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Soil Erodibility in European Mountain Beech Forests

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Soil Erodibility in European Mountain Beech

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Abstract

Forests in Europe are, at present not endangered by soil erosion, however, this can change with climate change or intensified forest management practices. Using a newly established network of plots in beech forests across Europe, the aims of this study were 1) discrimination of soil properties and erodibility indices in relation to bedrock, 2) determination of geochemical properties and Corg influencing erodibility, and 3) assessment of the effect of soil depth on erodibility indices. Seventy-six soil samples from 20 beech forests were collected in 11 countries to quantify soil properties influencing erodibility indices clay ratio, modified clay ratio, sodium adsorption ratio, and oxides ratio. Results indicate that dominant soil properties, determined by bedrock, that correlate with forest soil erodibility indices are: Corg, pH, EC, Ca and Na ion concentrations, total-water soluble cations, and the % of sand. According to the tested indices, soil susceptibility to erosion follows the sequence: granite>andesite>sandstone>quartzite>limestone. Deeper soil horizons on granite are more susceptible to erosion than surface horizons, while this is not the case for soils on limestones. In conclusion, forest management should consider the predisposition of different soil types to erosion.

Keywords: bedrock, environmental change, soil erodibility, texture, organic matter, geochemistry, CLIMO Cost Action

Introduction

At the forest site-level erodibility depends on physical and chemical properties of soil that are mainly a function of the bedrock material (Milodowski et al. 2015 a, 2015b). It is a measure of general susceptibility to the detachment and transport of soil particles by erosion processes and forces, varying spatially and by soil depth. However, the impact of bedrock on soil degradation through erosion is not sufficiently understood (Jiang et al. 2020) and changing environmental conditions (Christensen et al. 2013, Hartmann et al. 2013) influencing geochemical processes can alter soil properties. It is known that soil physical and chemical features determine soil erodibility, but it is less well known how their interactions alter erodibility (Wang et al. 2013). Considering the heterogeneous nature of soils more information is needed for a better understanding of the effect of primary particles on site-specific soil erodibility.

Indices of erodibility are based on several key properties interacting with each other. Some of the most important to be included in assessments of soil erosion resistance are particle size distribution and geochemical properties like clay mineralogy, sodium adsorption, relative cation content, pH and organic C (C_{org}) content (Grabowski et al. 2010). These also represent the most commonly analyzed soil properties, known from forest ecosystem surveys and monitoring (ICP Forest Program, www.icp-forests.net/page/level-ii).

Relative proportions of different-sized particles substantially affect erodibility. Sandy and silty soils, due to their uncohesive nature, have a small inherent resistance to erosion (Parlak 2009). Many clayey soils are sensitive to surface runoff and their erodibility increases when the clay content is greater than 50%, in contrast with an increase in clay content up to 30-50%, which improves particles' resistance to erosion (Grabowski et al. 2010).

The erodibility of clay soils is related to clay mineralogy and adsorbed cations. Erodibility is closely connected with the dispersion potential of clay minerals normally measured by sodium adsorption ratio (SAR) (Rengasamy et al. 1984). Clay erodibility also has been examined through the oxides ratio (Bennett 1926).

Some authors use quantitative relationships of soil particle size distribution, C_{org}, soil permeability, and soil structure (Wang et al. 2016).

The presence of stabilizing substances, like organic matter, oxides, carbonates and cations in soil solution, depends on the soil depth. The resistance to erosion most commonly decreases with the increase in soil depth (Bouyoucos 1935). In soils rich in C_{org}, particle size density can be a good erodibility indicator, while in humus-poor soils lack of humus (C_{org} lower than 2%) or quantitative relation of particle size distribution and cation ratio can be better indicators (Liu and Han 2020). Since soil characteristics vary by depth, different horizons might express different erodibility properties. By analyzing vertical variability of soil erodibility traits one can assess the entire soil's resistance to erosion.

