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Soil function assessment in high-mountain environments: Testing the SEPP tool in a ski resort in the Italian Alps

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Abstract

Soil function assessment (SFA) plays an important role in evaluating the impact of management practices, land-use changes and construction work. The Soil Evaluation for Planning Procedures (SEPP) tool is one of the few existing SFA tools that allow automated SFA. It was originally developed to address land-use planning issues, which traditionally play a minor role in high-mountain areas. Hence, the SEPP tool has not yet been applied to such environments. In this study, we tested the SEPP performance on high-mountain soils previously altered by construction work and land-use changes. Specifically, we evaluated soil data from 16 ski runs and 16 paired control sites in the Italian Alps, aiming to reflect land-use-driven differences in soil properties in the SFA results. The study revealed options to adapt SEPP assessment methods if high-mountain soils with special characteristics (e.g. shallowness or high coarse fragment content) are investigated. The main adaptation options are the consideration of further soil parameters and the adjustment of thresholds of function fulfilment levels. However, the assessment results of the current SEPP version already reflect the most relevant impacts of ski run construction on the soils in the study area: fulfilment of some of the soil functions was impaired and that of others improved, while most remained at a comparable level. We conclude that SFA with the SEPP tool provides valuable support for the evaluation of construction projects and land-use change in high-mountain environments. However, the significance of SFA can be improved by considering the intrinsic properties of high-mountain soils.

KEYWORDS

European Alps, land-use change, ski slope construction, soil evaluation, soils properties

1 | INTRODUCTION

Information (databases, classifications, and maps) on soils in the Alps is rather scattered and not readily available, especially for non-agricultural areas and those above the timberline (Baruck et al., 2016; Schaber & Geitner, 2020). However, results from several case studies indicate a remarkable diversity of soils in high-mountain regions, making them highly valuable for scientific purposes (Egli & Poulenard, 2016, Geitner et al., 2017, Masseroli et al., 2020). Additionally, healthy high-mountain soils fulfil various soil functions. According to Haslmayr et al. (2016), we understand soil functions as the performance of a soil in a specific functional context. Furthermore, each specific performance depends on the physical, chemical and biological properties of the soil that control the underlying processes (Greiner et al., 2017). Since the 1990s, the evaluation of soils has progressed beyond the assessment of the 'classical' agricultural potential to include further soil functions, such as surface runoff, climate regulation, and support of biodiversity (e.g. Greiner et al., 2017; Vogel et al., 2019). In addition, soil function assessment (SFA) is a valuable starting point for quantifying the contribution of soil functions to soil ecosystem services (Drobnik et al., 2018; Geitner et al., 2019; Lehmann et al., 2020).

Therefore, SFA is becoming increasingly important in land-use planning as an approach for integrating soil-related issues into decision-making processes (e.g. Haslmayr et al., 2016; Jenny et al., 2006; Lehmann et al., 2008). Although SFA in planning procedures aims to avoid the loss of particularly valuable soils, it can also show the impact of changes in management practices and/or natural conditions on soils. Furthermore, there are various SFA methods that depend on the soil function to be assessed and the availability of soil data. The evaluation is usually performed using empirical equations, pedotransfer functions, lookup tables, or a combination thereof (Greiner et al., 2018). The procedure can be time-consuming and error-prone, particularly if several soil functions and/or more than a handful of sites are considered. However, this can be supported and accelerated by tools that perform automated SFA. Nonetheless, to the best of our knowledge only a few SFA tools exist but they are not freely accessible. This might be explained by the fact that such tools are often developed and used for practical applications rather than for scientific studies. Regarding high-mountain soils, neither a general approach (regulating, e.g. the selection of soil functions and spatial resolution of soil data) nor a specific tool exists to assess their functions. This is despite their importance in high-mountain environments that are also subjected to intense use and specific infrastructure development (e.g. roads, ski resorts, or hydroelectric power plants). In this case, SFA allows steering, modifying, accompanying and evaluating development projects (Geitner et al., 2017).

The Soil Evaluation for Planning Procedures (SEPP) SFA tool, developed by the Department of Geography at the University of Innsbruck (Geitner et al., 2010–2020), was originally designed to support decisions regarding land-use planning. To date, the SEPP tool has already been applied in Alpine regions for environmental impact assessment (in Austria) and scientific studies (in Italy) (Gruber et al., 2019). The results of SFA performed using the SEPP tool were reasonable and provided a sound differentiation among most of the assessed soil functions. Nevertheless, all former applications were limited to locations below 1000 m a.s.l. As for high-mountain soils, their special characteristics (such as small-scale variability, shallowness, high stone and low clay contents, low biological activity, and specific humus forms (sometimes with thick organic layers), as well as disturbances because of erosion or accumulation processes (Baruck et al., 2016; Geitner et al., 2017)) might limit the suitability of the SEPP tool to perform SFA with the necessary level of differentiation and reliability.

This study aimed to test the SEPP tool in a high-mountain environment, namely, near natural sites and close-by ski run sites in a ski resort located in Northwest Italy. Using soil profile-based information from relatively undisturbed soils and soils that were subject to machine grading for the construction of ski runs as input for the SEPP tool, we provided detailed insights into the possibilities and limitations of the SEPP tool for evaluating high-mountain soils. Given that the negative impacts of ski run construction and management on soil properties (e.g. erosion, compaction and organic matter depletion) have been documented (Hudek et al., 2020), a reduction in soil function performance is expected (Freppaz et al., 2013), and it is desirable that SFA results reflect such differences.

Thus, a comparison of paired soil profiles (i.e. ski run soils versus undisturbed control soils) can support the testing of the SEPP tool in high-mountain environments and can indicate how it works and how it might eventually be adapted.

We aimed to answer two main questions. (1) Given the differences in soil properties between soils in the ski runs and the corresponding paired control plots, are the methods implemented in the SEPP tool adequate to reflect these differences in the SFA results? (2) If not, what improvements to the SEPP tool are necessary to perform a meaningful SFA for high-mountain soils?

2 | MATERIAL AND METHODS

2.1 | Study area

This study was performed on four ski runs located in the Monterosa Ski area in the Italian Alps (Ayas-Champoluc, Val d'Ayas) at elevations between approximately 2180 and 2650 m a.s.l. (Figure 1 and Table 1). The ski slopes were reshaped in previous decades [see Hudek et al., 2020 for specific information], and ski area managers provided detailed information on building operations, revegetation practices,

