Research Paper

Recovery of Topsoil Physico-Chemical Characteristics in Different Aged Landslides in Alaknanda Watershed, Uttarakhand, India

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The study analyzed the natural recovery of soil physico-chemical properties with time in two different aged landslides i.e., 7-year-old (L1 site) and 21-year-old (L2 site) in the Kalimath area of Uttarakhand. The collected soil samples were analyzed for various physical (bulk density, particle density, porosity, moisture content, particle size distribution) and chemical (pH, E.C., soil O.C., organic matter, and available N, P, K) characteristics. The results have demonstrated that the soils of landslide affected sites had less nutrient availability with reference to the control site. The concentration of various physico-chemical properties increases with the passage of time. The absence of a significant difference between the older site and the control site signifies the recovery of soil with the age of landslides. The recovery of soil organic carbon (S.O.C.) and accumulation of soil organic matter (S.O.M.) in the upper layer of soil plays a crucial role in the restoration of soil. It was observed that in a 21-year-old site, most of the soil characteristics had reached the level of about 85-95 % of the undisturbed site. On the other hand, available nitrogen showed a remarkable increase in concentration as the higher content of it was recorded in site L2 as compared to the undisturbed site.

Keywords: Recovery; Physico-chemical; Landslide; Soil organic carbon; Soil organic matter; Soil characteristics

Introduction

Landslides occur in hilly areas all over the globe, and particularly in areas of fragile geology and active seismic activity (Nadim *et al.*, 2006; Geertsema *et al.*, 2009). They are responsible for enormous social and economic losses of mountain people regarding the loss of human lives, natural resources, livelihood, and property (Sidle and Ochiai 2006; Restrepo *et al.*, 2009; Cheng *et al.*, 2016; Eynde *et al.*, 2017). In the Indian scenario, landslides occur very frequently in the rainy season in the Indian Himalayan Region (I.H.R.). Uttarakhand state being a part of this region, is highly vulnerable to landslides due to the presence of major structural discontinuity - Main Central Thrust (MCT), fragile rocks i.e. phyllites, quartzite, schist, etc. (Sajwan and Khanduri, 2016; Khanduri *et al.*, 2018), active seismic activity and unplanned development works along hill slope (Kumar *et al.*, 2020). Landslides can also have long-term effects on the environment (Geertsema *et al.*, 2009) and

significantly change the properties of the soil and plant ecosystems (Sidle *et al.*, 2006; Sassa and Canuti 2008; Cheng *et al.*, 2016).

Landslide involves the deterioration of soil characteristics related to crop production, infrastructure maintenance, and natural resource quality (Lal 2001). It includes the structural degradation of soil, loss of soil fertility and soil organic matter (S.O.M.), plant and soil nutrients loss, soil particles compaction, soil erosion, and loss of biodiversity (Acharya and Kafle 2009). Landslides induce drastic changes in soil characteristics (Walker 1994; Walker *et al.*, 1996) mainly by exposing parent bedrock (the C horizon) to the upper surface by removing the top organic-rich layer and A horizon. It also decreases the depth of regolith due to erosion (Trustrum and DeRose 1988) implicates significant differences in soil physical characteristics, especially water-holding capacity, which can also restrict plant growth (DeRose *et al.*, 1995). The considerable effect

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of landslides on the soil is the change in their texture also. In this regard, Zarin and Johnson (1995a, 1995b) found that landslide soils in a montane forest of Puerto Rico have lower clay content. Landslides can also cause considerable changes in soil chemistry at a particular site (Zarin and Johnson 1995a, 1995b; Hugget 1998; Geertsema *et al.*, 2009).