Under forest land use soil erosion is currently of minor importance in Europe (Borelli et al. 2006). Although forest soils are often found on steep terrain, a well-established root system and closed canopy cover prevents those soils from eroding. This is an argument for applying forestry management practice that maintains forests with a closed canopy. However, the resistance to erosion of forest soils can dramatically change in the wake of climate warming, with increasing occurrence of disturbance events such as outbreaks of pests and pathogens, for instance, satellite imagery reveals that the average patch size of harvested area, in reference to the period from 2004 to 2018, has increased by 34 percent across Europe, with a potential effect on soil erosion (Ceccherini et al. 2020). Although there are limitations in using erodibility indices, since each is specific to a certain erosion wildlife populations, or fire and concerning changes in forest management (Haas et al. 2020). process and force, they could be useful for monitoring changes in soil resistance to erosion in a changing environment, and for planning soil protective silvicultural measures.

European beech (*Fagus sylvatica* L.) is naturally distributed throughout much of Europe (EUFORGEN 2009) on a wide range of geological substrates (Leuschner et al. 1996). Because it is one of the most represented species throughout Europe, beech stands are ideal for determining criteria that would allow assessment of the forest soil/bedrock sensitivity to erosion. This study is part of the European Cooperation in Science and Technology (COST) action CA15226 “Climate Smart Forestry in Mountain Regions“ known as CLIMO (www.cost.eu/actions/CA15226). The CLIMO program is an integrative approach that aims to identify site-specific management practices to promote adaptive forest management including measures for soil protection (Bowditch et al. 2020). This study seeks possible erodibility indicators applicable for forest monitoring, which can be calculated from commonly monitored features under the forest surveys.

On 20 plots from the CLIMO COST Action network we set up the study focused on 1) discrimination of soil properties and erodibility indices in relation to bedrock material, 2) determination of geochemical and C_{org} properties influencing soil erodibility, and 3) assessing the effect of soil depth on geochemical properties and erodibility indices. With these objectives, we analyzed four erodibility indices: clay ratio (CR) (Bouyoucos, 1935), modified clay ratio (MCR) which considers soil C_{org} (Kusre et al., 2018), sodium adsorption ratio (SAR) (Rengasamy et al., 1984) and oxides ratio (Bennet, 1926), chosen based on the most widely assessed soil properties. The results obtained from 20 pure beech forest stands from 11 European countries are contributing to the knowledge on climate-smart forestry by showing how soils differ in their suseptability to erosion and how, among other things, erodibility should be considered when planning forest management measures.

Methods

Study sites and field sampling

From a total of 70 plots established within the CLIMO COST Action network, we selected 20 with predominant bedrock and soil types in Europe to assess inherent soil resistance to erosion pressure in beech forests (Figure 1, Table 1). Selected plots corresponded to five types of bedrock: granite (G; 5 plots), andesite (A; 1 plot), sandstone (S; 5 plots), quartzite (Q; 1 plot) and limestone and dolomite (L; 8 plots), , , , and (Table 1). Altitudes of plots vary between 415 and 1461 m a.s.l. and the slope ranges between 2.7 and 32 degrees. The mean annual air temperature (MAT) in these locations based on the observed period between 1961 and 1990 ranges from 3.4 to 10.5 °C, and mean annual precipitation (MAP) from 520 to 1100 mm. We included fully stocked unmanaged or just slightly managed (no silvicultural treatment over the last 10 years) stands, representing the natural dynamics of mountain beech forests and climate variation across Europe.

For this study, 76 soil samples from 20 plots in 11 countries (Bosnia and Herzegovina-BA, Bulgaria-BG, Czech Republic-CZ, Germany-GE, Italy-IT, Poland-PL, Romania-RO, Serbia-SRB, Slovakia-SK, Slovenia-SL, and Spain-SP) were collected during the fall of 2018 (Figure 1). One representative soil profile was analyzed per plot and general site characteristics are given in Table 1. Soil samples were collected at four depths in the profile 0-10 cm, 10-20 cm, 20-40 cm, and 40-80 cm, except at site 1 (BA1: soil depth was only 20 cm), 4 and 5 (CZ-1 and CZ-2: soil depth was only 40 cm). Approximately one kilogram of soil sample was taken from across a 1 m wide soil horizon, following the procedure given in the ICP Forest manual (Cools and De Vos 2016). Samples were labeled, stored in plastic bags, and shipped to the University of Belgrade where laboratory analyses were carried out.