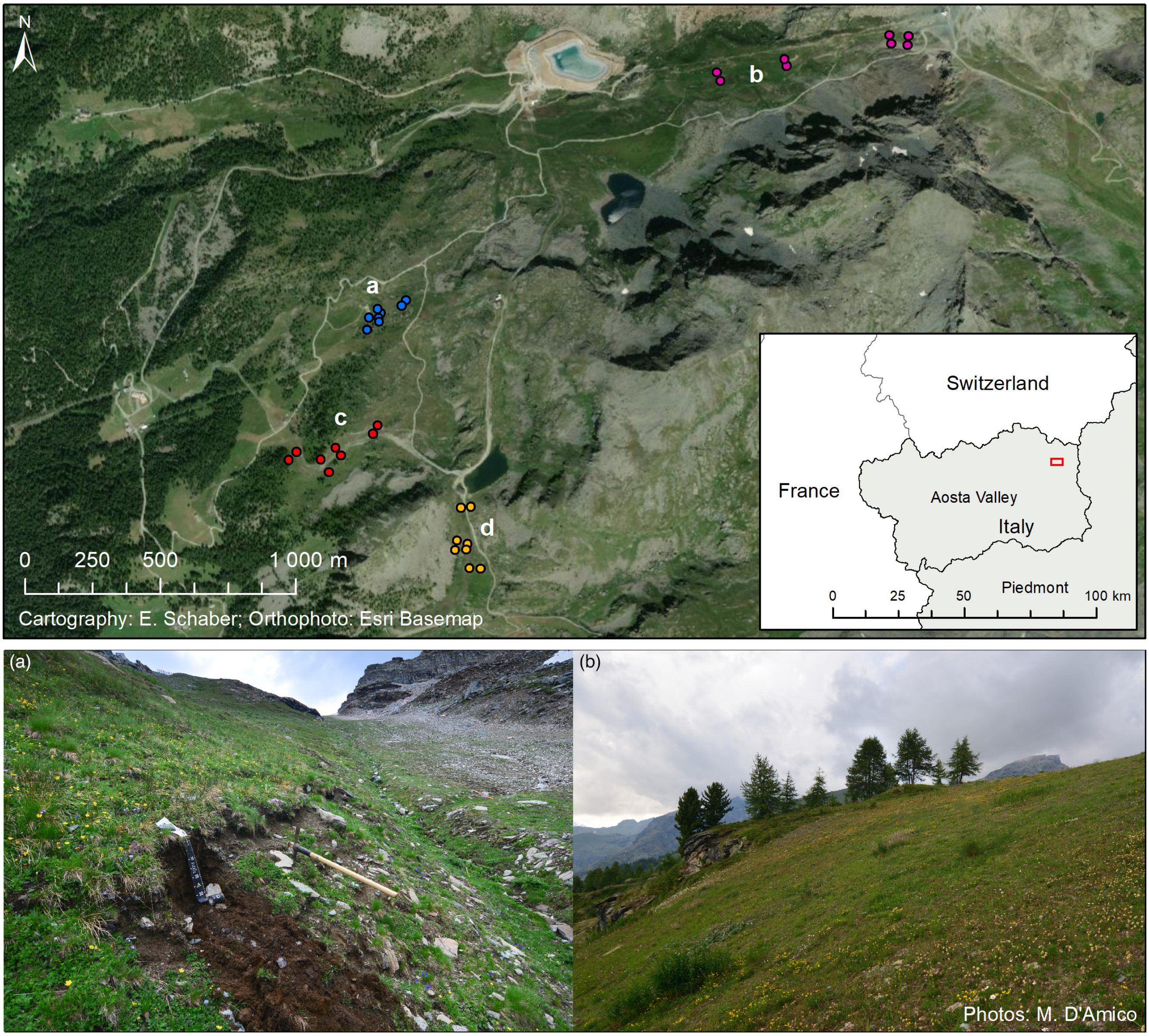

FIGURE 1 Top: Overview of the study area in the NW Italian Alps with the locations of the soil profiles within the ski runs (a – Del Monte, b – Del col, c – Del Lago, d – Contenery). Bottom left: View of the Del col ski run in the upper alpine belt with an open control soil profile next to the ski run. Bottom right: View of the Del Monte ski run in the higher subalpine belt with a mixture of grasses and herbs in the continuous but not dense vegetation cover

TABLE 1 Main properties of the four ski runs under study

Name of the ski run	Elevation range (m a.s.l.)	Aspect	Year of machine-grading
Del Colle	2300–2700	W	1988
Del Lago	1970–2450	W	1996
Del Monte	1970–2440	W	1990
Contenery	2210–2385	S	1994

and maintenance. Therefore, the research area represents an ideal experimental site for testing the SEPP tool in a high-mountain environment. The study area is characterized by an inner-Alpine subcontinental climate, with an average annual precipitation of 722 mm (Champoluc weather station, 1560 m a.s.l.) and a mean annual air temperature ranging from 2°C to −2°C at 2180 and 2650 m a.s.l., respectively (Mercalli, 2003). The maximum monthly precipitation (approximately 80 mm) occurs during May and June, whereas the winter months (December to February) are generally dry, with monthly precipitation between 30 and 50 mm (snow water equivalent). Snow cover lasts for an average of 228 days, with a mean snow depth of 95 cm during the winter trimester (Mercalli, 2003). Undisturbed soils in this area are classified as Leptosols, Umbrisols, Cambisols and Podzols, according to the WRB soil classification system (IUSS Working Group WRB, 2015). Furthermore, these soils developed mainly from morainic parent material composed of calcschists mixed with mafic rocks (D'Amico et al., 2020; Hudek et al., 2020). The semi-natural vegetation in the study area features acidophilus alpine grasslands (dominated by *Carex curvula*, *Festuca varia* and *Nardus stricta*), dwarf shrub heath (*Vaccinium myrtillus*, *V. vitis-idaea*, *V. uliginosum* subsp. *gaulterioides* and *Rhododendron ferrugineum*), and open subalpine stone pine (*Pinus cembra*) forest patches with *Rhododendron ferrugineum* in the understory at a maximum elevation of approximately 2350 m a.s.l. On nearby slopes, scattered *Pinus cembra* trees can be found up to approximately 2450 m a.s.l. Cattle grazing is a traditional practice in the study area, where transhumance is carried out. Thereby, during the summer season, high-mountain pastures are grazed with low animal density.

To obtain smooth, large surfaces to enhance skiing quality and make snow grooming easier (Hudek et al., 2020; Pintaldi et al., 2017), the original bumpy and rough terrain was levelled and reshaped. Thus, large stones and rock outcrops have been removed and/or ground, the soil has been distributed and mixed, and a drainage system has been excavated (Freppaz et al., 2013). When the rock substrate was close to the surface, it was ground and covered with thicker layers of soil and debris to enable levelling of the surface and digging drainage channels. These activities were performed between 1988 and 1996, using heavy machinery (Table 1). After these reshaping activities, the vegetation cover was restored using hydroseeding, with different long-term results across the elevation gradient (Hudek et al., 2020). Snow grooming and artificial snowmaking are also generally performed on these ski runs, which might affect the soil structure and bulk density, among other characteristics (Rixen & Freppaz, 2015).

2.2 | Soil data

We randomly selected four sites along elevation gradients in each of the four ski runs ($n = 16$) and paired control sites located under natural vegetation off the ski runs ($n = 16$). We excavated 32 soil pits, and described the sampled soil horizons of the soil profiles. Field descriptions of the soil profiles and sites were performed according to FAO (2006), and the soils were classified according to the WRB classification system (IUSS Working Group WRB, 2015).

A soil sample was collected from each genetic mineral horizon in each profile (n = 86), air-dried, sieved to 2 mm and analysed using standard methods (Van Reeuwijk, 2002). Thus, the pH was measured in water (soil: water = 1:2.5), and total carbon (TC) and nitrogen (TN) were analysed via dry combustion using a CN elemental analyser (CE Instruments NA2100, Rodano, Italy). The carbonate content was measured by volumetric analysis of carbon dioxide liberated by the reaction with a 6 M HCl solution. Total organic carbon (TOC) was calculated as the difference between the total C measured by dry combustion and carbonate-C. Soil organic matter (SOM) was calculated by multiplying the TOC values by 1.72.

2.3 | Soil function assessment using the SEPP tool

The collected soil information was used as the input for the SEPP software. This tool enables automated SFA based on soil physical, chemical and biological properties as well as site-specific information on land use, climate and topography. The level of soil function fulfilment is determined on an ordinal scale ranging from 1 (very low) to 5 (very high). In this study, 11 soil functions among those evaluated by the model were considered relevant: *habitat for drought-tolerant species*, *habitat for moisture-tolerant species*, *habitat for soil organisms*, *agricultural suitability*, *retention of precipitation*, *short-term retention of heavy precipitation*, *nutrient provision to plants*, *carbon storage*, *retention of heavy metals*, *retention of water-soluble contaminants* and *buffering of acidic substances*. Other functions, such as *transformation of organic contaminants*, *retention of organic contaminants* and *groundwater recharge*, were considered to be less relevant for high-mountain areas and were thus discarded.