In general, regarding variations in soil properties, landslides result in a reduction in soil organic carbon (S.O.C.) and nutrients availability because parent bedrock material at sub-surface typically contains less content of S.O.C. and available nutrients are exposed and redistributed to the upper surface (Guariguata 1990; Singh *et al.*, 2001; Wilcke *et al.*, 2003; Sparling *et al.*, 2003; Cheng *et al.*, 2016). Most of the authors have reported lower amount of organic carbon (O.C.), available nitrogen (N) and phosphorus (P), exchangeable basic cations (Ca^{2+} , Mg^{2+} , and K^{+}) in soils of recent landslides as compared to adjacent undisturbed soils (e.g., Lundgren 1978; Guariguata 1990; Reddy and Singh 1993; Dalling and Tanner 1995; Zarin and Johnson 1995a, 1995b; Singh *et al.*, 2001; Blonska *et al.*, 2016). Contradictory to these findings, Adams and Sidle (1987), found higher pH and a higher concentration of exchangeable Ca^{2+} in three recent landslides in Southeast Alaska. Similarly, Schrumpf *et al.*, (2001) argued that landslides ameliorate the soil fertility by bringing less weathered or less eroded and more nutrient-rich content to the upper ground layer from the surface below in landslide affected acidic and nutrient-poor soils of southern Ecuador. They reported the presence of less eroded phyllosilicates, higher pH, and more concentration of exchangeable nutrients in soils of radiocarbon-dated landslides (600-700 years of age).

In landslides, the top fertile layer of soil is carried downslope, and all the vegetation got uprooted; as a result, new plants are unable to germinate due to absence of fertile soil; therefore, the bare areas of landslides can remain visible for many years (Schuster and Highland 2007). To fill up the gap, quick successional changes occur on unstable soil, which leads to the recovery of the structure and functioning of the disturbed ecosystem (Mou *et al.*, 1993).

The pace of topsoil development is crucial for assessing the strength and resilience features of the

soil (Greenland and Szabolcs 1994; Seybold *et al.*, 1999) and its regeneration or recovery capacity after the losses due to the erosion of land (Lal 1994; Sparling *et al.*, 2003). Monitoring the same site over a period of time is generally considered to be the most effective way to assess variations in the characteristics of soil (Powlson and Johnston 1994; Powlson *et al.*, 1998; Sparling *et al.*, 2003). However, the natural process of pedogenesis, i.e., soil formation, is prolonged on the human time-scale and may take hundreds of years after the disturbances to reach equilibrium (Jenkinson *et al.*, 1987; Jenkinson 1990). Therefore, as a substitute, a single sampling on different aged landslides can be done to estimate the recovery of soil because it is as reliable as resampling a particular site with time (Sparling *et al.*, 2003). Hence, the same methodology has been implemented in the present study also.

Soil fertility restoration generally requires many decades, as Lundgren (1978) reported lower O.C. and clay content inside landslides compared to undisturbed soils seven years after the landslide occurrence in the Uluguru Mountains of Tanzania. Similarly, Zarin and Johnson (1995a, 1995b) found that the concentration of organic carbon and exchangeable basic cations (Ca^{2+} , Mg^{2+} , and K^{+}) in the soil does not recover to their pre-disturbance level even after a period exceeding 55 years. Temporal variations in different characteristics of soils in recent landslide have been observed by various other researchers also for soil O.C., available nitrogen (N), available phosphorus (P), C.E.C. and soil texture, with an increment of fertility in soil with time (Lundgren 1978; Lambert *et al.*, 1984; Joshi 1990; Reddy and Singh 1993; Sparling *et al.*, 2003; Rosser and Ross 2011; DeRose 2013; Noyes *et al.*, 2016; Eynde *et al.*, 2017).

However, very little attention and researches have been carried out to assess the effects of landslides on the natural environment as compared to the impacts on infrastructure and human lives (Schuster and Highland 2007; Geertsema *et al.*, 2009). In the present study area, no such study has been reported so far to demonstrate the recovery of soil health after the occurrence of landslides. Therefore, an attempt has been made to assess the restoration and recovery of soils in landslide affected areas.

Materials and Methods

Study Area

The study area is along the Kaliganga river valley near Kalimath village at about 1256 m above sea level (Fig. 1). Kalimath is at a distance of about 20 km

from Kedarnath (Kannaujiya *et al.*, 2019). The village is dedicated to divine Goddess Maa Kali which is bounded by 30°33' 10" to 30°43' 08" N latitudes and 79° 04' 35" to 79° 10' 23" E longitudes in Rudraprayag district of Uttarakhand state of India (Semwal *et al.*, 2013). The average annual precipitation and

temperature of the district are 1110.44 mm and 17.05, respectively.