Laboratory work

The Manual for sampling and analysis of soils (Cools and De Vos 2016) was followed for the selection and procedure of soil analyses. The following characteristics were determined on all samples: particle size distribution, the content of organic carbon (C_{org} in %), pH values, electrical conductivity (EC in μS), the content of $CaCO_3$ (%), nitrogen (N), C/N ratio, the concentration of water-soluble cations Al^{3+}, Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, Mn^{2+}, Fe^{3+}, total concentrations of elements Na, Mg, Al, Si, K and Ca (%) and content of SiO_2, Al_2O_3, and Fe_2O_3 oxides.

Particle size analyses

Grain size analysis was performed according to a standard wet sieving procedure (Dane and Topp 2002) using a set of sieve sizes ranging from 2.0 to 0.063 mm (2, 1, 0.5, 0.25, 0.125 and 0.063 mm). The sieved material was dried in an oven at 105 °C and weighed. A standard sedimentation procedure (pipette analysis) was performed for <0.063 mm fractionation of particles. Sodium hexametaphosphate (3.3 %) and an ultrasound bath were used as dispersing agents.

Measurements of pH values and electrical conductivity (EC)

Soil samples were analyzed for pH and EC in water using a 1:5 soil/water suspension. For these studies, a suspension of 4 g of soil and 20 ml of distilled water was used. The prepared sample was dispersed in an ultrasonic bath for 3 minutes, then the soil solutions were centrifuged at 10000 rpm for 20 minutes and filtered through a cellulose filter with 1 micron pore size. The pH values were determined using pH meter WTW INOLAB pH 720 (Welheilm, Germany) equipped with a glass electrode. The conductivity measurements were performed using WTW INOLAB 7110 conductometer (Welheilm, Germany).

Content of organic carbon (C_{org}) and nitrogen (N)

Soil samples were pulverized to a fine powder. Subsequently, the samples were placed in the oven at the temperature of 105 °C to eliminate hygroscopic moisture. Afterward, the dry residue was pre-treated with diluted hydrochloric acid (1:3, v:v) to eliminate carbonates. After the carbonates were removed, elemental analysis was performed to determine the contents of organic carbon. The measurements were done using a Vario EL III, CHNS/O Elemental Analyzer (Elementar Analysensystem GmbH, Germany).

Concentrations of major elements

Concentrations of major elements (Na, Mg, Al, Si, K, Ca, Fe) were determined using the X-ray fluorescence (XRF) method. After drying until constant mass at 105 °C, samples were prepared as pressed pellets by mixing soil and tableting aid wax (Hoechst wax micro powder produced by Merck, Lot number-K36429014636), at a ratio of 85:15, respectively. The pressure of 25t in a Retsch PP25 hydraulic press was applied for 5 min to the mixture to produce stable pellets which were 32 mm in diameter and approximately 3 mm thick. A Spectro Xepos Energy Dispersive X-ray Fluorescence spectrometer (XRF, Germany), equipped with a binary cobalt/palladium alloy thick-target anode X-ray tube (50W/60kV) and combined polarized/direct excitation was used. The analysis was performed with a high-resolution silicon drift detector (SDD) with an air-cooling system. For qualitative analysis, spectral recording, and data processing, a software program Xepos C and Fundamental Parameters (JRRM) method was used.

Concentrations of water-soluble cations

Concentrations of water-soluble cations Al^{3+}, Fe^{3+}, Mn^{2+}, Ca^{2+}, Na^{+}, K^{+}, Mg^{2+} were determined using the 1:10 soil/water dilution, following the procedure given by Faulkner et al. (2001). Total water-soluble cations (TWSC) were calculated as the sum of all cations.