Table 2 provides an overview of the parameters considered for each soil function. The parameters were subdivided into three groups: (i) primary soil parameters, (ii) complex soil parameters, which are calculated from several primary parameters, often by means of pedotransfer functions, and (iii) site parameters. The SEPP tool considers the entire soil profile and does not limit the assessment to the top one-metre layer of soil. Thus, the units of the calculated complex soil parameters were presented per m^2 instead of per m^3. Although the latter is more common, it does not allow for a comparison of soils deeper than 1 m with shallower soils. More details regarding the SEPP tool and the assessed soil functions are provided in the SEPP user manual (Supporting Information) and by

TABLE 2 Overview of the soil, complex soil and site parameters used as input for the SEPP tool to calculate the levels of soil function fulfilment based on one or a combination of two approved methods (i.e. 1: BayGLA and BayLfU, 2003, 2: Lehmann et al., 2008, 3: BVB, 2005, 4: Umweltministerium Baden-Württemberg, 1995, 5: Müller & Waldeck, 2011, 6: Gerstenberg & Smettan, 2005, 7: Ad-hoc-AG Boden, 2000)

	Evaluated soil functions										
	Habitat for drought-tolerant species	**Habitat for moisture-tolerant species**	**Habitat for soil organisms**	**Agricultural suitability**	**Retention of precipitation**	**Short-term retention of heavy precipitation**	**Nutrient provision to plants**	**Carbon storage**	**Retention of heavy metals**	**Retention of water-soluble contaminants**	**Buffering of acidic substances**
Methods based on	1, 2	1, 2	3	2	4, 1	2	5	6	1, 7	1	1
Primary soil parameters (field-estimated or analysed)											
Horizon thickness [cm]	o	o		o	x	x	o	o	x	o	x
Bulk density [$g\,cm^{-3}$ or class]	o	o		x	o	o	o	o		o	o
Texture [class]	o	o	x	o	o	o	o		x	x	o
Coarse fragment (>2 mm) content [%]	o	o		o	o	o	o	o	x	o	o
Soil organic matter content [%]	o	o		o	o	o	o	o	x	o	o
Humus form [class]											x
Aggregate structure [class]				x	o	o					
Primary aggregate structure content [%]				x							
Pot. rooting depth [cm]				x							
Ground water level [m]		x		x	x	x			x		
Soil moisture [class]			x								
Carbonate content [%]											x
pH			x	o			o		x		o
Soil type [class]	x	x	x		x	x			x		
Horizon name [class]					x	x			x		
Base-richness of the substrate [class]									x		
Complex soil parameters (calculated by SEPP per horizon)											
Amount of fine earth [$kg\,m^{-2}$]				x			x				x
SOM – amount of soil organic matter [$kg\,m^{-2}$]								x			

(Continues)

TABLE 2 (Continued)

	Evaluated soil functions										
	Habitat for drought-tolerant species	**Habitat for moisture-tolerant species**	**Habitat for soil organisms**	**Agricultural suitability**	**Retention of precipitation**	**Short-term retention of heavy precipitation**	**Nutrient provision to plants**	**Carbon storage**	**Retention of heavy metals**	**Retention of water-soluble contaminants**	**Buffering of acidic substances**
AWC – available water capacity [$\mathrm{l\,m^{-2}}$]	x	x		x							
FC – field capacity [$\mathrm{l\,m^{-2}}$]										x	
AC – air capacity [$\mathrm{l\,m^{-2}}$]				x		x					
WSC – water storage capacity [$\mathrm{l\,m^{-2}}$]					x						
Ks – saturated hydraulic conductivity coefficient [$\mathrm{cm\,day^{-1}}$]					x	x					
$\mathrm{CEC_{eff}}$ – effective cation exchange capacity [$\mathrm{cmol_c\,kg^{-1}}$]							x				
$\mathrm{CEC_{pot}}$ – potential cation exchange capacity [$\mathrm{cmol_c\,kg^{-1}}$]				x							x
Base saturation [%]				x							x
Site parameter (field-estimated or GIS-analysed											
Land use [class]	x		x					x			
Slope [degree]				x	x						
Mean air temperature in vegetation period [°C]				x							
Design event precipitation [$\mathrm{mm\,h^{-1}}$]						x					
Annual rainfall [mm]										x	
Mean annual evaporation [mm]										x	

Note: Primary soil parameters that were needed to derive the required complex soil parameters but were not directly used in the evaluation are indicated with an “o”. primary soil parameters directly used in the evaluation are indicated by an “x”, and those solely used to derive the required complex soil parameters are indicated by an “o”.

Gruber et al. (2019), who applied the tool. However, an updated version of the SEPP tool – in comparison to the version used by Gruber et al. (2019) – was used in this study, where the ordinal scale was inverted to match the logic of SFAs in Germany, Austria and Switzerland (see BayGLA and BayLfU, 2003; Greiner et al., 2018; Haslmayr et al., 2016), with 1 representing a low and 5 representing a high level of function fulfilment. The underlying, sometimes slightly modified, methods were originally developed in Germany and published by Ad-hoc-AG Boden (2000), BayGLA and BayLfU (2003), BVB (2005), Gerstenberg and Smettan (2005), Lehmann et al. (2008), Müller and Waldeck (2011), and Umweltministerium Baden-Württemberg (1995). All of these methods were developed to cover the most representative soils found in Germany and Austria. The methods implemented in the SEPP tool were chosen according to three criteria: (i) they were published and applied, (ii) they were based on the most decisive parameters for the respective soil function and (iii) the required parameters were generally available (i.e. part of a common soil survey).

To meet the requirements of the SEPP tool, the soil profile descriptions had to be adapted. The SEPP tool was developed to perform SFA with soil data structured and classified according to the Austrian soil classification system (Nestroy et al., 2011). The conversion from the FAO (2006) to the Austrian system affected the naming of the soil type, horizon names, soil moisture, aggregate structure and texture. Additionally, the dataset had to be complemented by information on humus forms, bulk density, and carbonate content. Humus forms were classified based on the thickness of the organic layers, A-horizon properties and vegetation (Nestroy et al., 2011). Bulk density was not measured in samples collected in the field because of excessive stoniness. Alternatively, a pedotransfer function based on measured data from 615 soil horizons sampled in the Alps (Aosta Valley, other Italian regions, France and Switzerland) was used. This enabled the estimation of bulk density from the organic carbon content: $\mathrm{BD} = -0.238 \times \ln(\mathrm{Corg}\ [\mathrm{g\,kg^{-1}}]) + 1.667$ (D'Amico et al., 2021). The clay content of the topsoil horizons was estimated from the texture of the subsoil horizon. For some soil functions, the evaluation requires differentiation between the topsoil and the subsoil. We classified all A-horizons as topsoil and E-, B- and C-horizons as subsoil.