Site Selection

In the study area survey was done to collect the preliminary information about the landslide sites. After the survey, landslide affected sites of different ages have been selected for the present study. Landslides occurred at site L1 in 2012 (7-year-old) (Fig. 2), and at L2 in 1998 (21-year-old) (Fig. 3), with reference to the sampling year 2019. One unaffected site (control site) has also been selected adjacent to the disturbed sites (30° 33' 33.52" N, 79° 05' 10.38" E) to compare differences in characteristics of the soil of the disturbed and non-disturbed sites (Fig. 4). All the sites are inclined at an angle of about 34°. The G.P.S. location of affected sites L1 and L2 are - 30° 33' 53.94" N, 79° 05' 06.18" E and 30° 33' 55.68" N, 79° 05' 02.88" E, respectively.

Soil Sampling and Laboratory Analysis

Soil sampling was done incorporating standard

Fig. 1: Study area Kalimath in Rudraprayag district (enlarged view of landslide sites – L1 (landslide occurred in 2012) and L2 (landslide occurred in 1998))

Fig. 2: Site L1

methods. In all three sites, after clearing the organic component from the surface and fine root parts from the soil, composite samples were collected at a regular grid of about 5 m at two depths: 0-15 cm and 15-30 cm. A total of 52 soil samples (18 samples in site L2 and control site and 16 samples in site L1) have been collected in the post-monsoon season. Soil samples were kept in plastic bags and were air-dried following standard methods. Air-dried soil samples were passed through a 2 mm sieve for physical analysis. The particle size distribution of soil (sand, silt, and clay content) was measured using the Hydrometer method (Bouyoucos 1962), and the textural class was identified using the USDA textural triangle. Moisture content was calculated using the gravimetric method before the air drying of samples. Soil particle density was estimated using pycnometer bottles, and bulk density was determined using core sampler. The porosity of soil was calculated using the formula:

$$\text{Porosity} = \left(1 - \frac{\text{B.D.}}{\text{P.D.}}\right) \times 100 \quad (1)$$

where B.D. is bulk density, and P.D. is particle density.

Fig. 3: Site L2

Fig. 4: Control site

Soil samples were sieved through a 0.2 mm sieve for chemical analysis. Soil pH was measured in soil-water suspension in a ratio of 1:2.5 (soil: deionized water) using a pH glass electrode after shaking of about 30 minutes. Electrical conductivity (E.C.) was measured from the supernatant of the same suspension, which was left undisturbed overnight. Soil organic carbon content (S.O.C.) was calculated using rapid titration method by Walkley and Black (1934), and soil organic matter (S.O.M.) was estimated by multiplying S.O.C. by a factor of 1.724 called as 'van Bemmelen factor.' Available nitrogen (N) was determined by using the Kjeldahl method (Subbiah and Asija 1956). Available phosphorus (P) was estimated colorimetrically by the ascorbic acid method developed by Watanabe and Olsen (1965) using Shimadzu UV-Visible (1800) spectrophotometer, and for available potassium (K) content soil was extracted with 1 N ammonium acetate at pH 7 and was

Table 1: Soil chemical characteristics (means $\pm$ standard error) of study site