Erodibility indices

To assess the erodibility of soils, four of the most common indices were tested: clay ratio (CR; Bouyoucos

1935), modified clay ratio (MCR; Kusre et al. 2018), sodium adsorption ratio (SAR; Rengasamy et al. 1984) and the oxides ratio of $\sum SiO_2/(Al_2O_3+Fe_2O_3$ (Bennett 1926). Bouyoucos (1935) proposed the CR, ratio between sand+silt (%) / clay (%), as a measure of binding due to the presence of clay and it is inversely related to soil erodibility, because high specific surface area clay particles are more reactive than coarse particles and can store higher amounts of carbon than sandy soils (Sulman et al. 2014). The MCR, ratio between sand+silt / clay+soil organic matter (%), might be more suitable for soils having high organic content (Kusre et al., 2018), which is true for most forest soils. The SAR was calculated using the following equation: SAR = [Na] / ([Ca + Mg]/2)0.5 where all concentrations are in mmol/L.

The applicability of four erodibility indices varies among different soil textural categories and also their referential values (Table 2). As mentioned previously, SAR and oxides ratio represents the means to assess erodibility of clayey soil, while CR and MCR values are suitable for all soil textural categories. Considering the stable physical characteristics of soils, SAR values are employed to try to predict the response of soils to environmental change.

Statistics

The similarity/dissimilarity of soils was assessed using Principal Component Analysis (PCA) including all analyzed soil features and soil erodibility indices (*N*=75). To test differences in erodibility indices between the bedrock types, a one-way analysis of variance (ANOVA) was performed. All values were square-root transformed for achieving normal distributions and equal variances. Pearson correlation was used to quantify relationships among soil erodibility indicators and selected physical and chemical properties. The variables were again square-root transformed. Statistical analyses were performed by using Minitab 19 (Minitab, LLC, 2021).

Results

Soil properties relative to bedrock

The soils used in this study were developed on 5 bedrock types: granite (G), andesite (A), sandstone (S), quartzite (Q), and limestone & dolomite (L), with marked differences in texture and physio-chemical properties.

Principal component analysis discriminated soils according to these five bedrocks groups with eigenvalues (Figure 2), describing how the variables are spread, 6.91 (PCA1), 5.43 (PCA2), and 2.49 (PCA3). Furthermore, PCA confirmed that the differentiation of soil characteristics is primarily determined by pH, EC, C_{org}, total and water-soluble contents of Ca and Mg in soils on limestones, the contents of Si, Al, K, Na for soils on sandstone, and the content of sand for soils on granites. Although erodibility indices will be discussed later, this result indicates that these parameters should be key parameters for determining if the soil is prone to erosion.

Soil texture varied considerably among bedrock groups (Figure 3). Soils on G and A bedrock were characterized as sandy clay to sandy clay loams. Soils on S and Q were sandy clays and on L mainly clays to sandy clays. On G, the soils had the lowest clay content (mean of 41.3 %) with the highest content of sand (47.5 %), soils on S, A, and Q had medium clay content (65.6 %) and soils on L showed the highest clay content (71.3 %) among the groups. These fractions were used further to describe erodibility indices.

Chemical soil properties also varied among soils grouped based on bedrock (S1; S2). Total amounts of Na, Mg, Al, Fe, K, Ca were similar among the groups. The most significant differences between analyzed groups were found for the amount of total Si, for which the highest values were in the soils on bedrock group S, and of Ca and Mg, with the highest values in soils in group L.

The mean pH values of 4.81 show that soils on G are more acidic than on L with a pH of 6.04. For all analyzed soil profiles, pH increased with an increase of a soil depth indicating cation depletion processes. Electrical conductivity for most soils pointed to a high ionic soil activity. Values of EC varied between 47.1 μS and 74.2 μS on A, G, Q, and S, while a higher value of 112 μS was determined on L.