3 | RESULTS AND DISCUSSION

3.1 | Soil properties

The undisturbed soils in the study area were generally characterized by low pH values and a relatively advanced degree of development, as indicated by the presence of humus-rich A-horizons and the saturated colours of the B-horizons (Figure 2). At the highest elevations, Eutric Cambisols or Eutric or Dystric Leptosols were found in alpine grasslands with periglacial solifluction. In turn, Dystric Cambisols or Umbrisols were observed in the southern slopes (on the Contenery ski run), below 2350 m a.s.l., whereas Entic Podzols, Albic Podzols and Albic Ortsteinic Podzols were common on the northern slopes, which are all commonly high in coarse fragment content. In ski runs, reworked soils normally lacked thick A-horizons and E- and B-horizons. Hence, they were all classified as Regosols. Calcaric Skeletic Regosols were common, particularly at high elevations, where soils were shallower. Eutric Skeletic Regosols were widespread as well. At a few locations in the subalpine belt, the ski run soils were severely leached and thus have been classified as Dystric Skeletic Regosols.

In general, the pH values were significantly higher, TOC content was lower and the structure was less developed in the soils of the ski runs than in those of the control sites. Humus forms in the ski runs could not be identified, as the organic layers were too thin to be clearly distinguished, and the granular aggregate structure in the mineral horizons was poorly developed. However, at some of the ski run sites with comparatively high pH values, mull-like humus forms were observed. In contrast, humus forms in grassland control sites were moders; moreover, mors were detected under subalpine vegetation in combination with Albic Podzols and Albic Ortsteinic Podzols. A detailed description of the soil profiles and properties is provided in Supporting Information. A summary of the descriptive statistics of the key soil properties at the study sites, including a comparison of the soil in the ski runs and control sites, is provided in Table 3.

3.2 | Soil function assessment results obtained by applying the SEPP tool

In all 32 soil profiles studied, the levels of fulfilment of the 11 soil functions were calculated using the SEPP tool. Figure 3 shows how the fulfilment levels of each soil function were distributed, as well as a comparison between the results obtained for the ski runs and those for the control sites. In general, SFA results demonstrated that the high-mountain soils (both ski runs and control sites) fulfilled some functions to a larger extent than they did others: The functions that contribute to the filtration and purification of groundwater (i.e. *retention of heavy metals* and *retention of water-soluble contaminants*), as well as *agricultural suitability* and *provision of nutrients to plants*, were fulfilled at rather low levels. The ability to retain water, and thus,

FIGURE 2 A selection of control soil profiles (top: a – Eutric Cambisol, 2641 m a.s.l.; b – Dystric Umbric Leptosol, 2442 m a.s.l.; c –dystric cambic Leptosol, 2306 m a.s.l.; and d – Skeletic albic Ortsteinic Podzol, 2182 m a.s.l.) and the paired profiles on the ski runs (bottom: e and f – Calcaric Skeletic Regosols, 2648 and 2442 m a.s.l.; g and h – Eutric Skeletic Regosols, 2319 and 2203 m a.s.l.).

reduce surface runoff and the ability to provide a habitat for soil organisms and drought-tolerant species, was comparatively high.

Regarding the comparison between ski runs and control sites, the SFA results were limited to the five levels of function fulfilment provided by the SEPP tool. Function fulfilment might have shown small variations within the limits of the respective level such that they were not visible in the output. Concomitantly, SEPP analysis results showed that the levels of fulfilment of most soil functions were, at most, only slightly impaired by the construction of a ski run approximately 30 years ago. This unexpected outcome is valid for the soil functions *agricultural suitability*, *short-term retention of heavy precipitation*, *nutrient provision to plants*, *retention of heavy metals* and *retention of water-soluble contaminants* (Figure 3). Simultaneously, the soil functions *habitat for soil organisms*, *habitat for drought-tolerant species*, and *retention of precipitation*, were even improved by altering soil properties. For example, in the soils of ski runs, pH and stoniness were higher, providing a better habitat for drought-tolerant scree plant species, and the thickness of the soil layer increased owing to the grinding of the rocky substrate, whereby the water holding capacity and retention of heavy precipitation both increased. Conversely, *habitat for moisture-tolerant species* was lower in soils under ski runs than in the control site soils. The function of *carbon storage* was also significantly decreased by the construction of ski runs. The levels of function fulfilment for *buffering of acidic substances* were similar for ski runs and control sites, with very low to medium (1–3) scores.

3.3 | Effectiveness of the SEPP tool regarding soil function assessment in high-mountain environments

The assessment of individual levels of soil function fulfilment depends on a varying set of soil parameters summarized in Table 2 and described in detail in the SEPP user manual (Supporting Information), for example, the level of influence of a parameter per function. Based on this information, the following sections address each soil function individually or, if reasonable, in a pairwise manner. In each case, we present the decisive soil and site parameters, as well as the respective soil property differences

TABLE 3 Descriptive statistics regarding soil data obtained via laboratory analysis, obtained via field estimation, or derived from other soil properties (see Sections 2.2 and 2.3) from field surveys, as well as sum parameters calculated by the SEPP tool. each statistical parameter was calculated for three groups, whereby the values are separated by vertical bars (all sites| ski run sites | control sites). The calculations of the statistics describing the topsoil (A-horizons) and subsoil (E-, B- and C-horizons) are based on weighted average values that take horizon thicknesses into consideration. All listed properties were used by the SEPP tool to obtain soil function fulfilment levels

	Average	Median	Std. deviation	Minimum	Maximum
Soil properties – topsoil					
pH	5.7 | 6.5 | 4.9	5.3 | 6 | 4.7	1.2 | 1.2 | 0.6	4.1 | 5.1 | 4.1	8.5 | 8.5 | 6.5
Clay content [%]	7.9 | 7.8 | 8	8 | 8 | 8	0.5 | 0.8 | 0	5 | 5 | 8	8 | 8 | 8
Soil organic matter content [%]	5.2 | 3.9 | 6.4	4.7 | 3.8 | 6	3.3 | 2.2 | 3.7	1 | 1 | 2.1	16 | 8.4 | 16
Coarse (>2 mm) fragment content [%]	41.8 | 52.9 | 30.7	50 | 50 | 30	19.5 | 4.8 | 22.4	0 | 45 | 0	71.7 | 60 | 71.7
Bulk density [$g\,m^{-3}$]	0.9 | 1 | 0.8	0.9 | 0.9 | 0.8	0.2 | 0.2 | 0.1	0.6 | 0.7 | 0.6	1.3 | 1.3 | 1.1
Carbonate content [%]	0.4 | 0.7 | 0	0 | 0 | 0	0.8 | 1.1 | 0	0 | 0 | 0	3.2 | 3.2 | 0
Soil properties – subsoil					
pH	5.9 | 6.5 | 5.2	5.5 | 6.4 | 5.1	1.2 | 1.2 | 0.6	4.6 | 5.1 | 4.6	8.7 | 8.7 | 6.5
Clay content [%]	7.2 | 7 | 7.3	8 | 8 | 8	1.3 | 1.5 | 1.2	5 | 5 | 5	8 | 8 | 8
Soil organic matter content [%]	2.6 | 1.6 | 3.6	1.9 | 1.3 | 3	2.3 | 1.4 | 2.6	0 | 0 | 0.3	10.6 | 5.7 | 10.6
Coarse (>2 mm) fragment content [%]	70.4 | 73.7 | 67.3	70 | 75 | 70	18.8 | 4 | 25.9	20 | 70 | 20	100 | 80 | 100
Bulk density [$g\,m^{-3}$]	1.1 | 1.3 | 1	1.1 | 1.2 | 1	0.3 | 0.3 | 0.2	0.7 | 0.8 | 0.7	2 | 2 | 1.5
Carbonate content [%]	0.3 | 0.6 | 0	0 | 0 | 0	0.9 | 1.2 | 0	0 | 0 | 0	3.7 | 3.7 | 0
Soil profile statistics					
Slope of the profile site [degree]	22.2 | 21.1 | 23.3	23 | 20.5 | 26	10 | 9.8 | 10.4	0 | 6 | 0	40 | 38 | 40
Rooting depth [cm]	45.4 | 38.1 | 52.8	39 | 39 | 46	20.2 | 6.5 | 26.2	25 | 29 | 25	120 | 55 | 120
Soil profile sum parameters (calculated by SEPP per profile)					
Fine earth (<2 mm) amount [$kg\,m^{-2}$]	164 | 106 | 222	125 | 99.5 | 157.5	120.9 | 44.3 | 145.1	51 | 51 | 77	600 | 224 | 600
Clay amount [$kg\,m^{-2}$]	12.3 | 7.8 | 16.9	9 | 6.5 | 12	9.3 | 3.8 | 10.9	4 | 4 | 6	43 | 18 | 43
Soil organic matter amount [$kg\,m^{-2}$]	5.8 | 2.6 | 8.9	4.5 | 3 | 9	4.6 | 1.3 | 4.6	1 | 1 | 4	22 | 5 | 22
Available water capacity [$l\,m^{-2}$]	43.7 | 24.3 | 63	31.5 | 20.5 | 57	30.5 | 8.5 | 32.5	15 | 15 | 25	139 | 46 | 139
Field capacity [$l\,m^{-2}$]	66.2 | 36.6 | 95.8	49 | 31 | 87.5	46.2 | 12.6 | 48.8	23 | 23 | 37	210 | 69 | 210
Air capacity [$l\,m^{-2}$]	24.4 | 16.9 | 32	19 | 17 | 25.5	14.8 | 4.5 | 17.7	11 | 11 | 14	70 | 27 | 70
Water storage capacity [$l\,m^{-2}$]	44.4 | 24.3 | 64.6	31.5 | 20.5 | 57	31.3 | 8.5 | 32.9	15 | 15 | 25	139 | 46 | 139
Minimal hydraulic conductivity coefficient [$cm\,day^{-1}$]	187.4 | 268.1 | 106.6	300 | 300 | 45	139 | 87.1 | 135.8	1 | 45 | 1	300 | 300 | 300
Effective cation exchange capacity [$cmol_c\,m^{-2}$]	1558.4 | 1027.1 | 2089.8	1181.5 | 923 | 1704.5	1147.2 | 405.3 | 1397.6	543 | 543 | 689	6391 | 2152 | 6391