Soil properties	Soil depth (cm)	Sites (year of landslide occurrence)		Control
		L1 (2012)	L2 (1998)	
pH	0-15	5.96 $\pm$ 0.145	5.08 $\pm$ 0.053	5.15 $\pm$ 0.125
	15-30	6.11 $\pm$ 0.121	5.05 $\pm$ 0.064	5.39 $\pm$ 0.112
¹ E.C. (μ S/cm)	0-15	68.39 $\pm$ 13.149	73.37 $\pm$ 12.635	154.78 $\pm$ 7.565
	15-30	53.45 $\pm$ 7.458	68.57 $\pm$ 9.592	127.91 $\pm$ 10.79
² S.O.C. (%)	0-15	0.31 $\pm$ 0.031	2.09 $\pm$ 0.098	2.19 $\pm$ 0.13
	15-30	0.19 $\pm$ 0.022	2.02 $\pm$ 0.074	1.76 $\pm$ 0.057
³ S.O.M. (%)	0-15	0.54 $\pm$ 0.053	3.61 $\pm$ 0.168	3.77 $\pm$ 0.225
	15-30	0.33 $\pm$ 0.038	3.48 $\pm$ 0.127	3.03 $\pm$ 0.099
⁴ Avail. N (kg/ha)	0-15	53.31 $\pm$ 8.126	780.52 $\pm$ 106.951	755.43 $\pm$ 19.699
	15-30	31.36 $\pm$ 5.807	674.59 $\pm$ 35.65	643.93 $\pm$ 24.825
⁵ Avail. P (kg/ha)	0-15	15.16 $\pm$ 0.647	27.67 $\pm$ 0.649	30.32 $\pm$ 1.686
	15-30	11.72 $\pm$ 0.707	23.17 $\pm$ 0.9	23.48 $\pm$ 1.53
⁶ Avail. K (kg/ha)	0-15	298.52 $\pm$ 8.37	381.86 $\pm$ 6.276	455.74 $\pm$ 28.479
	15-30	285.86 $\pm$ 8.006	378.02 $\pm$ 10.979	442.95 $\pm$ 18.013

¹electrical conductivity, ²soil organic carbon, ³soil organic matter, ⁴available nitrogen, ⁵available phosphorus, ⁶available potassium

determined using Agilent (280 FS G 8434) atomic absorption spectrophotometer.

Statistical Analysis

Differences between the landslide affected and unaffected sites were analyzed using one-way ANOVA and Tukey's HSD post-hoc test. The relationship strength between various properties of soil was determined by using Pearson's correlation coefficient. All the computation of statistics was performed using the SPSS software for windows.

Results

Recovery of Soil Chemical Properties Studied

The average values of chemical characteristics of the soil of landslide affected and unaffected (control) site are shown in (Table 1). All the chemical properties of soil studied were found to have a significant difference between the different sites, i.e., landslide affected and unaffected sites (ANOVA, $p < 0.05$). Soil pH ranges from 5.05 to 6.11, which shows that the moderate acidic conditions prevail in site L2 as the pH of soil decreases as compared to the L1 and control site. But it doesn't show any clear relationship with the age of landslide. pH shows a significant

negative correlation with all parameters ($p < 0.01$) except for positive correlation with B.D., P.D., and sand content (Table 3). On considering the electrical conductivity (E.C.), it tends to increase from 68.39 μ S/cm (L1) to 73.37 μ S/cm (L2) at the upper surface (0-15cm), and 53.45 μ S/cm (L1) to 68.57 μ S/cm (L2) at lower surface (15-30cm) with the age of landslide and maximum was found in the control site.

In the context of soil fertility and availability of nutrients, soils of landslide L1 (7 years old site) is characterized by very low content of soil O.C. and organic matter (O.M.). The availability of other nutrients like N, P, and K are also found to be very less in concentration. On the contrary, in site L2 (21 years old site), the concentration of all the nutrients along with O.C. and O.M. content reaches to the levels comparable to the reference site.

The concentration of S.O.C., S.O.M., available P, and K reaches a similar level to that of the control site in a short period of 21 years after the triggering of the landslide in 1998. The noteworthy point is that the concentration of S.O.C. (2.09%) and S.O.M. (3.61%) reached a level of about 95-96% of the undisturbed site (2.19% and 3.77%). Similarly, other chemical properties like available P and K also

Table 2: Soil physical characteristics (means $\pm$ standard error) of study site