As an indication of the soil resistance to depletion and dispersion, values of TWSC varied between 99.7 μg/g (A) and 313.2 μg/g (L). The lowest average concentrations of Ca ion were found in G and S (22.5 μg/g and 25.2 μg/g, respectively) and the highest was found in L (188.6 μg/g). We found the highest amount of Mg ion also on L (3.1 μg/g), whereas the lowest was found on Q and A. Concentration of Al ion, an indication of soil acidification, was highest with 14.5 μg/g in soil on G, followed by S and A. The average amount of C_{org} varied between 1.27 (Q) and 4.19 % (L). The largest C_{org} concentrations (3.2 to 12.4 %) were found in the upper soil layers (0-10 cm) for Q and L bedrock and the lowest amounts ranged from 0.1 to 0.9 % in deep soil layers (>20 cm).

Soil erodibility indices concerning bedrock and soil depth

With the one-way ANOVA test, we found significant differences ($p < 0.01$) in all four soil erodibility indices CR, MCR, SAR, and oxides ratio among bedrock groups (Figure 4, S2). Soil erodibility indices decreased in the following sequence G>A>S>Q>L. The only deviation from this result was found for the oxides ratio is observed in S, which showed higher resistance to erosion than soil on L. An increase in soil erodibility indices was associated with an increase in sand content and a decrease in C_{org}, TWSC and pH values. Also, soil erodibility indices CR, MCR, and SAR increased with soil depth for G, A, and Q, while similar erodibility indices were found across depths for S and L.

As shown in Figure 4, the indices of erodibility varied considerably within each bedrock group. Such differences in erodibility are the result of the variability of soil properties. A high amount of sand and low pH values, which are associated with the G group, were significantly correlated with the values of CR, MCR, and SAR (Table 3). The S bedrock group showed contrasting indices when SAR and oxides ratio were compared to L, which is probably linked to a higher heterogeneity of this group. This indicates the need to combine all four indices for assessing erodibility of soils on S. A high amount of the C_{org} indicates the need to include MCR instead of CR, particularly in topsoil. Soils on L were attributed to the high content of C_{org} indicating that MCR is a better indicator of erodibility than CR and SAR. Herein, the value of MCR should be combined with TWSC and Ca and Mg cation concentrations which were significantly negatively correlated.

As shown in Table 3, a significant negative correlation was found between soil C_{org} and SAR, and between pH, EC, Ca ions, TWSC and CR, MCR, SAR. A significant positive correlation was found between sand content and SAR, and also among indicators MCR, SAR, and oxides ratio.

All soils show an increasing trend of soil erodibility with an increase in soil depth (Figure 4, S2) with a strong increasing trend in soil erodibility is observed in G, A and Q groups. The other two groups (S and L) expressed less vertical dissimilarity in erodibility indices CR, MCR, and SAR. Soil C_{org} and TWSC in most soils were decreasing with increasing soil depth, while sand content and pH values increased with soil depth.

Discussion

Soil erodibility indices in relation to soil and bedrock material

Soils on different bedrock expressed significantly different values of erodibility indices. Our results indicate that tested beech forest soils in the current state are stable and not prone to erosion. Based on susceptibility to erosion soils followed the sequence G>A>S>Q>L, where accordingly, soil on G points to highest and soils on L to lowest susceptibility to erosion.

Although our results indicate that these forest soils in their current state are stable and not prone to erosion, it is expected that they would respond differently under changed environmental conditions. The expected impact of climate change on perturbations in most forest ecosystems includes more violent weather phenomena, drought and changes in drying and rewetting cycles (Reichstein et al. 2013). Such weather extremes increase the release of nutrients due to physical disruption of the soil structure (Bünemann et al. 2013) and loss of soil organic matter. The highest susceptibility to erosion was found for the soils of a granitic group of bedrock based on all four observed indices (Figure 4). This is explained by the high amount of non-cohesive fraction in sandy clays to sandy clay loams. The granitic group of rocks produces a lot of coarse texture regolith due to weathering processes. It is known that bedrocks that produce more loose and coarse-textured soils are more prone to erosion (Grabowski et al. 2011). The link between bedrock and texture affecting soil resistance to erosion in temperate regions is most evident in young soils, i.e. early phases of soil development when they are most similar to bedrock. This is common for forest soils on hillslopes. Although, granit group expressed the highest erodibility, with a considerable amount of clay (>40%; Figure 3 and S1) these soils most probably have the maximum erosion thresholds (Grabowski et al., 2010), due to the influence of clay on hydrodynamic smoothing, clay/sand adhesion and clay cohesion.