between the ski runs and control sites. Furthermore, we discuss whether soil property differences are reflected by the SFA results and identify potential weak points of the SEPP tool.

3.3.1 | Habitat for drought-tolerant species and habitat for moisture-tolerant species

These two functions consider the habitat potential of the soil for plants and animals that live in the soil or close to the surface but not for microorganisms. The SEPP rating for all investigated soils in the study area was based solely on the available water capacity (see Table 2), which was medium in the control sites and rather low in the ski runs. Water capacity is controlled by soil organic matter and clay amounts, which are comparatively low in the stony soils found at high elevations, whereby edaphic drought is fostered at these sites. The thresholds for the water capacity classes differ between the two functions, which explains why the distribution of the levels is not simply an inverted mirror image. The assessment results showed that the SEPP tool was able to reflect the differences between ski runs and control sites, as all levels were covered, and a clear shift was observed.

3.3.2 | Habitat for soil organisms

The SFA of the function *habitat for soil organisms* evaluates favourable living conditions for microorganisms and

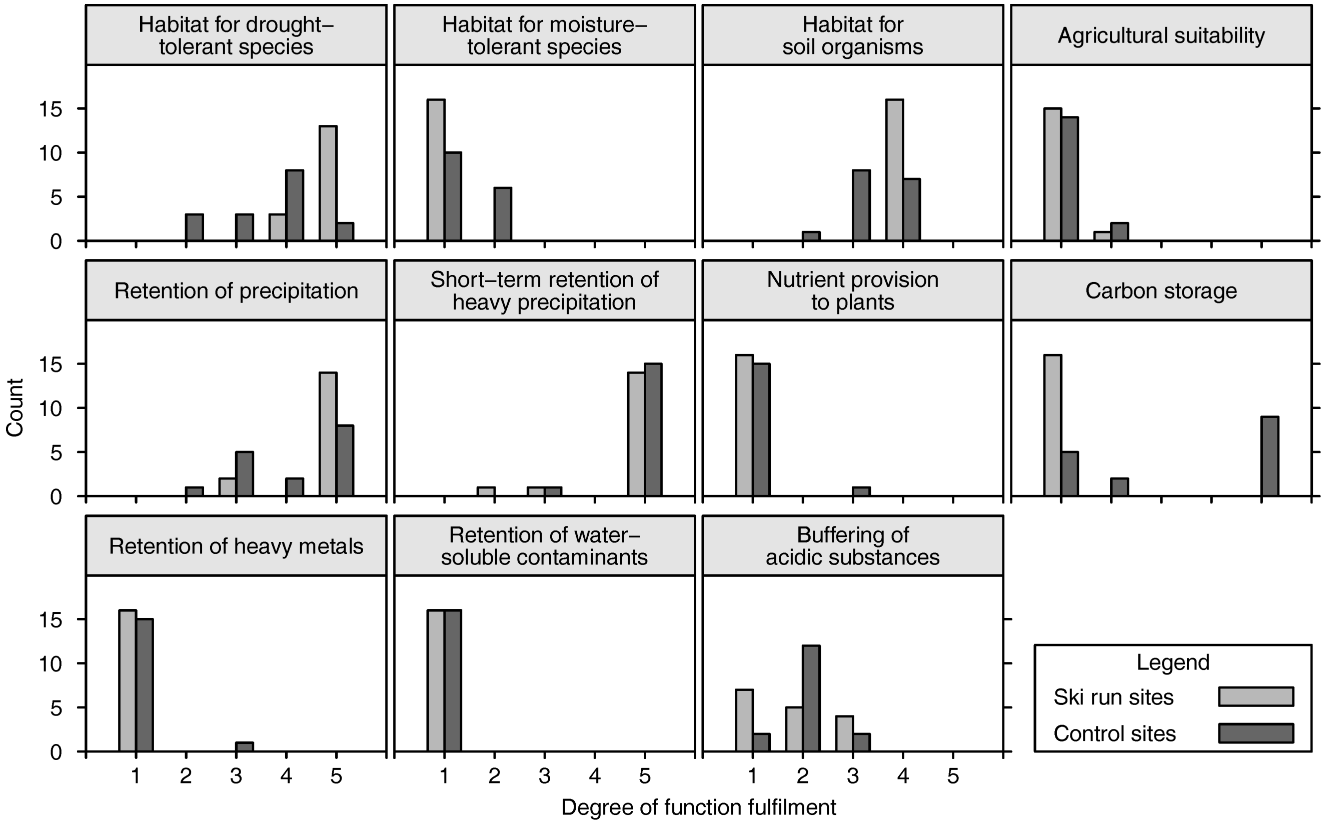

FIGURE 3 Bar charts representing the distribution of the soil function fulfilment levels [from 1 (very low) to 5 (very high)] of the 32 soil profiles in the ski runs (light grey) and the corresponding control sites (dark grey) assessed by the SEPP tool

soil fauna that are crucial for decomposition and bioturbation processes. Within the test dataset, pH was the decisive parameter for this function because the other three input parameters (i.e. land use, soil moisture and soil texture) did not reveal any significant difference between the ski runs and control sites. The results obtained by applying the SEPP tool suggest better fulfilment of this function among ski run sites, as they mostly have higher pH values. Although this SFA method is suitable for high-mountain environments, an adaptation that includes widespread soil shallowness seems to be an opportunity for improvement. In addition, although the much lower organic matter and mineral nutrient contents might support small populations of specialized organisms, such a condition cannot be assessed by the model in its present form.

