertainty in DEMs from repeat topographic surveys: Improved sediment budgets. Earth Surf. Process. Landforms 35, 136–156.

Wilkinson, S.N., Kinsey-Henderson, A.E., Hawdon, A.A., Hairsine, P.B., Bartley, R., Baker, B., 2018. Grazing impacts on gully dynamics indicate approaches for gully erosion control in northeast Australia. Earth Surf. Process. Landforms 43, 1711–1725.

Williams, R.D., 2012. DEMs of difference. Geomorphol. Tech. 2, 1–17.

Wu, J., Feng, Y., Zhang, X., Wurst, S., Tietjen, B., Tarolli, P., Song, C., 2017. Grazing exclusion by fencing non-linearly restored the degraded alpine grasslands on the Tibetan Plateau. Sci. Rep. 7, 15202.

Wu, N., Ismail, M., Joshi, S., Yi, S. Liang, Shrestha, R.M., Jasra, A.W., 2014. Livelihood diversification as an adaptation approach to change in the pastoral Hindu-Kush Himalayan region. J. Mt. Sci. 11, 1342–1355.

Zachar, D., 2011. Soil Erosion, 10. Elsevier Scientific Pub. Co.

Zhao, H.L., Zhao, X.Y., Zhou, R.L., Zhang, T.H., Drake, S., 2005. Desertification processes due to heavy grazing in sandy rangeland, inner Mongolia. J. Arid Environ. 62, 309–319.

Zhao, W.Y., Li, J.L., Qi, J.G., 2007. Changes in vegetation diversity and structure in response to heavy grazing pressure in the northern Tianshan Mountains, China. J. Arid Environ. 68, 465–479.

Zucca, C., Canu, A., Previtali, F., 2010. Soil degradation by land use change in an agropastoral area in Sardinia (Italy). Catena 83, 46–54.

Zuri, I., Terkel, J., 1997. Summertunneling activity of mole rats (Spalax ehrenbergi) in a sloping field with moisture gradient. Mammalia 61, 47–54.