Similar erodibility values of CR and MCR are found for andesites, sandstones, quartzite, and limestone-dolomite groups of bedrock. Erodibility of soils that contain higher percentages of the clay fraction is generally lower; for better insight, clay chemical and mineralogical properties are important to consider. The high adsorption capacity of clays may show higher erodibility and, in that case, TWSC may influence higher susceptibility to erosion. In contrast, cation exchange capacity can also be negatively correlated with soil erodibility depending on soil water chemistry (Gerbersdorf et al. 2007). Therefore, SAR and oxides ratio are here important predictors of dispersiveness and detachment. Soils formed on limestone have different properties from the bedrock as defined by the quantity and mineralogy of clay fraction. The clay fraction will express different levels of erodibility in relation to mineralogy. Sandstones show high variability which is most likely an effect of different sediment origins and physio-chemical properties. Their erodibility indices should also be determined using a combination of both soil texture and chemical properties. Such differences initially will affect variation in erodibility indices. Sandstones that have a high clay content (transitioning to claystone) express the highest resistance to erosion.

Bedrock types chosen in this study are among the most frequent in the lithosphere: granite and granodiorites account for 22%, sandstones for 1.7, and carbonate rocks for 2% (Amelung et al. 2018). The estimated erodibility indices can be useful for monitoring forest soils if these values are compared to commonly determined levels of visual change in the landscape. The range of erodibility values can be determined for different types of beech forests to be monitored under regular monitoring programs which could be more sensitive for the prediction of erosion.

Influence of soil physical and geochemical properties on soil erodibility

In our study, we found that soil erodibility of beech forest soils, determined through erodibility indices, was significantly influenced by the amount of sand, water-soluble cations, the concentration of Ca ion, the content of soil C_{org}, values of pH and EC, which agrees with previous studies (e.g. Grabowski et al. 2011). Regarding interactions among soil physical and chemical properties, different geological substrates act differently.

Properties determining the major character of soil should be considered when estimating erodibility. The major characteristics describing the granitic group is sand content (Figure 2), which is significantly correlated to CR, MCR, and SAR. In sandy soils with small amounts of organic matter, the amount of sand is an important predictor of erosion processes. Soils formed on sandstone were the most heterogeneous group in texture. Sandstones were strongly characterized by clay content and Fe, Al and Mn cation concentrations (Figure 2). Therefore, due to a high clay content, erodiblity indicies hereafter should be combined with oxides ratio values, SAR and Ca/Mg ratio, to evaluate soils of a similar texture. The soils on limestone and dolomites were characterized by high Ca and Mg ions concentrations, C_{org}, pH, and EC values, which are all important to consider when assessing the potential for soil loss.

When looking at CR and MCR, the relationship between texture and erodibility is not straightforward. Although erodibility is very sensitive to small changes in soil grain size distribution, it should be considered concerning other physical and chemical soil properties (Wischmeier and Mannering 1969). Two tested erosion indices, CR and MCR, are primarily based on soil grain size characteristics as a measure of binding due to the presence of clay, which is inversely related to soil erodibility. Due to a high specific surface area, clay particles are more reactive than coarse particles and can store higher amounts of carbon than sandy soils (Sulman et al. 2014). Brayan (1968) indicates that the higher the percentage of clay the more reliable the index is, with a clay content higher than 10% CR considered reliable. Because this ratio neglects the presence of organic matter, which is probably even a more important aggregate-cementing agent (Robinson and Page 1950), it should be used for layers with a low content of organic C. The MCR is more suitable for soils having high organic content (Kusre et al. 2018) which is true for forest soils. The obtained values of MCR for most forest soils are also indicating that tested soils are stable (Figure 4).