3.3.3 | Agricultural suitability and nutrient provision to plants

With respect to a*gricultural suitability* and *nutrient provision to plants*, almost all studied soils fell into the lowest class of function fulfilment. This can be partly explained by the low cation exchange capacity (CEC) values that characterized most soils owing to their low clay content and poor organic matter stocks, in turn caused by their small depth, shallow rooting depth and high coarse fragment contents. Only one control site, where the soil profile was dominated by a thick A-horizon with 100% fine earth, showed a medium function fulfilment level regarding *nutrient provision to plants*. The *agricultural suitability* was also limited by poor water and air supplies (i.e. low available water capacity and low air capacity, respectively), when compared with less shallow soils, as well as by the low mean annual temperature and partly by the steepness of slopes (see Table 2). In general, the evaluation method used for *agricultural suitability* is applicable to all forms of agriculture. However, the soils at the sites examined in this study are only suitable for grazing and as meadows, especially if the slope is not steep, while they have been used for pastures or meadows. Among other reasons, this limitation is owed to its low accessibility and steepness. Therefore, the SEPP tool underestimated the suitability of these soils to this particular agricultural use, as plant nutrient requirements from grazing land are lower than those from arable land. Furthermore, the SEPP tool considers the total water and air capacities of the entire soil profile, while comparatively short grassroots can only access air and water in the uppermost decimetres of the soil. Therefore, the SEPP tool shows a weak point in that it does not differentiate between soil suitability for arable farming and grazing.

3.3.4 | Retention of precipitation

The assessment of the soil function *retention of precipitation* is mainly based on the soil water storage capacity and hydraulic conductivity (see Table 2). The level of function fulfilment increases with both the parameters. Regarding hydraulic conductivity, only the lowest value among all mineral horizons is considered (henceforth referred to as the minimal hydraulic conductivity) because this horizon limits the percolation rate of the entire profile (SEPP user manual (Supporting Information)). Although the SEPP tool calculated a lower average water storage capacity for ski runs, the tool assessed the corresponding function fulfilment for *retention of precipitation* as being higher than that in control sites, because of higher minimal hydraulic conductivities in ski run soil. This was mainly owing to the considerably thick layers of unconsolidated material above the impermeable bedrock as a result of the construction works, which often included a reshaping of the rocky substrate and a consequent breaking of hard rocks into stone and sand particles. These layers with coarse fragment contents greater than 60% were attributed the maximum hydraulic conductivity coefficient (i.e. 300 cm day^{-1}) by the SEPP tool. On the other hand, control soils cannot use the potential of their high water storage capacities because of their low minimal hydraulic conductivities that do not allow water to percolate fast enough into deeper layers. Generally, the presence of solid rock within the first few decimetres of the soil was the main limiting factor for water conductivity in high-mountain soils, particularly in our control sites. Moreover, the SEPP tool assigns a hydraulic conductivity coefficient of 1 cm day^{-1} to the solid rock layers. Thus, even a very high water storage capacity of over 300 L m^{-2} would only lead to a soil function fulfilment level of two, showing that the minimal hydraulic conductivity coefficient is often the dominant factor in this assessment in mountainous environments. Therefore, it is important to scrutinize the input parameters of the C-horizon. Although it is highly probable that a solid rock exists beneath these thick unconsolidated layers in the ski runs in the tested area, the prevailing stoniness strongly hindered deeper soil excavation. If the solid rock in the uppermost metre of the soil profile is overseen, the SEPP tool will significantly overestimate the *retention of precipitation* function. An adaptation of the SEPP water storage capacity thresholds according to the shallowness of most high-mountain soils would allow for better identification of differences in such environments.

3.3.5 | Short-term retention of heavy precipitation

The function fulfilment levels of *short-term retention of heavy precipitation* showed almost no differences between the ski runs and control sites. The assessment is based on the ratio between a design even precipitation (rainfall amount per hour with a 10-year return period) and air capacity in the upper decimetres of the soil, coupled with a correction factor according to the minimal hydraulic conductivity coefficient in the corresponding horizons (SEPP user manual (Supporting Information)). The main reason for the high level of function fulfilment in almost all soils under study was the comparatively low design event precipitation of 25 mm h^{-1}, which is typical for inner-Alpine climates in the Aosta Valley (Fondazione CIMA, 2009). Thus, the fulfilment level thresholds in the SEPP tool are probably not ideal for high-mountain soils in inner-Alpine areas.

3.3.6 | Carbon storage

The SFA results regarding *carbon storage* showed significantly lower levels of fulfilment for the soils in the ski runs than those in the control sites. This pattern can be explained by the reduction of carbon storage with less dense vegetation, the almost complete loss of organic layers and the decline of organic matter in mineral soil horizons in ski runs. The latter was caused by mixing with deeper layers and by the partial loss of the former surface horizons during ski run construction because of erosion. Soil mixing also causes the disruption of aggregates, significantly decreasing the physical protection of organic matter, which is subsequently easily mineralized (Six et al., 2002). However, the methods used by the SEPP tool to assess this function must be critically discussed. The carbon storage calculation was dominated by land use parameters. In particular, the SEPP tool automatically assigns the highest soil function fulfilment level to forest soils because the entire forest ecosystem stores high amounts of carbon in the mineral soil, partly thick organic layers and trees. This was applied to nine out of the 16 sampled control sites. For all other soils, the amount of stored carbon was only calculated from the amount of SOM in the mineral soil, and the organic layers (and vegetation cover) were neglected by the SEPP tool. This procedure is reasonable for both agricultural and urban soils. However, in areas dominated by shrubs near or above the timberline, we found soils that indeed show forest soil characteristics, whereas typical forest vegetation (i.e. trees) is sparse, and the thicknesses of the organic layers vary widely. If the amount of SOM in the mineral soil, but not land use, was considered, five of the nine, three and one sampled forest soils were assigned level 1 (very low), level 2 (low) and level 3 (medium, see Figure 4), respectively. As all ski run sites were attributed to very low levels of function fulfilment, the statement that this function is strongly impaired by ski run construction is still valid, although the effect may not be as severe as the SEPP results suggested. The average SOM amount in the mineral layers of the soils in the control sites alone (8.9 kg m^{-2}) was already 3.4 times higher than that in the soils beneath the ski runs (2.6 kg m^{-2}). Forest soils had an average SOM amount of 9.9 kg m^{-2} plus a total thickness of organic layers ranging between 3 and 16 cm, with the latter being currently neglected by the SEPP tool. To improve the method and adapt it to high-mountain environments, the carbon storage in the mineral and organic soil layers should be calculated from actual data, regardless of land use. The latter can be derived from the organic layer thickness and the typical carbon amounts of OL, OF, and OH, as determined by Djukic et al. (2010) and Egli et al. (2009) for different sites in the Alps. For example, we used the SOM amount of 0.75 kg m^{-2} per centimetre of organic layer thickness (Djukic et al., 2010), which led to a new distribution of function fulfilment levels, with five and four forest soils classified as low and medium, respectively (see Figure 4).

3.3.7 | Retention of heavy metals

The function *retention of heavy metals* is controlled by clay minerals and organic components that can immobilize heavy metals depending on pH. Thus, the relative bonding strength to retain heavy metals increases with increasing amounts of fine earth, clay and organic matter content and pH (SEPP user manual (Supporting Information)). Except for one, all profiles were assigned the lowest level of function fulfilment. Owing to the class limits (relative bonding strength: <1.5, 1.5 to <2.5, 2.5 to <3.5, 3.5 to <4.5, and ≥4.5), no differences between control sites and ski runs were observed, although the determining properties varied. This situation changes if the criteria "relative bonding strength" is reclassified. Table 4 shows the distribution when level 1 is subdivided into five new classes with a range of 0.25. After the reclassification, the direct comparison of ski runs with the corresponding paired control sites showed that the function was impaired for 11 paired soils, remained similar for four pairs, and increased for only one pair, in which the ski run had a higher function fulfilment level. This exceptional ski run profile with a considerably higher function fulfilment score than its undisturbed counterpart was characterized by a stone-free, deep topsoil.