Soil properties	Soil depth (cm)	Sites (year of landslide occurrence)		Control
		L1 (2012)	L2 (1998)	
¹ B.D. (g/cm ³)	0-15	1.73 $\pm$ 0.024	1.17 $\pm$ 0.021	1.20 $\pm$ 0.044
	15-30	1.83 $\pm$ 0.027	1.28 $\pm$ 0.02	1.32 $\pm$ 0.04
² P.D. (g/cm ³)	0-15	2.5 $\pm$ 0.031	2.16 $\pm$ 0.014	2.27 $\pm$ 0.049
	15-30	2.58 $\pm$ 0.022	2.25 $\pm$ 0.019	2.34 $\pm$ 0.035
Porosity (%)	0-15	30.58 $\pm$ 0.813	45.65 $\pm$ 0.723	47.00 $\pm$ 1.205
	15-30	28.91 $\pm$ 0.785	43.28 $\pm$ 0.589	43.48 $\pm$ 1.191
Moisture content (%)	0-15	8.90 $\pm$ 1.102	26.10 $\pm$ 3.468	22.68 $\pm$ 2.8
	15-30	8.63 $\pm$ 1.132	20.21 $\pm$ 2.111	20.33 $\pm$ 2.509
Sand (%)	0-15	87.33 $\pm$ 1.33	74.67 $\pm$ 2.404	76.67 $\pm$ 1.202
	15-30	87.33 $\pm$ 2.667	72.67 $\pm$ 2.404	78.67 $\pm$ 0.667
Silt (%)	0-15	10 $\pm$ 2.0	17.33 $\pm$ 1.764	18.33 $\pm$ 1.202
	15-30	9.33 $\pm$ 2.404	19.33 $\pm$ 3.528	15.33 $\pm$ 0.333
Clay (%)	0-15	2.67 $\pm$ 0.667	8 $\pm$ 1.155	5 $\pm$ 0.0
	15-30	3.33 $\pm$ 0.667	8 $\pm$ 1.155	6 $\pm$ 0.577

¹bulk density, ²particle density

reached about 91% and 84% of the adjacent undisturbed site, respectively (Table 1). On an average available P and K ranges from 13.44 kg/ha and 292.19 kg/ha in 7 years old site to 25.42 kg/ha and 379.94 kg/ha in 21 years old site respectively. Available nitrogen (N) exhibit the remarkable increment in the concentration as it overshoots the concentration of adjacent undisturbed site 755.43 kg/ha (0-15cm) and 643.93 kg/ha (15-30cm) to 780.52 kg/ha (0-15cm) and 674.59 kg/ha (15-30cm) in 21 year old landslide site (L2) (Table 1 and Fig. 5). The amount of S.O.C., S.O.M., available N, P, and K were positively strongly correlated ($p < 0.01$) with each other in landslide affected and unaffected areas (Table 3).

Recovery of Soil Physical Properties Studied

Assessment of physical characteristics of soil exhibited remarkable trends in particle size distribution (sand, silt, and clay content), bulk and particle density, porosity, and moisture content (Table 2). Similar to the chemical properties, the physical characteristics also exhibits the significant differences between the three different sites considered (ANOVA, $p < 0.05$). Bulk density and particle density decreased as the age of landslide increased and with the accumulation

of O.C. and O.M. after the specific disturbance. They have reached the level of about 96-97 % and 95-96% of the non-slipped site, respectively. On average, porosity was initially low (29.74 %) in the recent landslide (L1), but in the older site (21 years) reached levels (44.46 %) comparable to the undisturbed site (45.24 %).

On the other hand, moisture content doesn't show any specific trend as the minimum amount (mean – 8.76 %) was found to be in site L1 and maximum (mean – 23.15 %) was found in the site L2 as compared to the control site (Table 2 and Fig. 6). The fraction of sand, silt, and clay content vary over a wide range in the different sites. The clay content ranges from 2.67 % (minimum content in L1) to 8 % (maximum content in site L2) as compared to the undisturbed adjacent site 5-6 %. Similarly, sand and silt also have a varied fraction, which ranges from 87.33 to 72.67% and 9.33 to 19.33%, respectively (Table 2). On performing correlation analysis between the studied physical and chemical characteristics it was found that the chemical parameters exhibit the strong negative correlation with B.D., P.D. and sand content ($p < 0.01$) whereas the strong positive correlation with porosity, moisture and silt and clay content ($p < 0.01$) (Table 3).