Because the tested indices based on physical characteristics indicated that beech forest soils are generally more stable, the SAR based on chemical compositions was used to predict the response of soils to environmental change. It should be underlined that SAR is primarily designed for sodic material, and none of the forest soils strictly fall into this category. However, we chose SAR as one of the few erosion indicators based on chemical composition. Sodium adsorption ratio values below 1 indicate stable soils (S2). Rengasamy et al. (1984) used the SAR/EC ratio to determine the dispersivity status of red-brown soils in Australia. Naidu et al. (1995) and later Faulkner et al. (2000, 2003) supported the use of this ratio for soils potentially exposed to erosion. According to the classification given by Rengasamy et al. (1984), which is based on the ratio between SAR and sum of all cation concentrations (TWSC), the soils in our study are potentially dispersive since SAR is < 3 and the sum of water-soluble cation concentration is < 3.8.

Furthermore, Faulkner et al. (2000) suggested the use of SAR/pH as a site signature due to the buffering role of calcium. This ratio shows that SAR depends on soil pH values with a correlation of -0.633. However, two trends are present. In conditions of pH <5.6 the SAR has values ranging from 0.026 to 0.353, while in soils with pH >5.6 SAR is generally lower and falls in the range from 0.05 to 0.09. This difference discriminates the soils by bedrock type. Correlation between pH and SAR is statistically significant for soils on limestone (r=-0.632) and sandstone (r=-0.648), while it is statistically not significant on granite soils (r=-0.112). Andesite and quartzite soils cannot be discussed in detail due to the limited number of samples. However, both of these soils are closer to granite soils.

Generally, the indices CR, MCR, and SAR used in our study appear promising for the erodibility assessment of the beech forest soils. If analyzed together with the content of major and minor elements in soils, subtle differences in soil properties on different bedrock are accentuated (Figure 2). Limestone soils are richest in the content of C_{org}, have the highest pH, the highest content of both available and total Ca and Mg, the highest clay content, and therefore are the least prone to erosion. On the contrary, granitic soils are all grouped around high erosion indices, together with sand content, indicating the greatest potential sensitivity to environmental change, i.e. through increased forest disturbance events. Sandstone soils have the highest content of Si, Al, K and Na as a consequence of the usual mineralogical composition of sandstone being dominated by quartz and feldspars.

The effect of changes in physical and chemical properties

An increase in soil erodibility in deeper layers points to higher erosion potential of the upper soil layer if the soil's physical and chemical properties are altered due to environmental change. Despite the well-established fact that soil properties change with an increase in soil depth, there is still not enough information regarding how these changes affect the potential erodibility of forest soils. The stability and content of soil organic carbon vary greatly among soil horizons as a consequence of a change in soil chemical and physical properties (Rumpel and Kögel-Knabner 2011). Conforti et al. (2016) indicated that most studies of carbon storage are focused on the topsoil horizon and neglect the deeper mineral horizons that are important for the storage of total soil organic carbon, especially in forest ecosystems. Under changing environmental conditions, which might accelerate soil erosion of the topsoil horizon, the characteristics of the subsurface soil horizons will determine the rate of further soil processes. One of the most prominent consequences of such changes in the vertical and lateral water movement through soil and nutrient leaching (Johnson 1994). Pennock and van Kessel (1997) studying medium-term plots (6 to 20 years) after clear-cutting observed higher losses of soil organic carbon, nitrogen, exchangeable Ca and Mg, soluble phosphorus, base saturation in the soil surface 0 - 15 cm, while these losses were much smaller in the 15-45 cm soil horizon. However, contrasting results can be found in the literature. According to a meta-analysis of forest soil carbon, James and Harrison (2016) found that the response of the soil organic carbon to harvesting in forest soils varies with depth. These authors report that the highest losses were reported to occur in the O soil horizon, followed by significant losses in the deep soils (from 60 to 100 cm).