3.3.8 | Retention of water-soluble contaminants

The main reason for the function *retention of water-soluble contaminants* to have been evaluated as very low across all sites is the high amount of water that percolates through the soil. Annual leaching of at least 540 mm, owing to an over 722 mm of annual precipitation (Champoluc weather station, 1570 m a.s.l.; Mercalli, 2003) and approximately 170 mm of annual evapotranspiration (Filippa et al., 2019), was the determining factor. The final level of function fulfilment depends on the ratio of the leaching rate to the field capacity. The higher the ratio, the higher the exchange rate of soil water and the more water-soluble contaminants enter groundwater bodies, or particularly in mountainous areas, into rivers via interflow. In all soils in the study area, the field capacity was below 210 mm, implying that soil water was exchanged at least 2.6 times per year, while in the SEPP tool, the limit for the lowest level was defined at an exchange rate of 2.5 or higher. Thus, the threshold values do not seem to be ideal for the evaluation of this function in high-mountain soils.

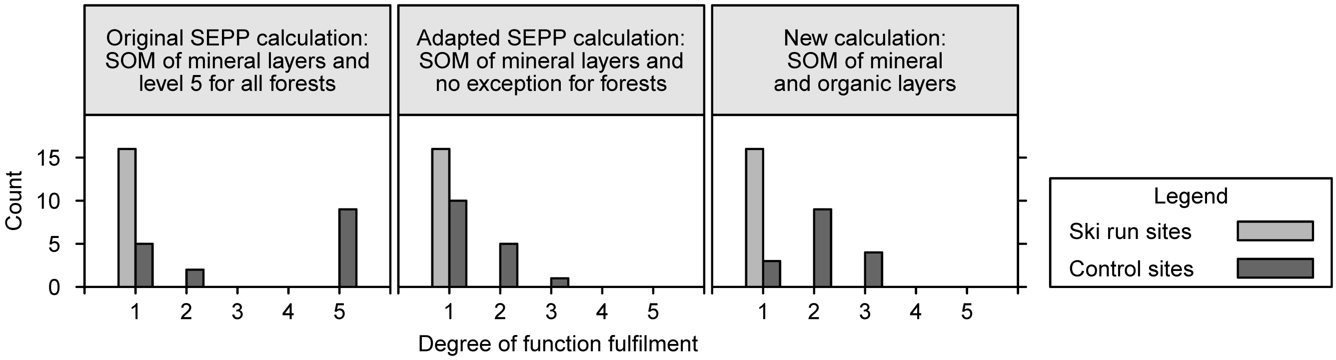

FIGURE 4 Function fulfilment levels for carbon storage using three different approaches. Left: Soil organic matter (SOM) in mineral soil plus level 5 for all forest profiles; middle: Only SOM in mineral soil; right: SOM in mineral soil plus SOM in organic layers

TABLE 4 Distribution of profiles into new classes of relative bonding strength for heavy metals, which is the indicator for the function *retention of heavy metals*

New level of function fulfilment *retention of heavy metals*	Relative bonding strength	No. of ski run sites	No. of control sites
1	0–0.25	3	1
2	>0.25–0.5	10	5
3	>0.5–0.75	2	3
4	>0.75–1	1	2
5	>1	0	5

3.3.9 | Buffering of acidic substances

The function *buffering of acidic substances* is controlled by the availability of exchangeable cations, carbonate-dependent buffer capacity and the buffer capacity of the organic layers. In turn, the availability of exchangeable cations is based on the amount of fine earth, CEC_{pot} (calculated from the organic matter content, clay content, and texture) and base saturation (SEPP user manual (Supporting Information)). Furthermore, while the fine earth amount and CEC_{pot} varied more among the control sites, pH-controlled base saturation showed a wider range in ski runs. The carbonate-dependent buffer capacity only contributed to the buffering of acidic substances in ski run soils. In contrast to the carbonate-free control sites, 7 out of 16 ski run soils contained carbonates with a maximum content of approximately 3.5% (see Table 3). The contribution of the organic layers of the soils in the control sites had a lower impact on the function fulfilment level. None of the soils exceeded level three in the SEPP evaluation, mainly because of low amounts of fine earth, which considerably influences the availability of exchangeable cations, as well as the carbonate-dependent buffer capacity. If the SEPP thresholds would take into account that fine earth amounts in high-mountain soils are comparatively much lower than in soils at lower elevations, it would certainly help to better differentiate high-mountain soils.

3.4 | Potential adaptations of the SEPP tool for the evaluation of high-mountain soils

The present study showed that although the use of the SEPP tool in high-mountain environments works well for the evaluation of some soil functions, it definitely has several shortcomings, especially regarding the degree of differentiation. In particular, the major limitations observed are caused by the determining thresholds of decisive parameters and function fulfilment levels, the quality and spatial resolution of climatic input data, and the algorithms implemented in the assessment methods.

3.4.1 | Thresholds

The methods implemented in the SEPP tool have been developed for landscapes below the timberline. Thus, the class limits were not set according to the range of possible values in high-mountain soils; instead, they were set according to the range of all soils occurring in a temperate climate at lower elevations. Consequently, existing differences or potential changes in properties within the context of high-mountain soils do not necessarily result in a shift in the assigned level of function fulfilment. To detect such changes, these limits must be adapted for studies in actual high-mountain environments. For example, for the functions *retention of heavy metals* and *buffering of acidic* substances, this improvement option would be sufficient to adequately assess the function fulfilment levels of high-mountain soils characterized by low fine earth content. However, for other functions, the adaptation of the class limits is not the only needed improvement measure to enable a high-mountain-specific SEPP tool. Because grazing in high-mountain environments and sometimes mowing are the only agricultural practices possible, the relevant thresholds (i.e. nutrients, air and water capacities, and slope) should be adapted to this particular agricultural use in the assessment of *agricultural suitability*. Alternatively, only the uppermost 30 cm of the soil might enter the evaluation process for grasslands, as grass roots can hardly access deeper layers. Similarly, the soil function *retention of precipitation* would benefit from threshold adaptation, as shallow high-mountain soils have low water storage capacities. However, a comparison of ski runs with control sites showed that the decisive component for the assessment of this function was hydraulic conductivity. Thus, class-level adaptation alone cannot resolve this issue. Also, the level of fulfilment of the function *retention of water-soluble contaminants* was very low for all the soils investigated here, which suggests the need to adapt the threshold values regarding the factor field capacity accordingly. For the Aosta Valley, with low annual precipitation, this would enable the differentiation of shallow, stony soils. However, owing to major climatic differences, annual leaching in the Alps varies over a broad range. Therefore, more studies are needed to determine if this adaptation would really benefit the assessment of *retention of water-soluble contaminants* in high-mountain soils. The situation is very similar for the *short-term retention of heavy precipitation*, as the design event precipitation in other high-mountain areas is not necessarily as low as it is in the Aosta Valley.

However, with the current limits, it is evident what soil functions are generally well fulfilled by high-mountain soils, and what functions are rather poorly fulfilled, compared with soils from low-lying areas. This information is lost if limits are adapted. To avoid this and still be able to reflect smaller soil changes, a better option would be to maintain the original limits and fulfilment levels (1–5) and concurrently introduce additional sublevels (e.g. 1.1, 1.2) according to more differentiated soil parameter limits.