Table 3: Correlation between physico-chemical characteristics of soil

	pH	EC	SOC	SOM	N	P	K	BD	PD	Porosity	sand	silt	clay	Moisture
pH	1	-0.415*	-0.875**	-0.876**	-0.891**	-0.847**	-0.630**	0.879**	0.786**	-0.882**	0.799**	-0.692**	-0.720**	-0.724**
EC	-0.415*	1	0.515*	0.515*	0.499*	0.583**	0.721**	-0.511*	-0.330	0.576**	-0.266	0.336	0.018	0.470*
SOC	-0.875**	0.515*	1	1.000**	0.972**	0.906**	0.804**	-0.980**	-0.902**	0.974**	-0.875**	0.783**	0.737**	0.880**
SOM	-0.876**	0.515*	1.000**	1	0.972**	0.906**	0.803**	-0.980**	-0.901**	0.974**	-0.874**	0.782**	0.737**	0.880**
N	-0.891**	0.499*	0.972**	0.972**	1	0.946**	0.834**	-0.980**	-0.875**	0.989**	-0.857**	0.779**	0.696**	0.875**
P	-0.847**	0.583**	0.906**	0.906**	0.946**	1	0.849**	-0.926**	-0.790**	0.955**	-0.751**	0.698**	0.576**	0.811**
K	-0.630**	0.721**	0.804**	0.803**	0.834**	0.849**	1	-0.806**	-0.609**	0.864**	-0.658**	0.647**	0.432*	0.753**
BD	0.879**	-0.511*	-0.980**	-0.980**	-0.980**	-0.926**	-0.806**	1	0.938**	-0.985**	0.858**	-0.774**	-0.708**	-0.919**
PD	0.786**	-0.330	-0.902**	-0.901**	-0.875**	-0.790**	-0.609**	0.938**	1	-0.865**	0.805**	-0.706**	-0.706**	-0.912**
Porosity	-0.882**	0.576**	0.974**	0.974**	0.989**	0.955**	0.864**	-0.985**	-0.865**	1	-0.841**	0.769**	0.671**	0.882**
sand	0.799**	-0.266	-0.875**	-0.874**	-0.857**	-0.751**	-0.658**	0.858**	0.805**	-0.841**	1	-0.946**	-0.734**	-0.705**
Silt	-0.692**	0.336	0.783**	0.782**	0.779**	0.698**	0.647**	-0.774**	-0.706**	0.769**	-0.946**	1	0.474*	0.598**
Clay	-0.720**	0.018	0.737**	0.737**	0.696**	0.576**	0.432*	-0.708**	-0.706**	0.671**	-0.734**	0.474*	1	0.662**
Moisture	-0.724**	0.470*	0.880**	0.880**	0.875**	0.811**	0.753**	-0.919**	-0.912**	0.882**	-0.705**	0.598**	0.662**	1

**Correlation is significant at the 0.01 level; *Correlation is significant at the 0.05 level

Discussion

The inferred data from the study had demonstrated that landslides have a prominent impact on the various soil physico-chemical properties. It was found that the significant differences exist in all the physical as well as chemical characteristics between the recently affected landslide site (L1) and the control site (Tukey HSD, $p < 0.05$). These results are supported by other authors also as most of the authors have observed lower concentration of organic carbon (O.C.), available nitrogen (N), available phosphorus (P), exchangeable Ca^{2+} , Mg^{2+} and K^{+} in landslide affected soils as compared to adjacent undisturbed soils (e.g., Lundgren 1978; Pandey and Singh 1985; Guariguata 1990; Joshi 1990; Reddy and Singh 1993; Dalling and Tanner 1995; Zarin and Johnson 1995a, 1995b; Singh *et al.*, 2001; Sparling *et al.*, 2003; Blonska *et al.*, 2016; Eynde *et al.*, 2017).

On comparing both the landslide affected sites (L1 and L2), it was observed that the young landslide site L1 has a lesser amount of O.C., O.M., available N, P and K content as compared to the older site L2, because of loss of nutrients in site L1 (7 years old) due to increased leaching and surface runoff. On the other hand, the younger site has a higher amount of B.D., P.D., and sand content as compared to site L2. This indicated that there is an increment in the concentrations of soil O.C., O.M., and K and decrease of B.D., P.D., and sand content with time and considered as the good indicators of soil quality and fertility (Sparling *et al.*, 2003). This increase and decrease in the concentration of various chemical and physical parameters, respectively, with time, may be due to the input of litter fall which further converts into the humus and finally into organic manure, weathering of minerals, and accumulation of colluvial material. Furthermore, the absence of significant differences (Tukey HSD, $p < 0.05$) between the soils of disturbed site L2 (older site) and control site for soil O.C., O.M., B.D., and sand content suggests that there is a recovery of soil for the various parameters