3.4.2 | Climatic parameters

The climatic SEPP input parameters, namely annual precipitation, design event precipitation, annual evaporation, and mean annual temperature, were set only once for the entire study area without further spatial differentiation. This originates in the structure of the SEPP tool but does not ideally represent real climatic conditions. In particular, temperature decreases, while precipitation increases with altitude, with a concurrent prevalence of snow precipitation events. Additionally, the microclimate above the timberline is strongly determined by the terrain, for example, through small-scale patterns of snow cover and water, as well as heat budgets (Stöhr, 2007). Consequently, the functions *agricultural potential*, *short-term retention of heavy precipitation* and *retention of water-soluble contaminants* entail a certain degree of uncertainty. This should be addressed by importing climatic information such as other site parameters (e.g. slope and land use) profile-wise.

3.4.3 | Algorithms

In addition to modifying the class limits and climatic input parameters, our study revealed two main options for adapting the SEPP tool to enable greater differentiating power to capture even subtle differences among high-mountain soils, which are often similar owing to their intrinsic soil properties (e.g. stoniness, shallowness, comparatively low clay content and partly thick organic layers including such types as root felt).

First, the humus forms should be better differentiated and considered for more soil functions. When assessing high-mountain soils, this improvement is particularly essential for *carbon storage*. But also other functions, such as *retention of precipitation* and *nutrient provision to plants*, are strongly influenced by organic layers, whereas the humus form itself is a good indicator of habitat suitability for earthworms, fungi or arthropods (Prescott & Vesterdal, 2021; Zanella et al., 2018). As for *carbon storage*, the selection of the most suitable values for the amount of carbon stored per square metre per centimetre of organic layer thickness is crucial. It needs to be differentiated among organic soil layers (OL, OF, and OH) because they have different densities and soil organic matter qualities, and therefore, different amounts of carbon (Vanguelova et al., 2016; Zanella et al., 2018).

Second, almost all the assessed functions depend on the amount of clay and organic matter in the mineral soil (see Table 2). As clay amounts are generally low in high-mountain soils, organic matter amounts are more important for CEC, water-holding capacity and the retention of pollutants; thus, they should have a greater weight for assessment purposes.

In addition, the SEPP tool does not explicitly consider biodiversity, although especially high-mountain environments can support species with very different demands in comparatively small areas (Hagedorn et al., 2019; Körner, 2003). Our assessment results for the functions *habitat for drought-tolerant species* and *habitat for moisture-tolerant species* do not support the findings reported by Hudek et al. (2020), who investigated the same sites but focused on vegetation and root morphology. However, integration of plant species data contradicts the intention of the SEPP tool to work with standard soil parameters. Similarly, new methods to identify present species, such as genetic characterization using molecular methods (e.g. nucleic acid analysis), offer new opportunities regarding the function *habitat for soil organisms* (Orgiazzi et al., 2015; Römbke et al., 2018). However, as long as such analyses are not standard, the advantage of the SEPP tool remains that it works with comparatively simple parameters that are mostly covered in traditional soil sampling procedures. A similar situation applies to *agricultural suitability*. Some parameters that would help to assess these two functions more accurately are not considered because sophisticated analytical methods are required. In particular, soil nutrient content normally correlates well with total organic matter, and in ski run soils, both N and available P were significantly lower than in the control plots (Hudek et al., 2020). Thus, the actual differences in soil fertility, with control sites being able to support much larger biomass than ski run sites, cannot be reflected by SEPP results.

Table 5 summarizes the estimated suitability of the SFA methods currently implemented in the SEPP tool as

TABLE 5 Suitability of SEPP to reflect soil function fulfilment in high-mountain environments and identified options for their adaptation

Soil function	Suitability to evaluate high-mountain soils	Options for adaptations
Habitat for drought-tolerant species Habitat for moisture-tolerant species	Yes Yes	Option 1: Instead of these two functions, create one function that reflects biodiversity. Disadvantage: Soil data is needed that is generally not available and requires new sampling. Option 2: Integrate—in addition to water conditions—pH, carbonate content, and stoniness. Option 3: Merge these two functions to one function "habitat for drought- or moisture tolerant species".
Habitat for soil organisms	Yes	Include soil depth (more soil can support more soil organisms) and humus form.
Agricultural suitability	Partial	Adapt the thresholds regarding rooting depth, available water capacity, air capacity, nutrient availability, and maybe slope (as high-mountain areas are only used for pasture or in some cases meadows, but not for crop production).
Retention of precipitation	Partial	Make sure soil descriptions used as input parameters cover at least 1 m to avoid overseeing impermeable layers close to the surface, such as solid rock, that might hinder percolation. Optional: Adapt the thresholds for water storage capacity in high-mountain soils according to the widespread shallowness of soils.
Short-term retention of heavy precipitation	Yes	No adaptations needed.
Nutrient provision to plants	No	Adapt thresholds (nutrient stock).
Carbon storage	No	Remove land-use parameter from assessment and include organic matter amount of organic layers instead. Optional: Slightly adapt threshold (amount of C_{org} in soil).
Retention of heavy metals	No	Adapt threshold (relative binding strength for heavy metals [Cd-equivalent]).
Retention of water-soluble contaminants	No	Adapt threshold (exchange rate of soil water).
Buffering of acidic substances	Yes	Optional: Slightly adapt thresholds (buffer capacity).

well as suggestions for their adaptation. To identify new thresholds of a potential high-mountain version of the SEPP tool, it should be further tested with high-mountain soils with a broad variety of characteristics to avoid an implementation that is useful only at very specific sites. Additionally, uncertainty estimations of SFA results based on the comparison of modelled (by the SEPP tool) and observed (in field experiments) processes, such as the infiltration and percolation of precipitation, would be highly valuable.

3.4.4 | Further soil functions

It must be noted that SEPP is centred mainly on low-elevation land uses and functions; other more strictly ecological functions, such as support for specific and "endemic" vegetation types and species, have been neglected. Considering that high-mountain areas are mostly left to natural evolution and are suitable for tourism and nature conservation, the inclusion of these non-productive ecological functions would be highly beneficial.

4 | CONCLUSIONS

In this study, we tested the SEPP tool, which enables automated SFA in a high-mountain environment. Specifically, we evaluated 11 soil functions in 16 soil profiles in the constructed ski runs, and 16 paired control profiles in the Italian Alps. Our study demonstrated that several assessment methods of the SEPP tool should be further adapted specially to high-mountain conditions to ensure that the model can capture even small soil property changes in such environments. Potential adaptations range from including new soil parameters or indicators to simply adjust the thresholds that determine the soil function fulfilment level. Nevertheless, the current version of the SEPP tool allows for the identification of relevant changes in soil function fulfilment that are attributable to ski run construction. Thus, when comparing ski runs versus control sites, most soil functions were fulfilled to comparable levels; some to a lesser extent (e.g. *carbon storage*), while others to an even greater extent (e.g. *retention of precipitation*). An aspect that is not considered by SFA is the small-scale pedodiversity in control sites, which is mostly related to topographical microrelief. Owing to the disturbance caused by land levelling during construction of the ski runs in our study area, these soils were more homogenous than those in the control sites, and thus, showed smaller variability in all soil properties, except for carbonate content, and consequently, pH. Overall, we conclude that SFA is generally a good basis for evaluating the impacts of land-use change, even on high-mountain soils, provided that the assessment methods are examined thoroughly, and if necessary, adapted.

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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