studied. The findings of the conducted study were similar to the results of the other researchers as the temporal variations were observed in soil characteristics of landslide sites for organic carbon (O.C.), organic matter (O.M.), exchangeable basic cations and soil texture, with an increment in soil fertility and quality over time (Joshi 1990; Reddy and Singh 1993; Singh *et al.*, 2001; Sparling *et al.*, 2003; Wilcke *et al.*, 2003; Blonska *et al.*, 2016; Eynde *et al.*, 2017). In this regard, Eynde *et al.*, (2017) also reported that soils of older landslides had an even higher content of organic carbon as compared to soils adjacent to the landslide. Available phosphorus (P) is also gets replenished in soil due to solubilization of immobilized forms and break down of primary minerals in parent rock material, which may increase in the landslide affected soils due to chemical actions with time. Low levels of available phosphorus in landslide soils in comparison to the control site are also reported by Guariguata (1990), Dalling and Tanner (1995), and Wilcke *et al.* (2003). Guariguata (1990) also suggested that most of the phosphorus is biologically unavailable in the recent landslide sites and weathered bedrock. The remarkable increase in the concentration of available nitrogen in site L2 (early successional stage – 21 years old) was due to the increased pace of nitrogen fixation and mineralization as also reported by several other researchers in disturbed forests (Vitousek *et al.*, 1989; Singh *et al.*, 2001). On the other hand, a lower concentration of available N in soils of the control site shows that there is a high uptake of nitrogen by plants at a later stage of succession (climax forest).

The recovery of soil characteristics was rapid during the early stages of recovery after disturbances, as it was observed that after 21 years of the landslide, most of the soil characteristics had reached the level of about 85-95 % of the undisturbed site. The findings of the study conducted were also ascertained by other authors (Trustum and DeRose 1998; Singh *et al.*, 2001). Ross *et al.* (1984) also reported the rapid recovery of soil characteristics after soil mining in the Wellington region: soil organic matter content and biochemical properties had reached to 60-90% of the values of the unstripped areas within 5 years of pasture restoration. Joshi (1990) found that in Kumaun Himalayas, the concentration of different soil characteristics increased with the advancement of succession and age of landslides. The researcher also

concluded that the rate of change of soil nutrients was maximum during the initial stages of succession.

Similarly, in the Luquillo Experimental Forest, Puerto Rico, Zarin and Johnson (1995a, 1995b) found that along the chronosequence, the base saturation index in the upper layer of soil (0-10 cm) increases during the early stages of succession. Lambert *et al.* (1984, 1993) and Sparling *et al.* (2003) concluded that topsoil properties on landslide scars in the Wairarapa region in New Zealand recovered to about 70-80 % of non-slipped sites. Similar results were also demonstrated by Blonska *et al.* (2016) as they found that O.C. content reached similar levels of undisturbed forest area after a short period of 15 years after the triggering of a landslide.

The recovery and accumulation of S.O.M. in the upper layer of soil play a critical role in the restoration of soil, as it determines the availability of nutrients, structure of soil and moisture content which in turn can be used as a reliable tool for assessing the variations in soils after the landslide occurrence. Reeves (1997) considered the organic matter as one of the essential parameters in evaluating the soil quality indices, as it reflects significant effects on other physical and chemical properties and other indices. Fekete *et al.* (2012) demonstrated that the organic matter content in soil has a strong positive correlation with soil moisture, which in turn facilitates the stimulating impact on soil microbial properties. Similarly, Blonska *et al.* (2016) showed that the soil organic matter has a positive effect on soil carbon content, nitrogen and phosphorus content, and various microbial and enzymatic activities. The present study conducted confirms these observations as authors of the present study also observed the significant positive correlation of S.O.M. with other physical and chemical parameters studied ($p < 0.01$) (Table 3).

The soil texture ranged from sandy (in site L1) to loamy sand (in control site) and sandy loam in site L2. Soil texture has a substantial impact on the development of soil and vegetation and the establishment of nutrient cycling, as it controls the availability of air, water, and nutrients necessary for good soil quality and fertility and also for the establishment of plants (Singh *et al.*, 2001). The increase in a coarse soil mass due to landslides results in rough-textured sandy soil in the recently formed

Fig. 5: Soil chemical characteristics in landslide affected and unaffected sites. (A) pH, (B) electrical conductivity (E.C.), (C) soil organic carbon (S.O.C.), (D) soil organic matter (S.O.M.), (E) available nitrogen (N), (F) available phosphorus (P), (G) available potassium (K). Data has been shown for upper soil surface (0-15 cm) and lower soil surface (15-30 cm) with means $\pm$ standard error

site (7-years-old), showing a higher degree of compaction, bulk and particle density, which tend to decrease in older site L2 due to the loosening impact of root hairs growth, input of organic matter and development of soil structure. Due to compaction the

Fig. 6: Soil physical characteristics in landslide affected and unaffected sites. (A) bulk density (B.D.), (B) particle density (P.D.), (C) porosity, (D) moisture content, (E) sand content, (F) silt content, (G) clay content. Data has been shown for upper soil surface (0-15 cm) and lower soil surface (15-30 cm) with means $\pm$ standard error

porosity eventually decreases in site L1 especially by reducing the volume of large inter-aggregate pores.

The higher rock fragment content in young landslides as compared to the undisturbed site was

observed by Cheng *et al.* (2016) and Eynde *et al.* (2017). The significant difference exists in sand content between the L1 site (young site) and the control site, as also observed by Zarin and Johnson (1995a). But on the other side, the absence of significant difference (Tukey HSD, $p < 0.05$) in sand content between L2 site (older site) and control site may be due to the weathering of coarser particles, physical and chemical disintegration of rocky substances and deposition of colluvial materials with the passage of time. Similar results were also observed by Knapen *et al.* (2006) and Eynde *et al.* (2017).

The remarkable positive trend of O.C. and O.M. in landslide affected areas with an age of landslides suggests that they can be often recommended as an indicator for the age of landslide and good soil quality indicator, respectively (Sparling *et al.*, 2003; Eynde *et al.*, 2017). In summary, the soils of landslide affected sites (L1 and L2) had less nutrient availability in the upper surface layer with reference to the control site, and the concentration of various physico-chemical properties increases with the passage of time.

Conclusions

From the study, it is concluded that landslides have a very significant impact on the various physico-chemical properties of soil. Soil characteristics in landslide affected areas recovered with the passage of time. Most of the chemical, as well as the physical properties, reaches about 85-95 % of the undisturbed site within a short period in site L2 (21-year-old). Therefore, in case of recovery of soil properties in disturbed sites, to accelerate the process, it is recommended that better management practices are required, especially during the initial stage of development.

Landslides are responsible for the degradation of soil fertility in terms of various physico-chemical characteristics, especially the decrease in O.C. and O.M. content in the topsoil leads to a considerable loss of nutrients in the soil as observed in the present study especially in young landslide site L1 (7-year-

old). Therefore, it is concluded that in landslides due to the unavailability of nutrients, the site remains devoid of vegetation for many years. In landslide sites, the nutrients in topsoil are unable to accumulate as the soil becomes more erosion-prone, and nutrients are easily washed out due to the absence of vegetation.

It is suggested that the various physical, chemical, and biological properties in the top soil are a useful indicator for mapping of the past landslides. It is also recommended that during soil sampling in mountainous areas the impact of landslides should be considered apart from the effects of vegetation and parent materials as landslides results in the drastic reduction in S.O.C., total nitrogen and poor soil structure, which in turn influences the vegetational growth, biodiversity, and net primary productivity.

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Conflict of Interest

All authors agree that this is an original contribution, all have contributed to its development, and there is no conflict of interest.

Author Contributions

We, the author(s), certify that:

- We have seen and approved the final version of the manuscript, and all subsequent versions.
- We have made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data;
- We have drafted the article or revised it critically for important intellectual content.

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