Based on our results it is still not possible to propose a new erosion index that would be suitable for forest soils and it remains the task for further studies based on empirical measurements of soil transport and loss. However, this index should include textural characteristics, the content of organic matter, and the content of major elements.

Conclusions

Under current conditions, forest soils in European mountain regions are generally not threatened by soil erosion. However, the potential of forest soils to resist erosion may dramatically change under climate change and forest management alterations. To assess susceptibility to erosion of pure beech forest soils, four erodibility indices, derived from textural (clay ratio, modified clay ratio) and geochemical (sodium adsorption ratio and oxides ratio) characteristics, were tested. The selected indices proved to be useful for the assessment of forest soil erodibility. However, none of them was sufficient when used alone, but instead, they should be combined to increase the reliability of the assessment of soil erodibility. The erodibility index most suitable for forest soils should combine textural, geochemical properties, and content of organic matter. However, based on existing indices, our results indicated that all soils under study would not erode easily under current conditions.

We show that soil texture, the content of organic carbon, pH value, electrical conductivity, and total water-soluble cations, as components of erodibility indices, clearly differentiated forest soils by the type of bedrock, and were proved to be explanatory variables. In conditions of climate or land-use change, soil erosion can be expected to occur and erodibility would decrease in the following sequence: granitic rocks > andesite > sandstone > quartzite > limestone.

Environmental change will likely cause erosion of the topsoil horizon, so the characteristics of the subsurface soil horizons will determine the rate of further processes. The sequence-based on the bedrock type mentioned above would be accentuated in this case. Deeper soil horizons on granitic rocks are more erodible than surface horizons, while soils on limestone do not differ in erodibility with depth.

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Table 1. COST Action CLIMO network beech research plots from which soils were tested

No	Country abb.	Latitude	Longitude	MAT (1961-1990) °C	MAP (1961-1990) mm	Exposition	Slope °	Altitude m a.s.l.	Bedrock	Soil type (WRB)
1	BA	43.70694444N	18.26222222E	6.7	1085	N -NW	14	1290	Limestone	Calcic Cambisol
2	BA	44.64408611N	16.66843333E	10.5	1060	E-NE	4	524	Limestone	Calcic Cambisol
3	BG	42.77916667N	23.88111111E	6.3	648	W-NW	25	1350	Sandstone	Cambisol
4	CZ	49.28516667N	16.73927778E	7.8	525	E	2.7	490	Limestone	Leptosoil
5	CZ	49.28475000N	16.74008333E	7.8	525	S	4.1	485	Limestone	Leptosoil
6	CZ	49.03563889N	18.01875000E	7.1	520	0	0	415	Sandstone/	Cambisol ‘modal’
7	CZ	49.02344444N	18.02519444E	7.1	550	0	0	620	Sandstone/	Cambisol ‘modal’
8	GE	49.06274444N	13.27144444E	6.7	1157	SW	10	720	Granite	Cambisol
9	IT	46.11888889N	12.42972222E	7.4	1749	NE	5	1090	Limestone	Luvisols
10	PL	49.43298333N	20.90310000E	5.8	929	SW	20	830	Sandstone	Cambisol
11	PL	49.62243056N	18.91460278E	7.1	1085	SW	22	520	Sandstone	Cambisol
12	RO	45.53811111N	25.91673889E	4.0	840	NE	25	1277	Quartzite	Eutric Cambisol
13	RO	45.49583333N	25.18777778E	3.4	915	NV	20	1461	Limestone	Eutric Cambisol
14	SRB	43.40625278N	21.37824722E	9.0	688	E	20	695	Granites	Cambisol dystric
15	SK	48.67796667N	19.47016667E	4.3	1004	N	10	1180	Andesite	Andic Cambisol
16	SL	46.35972222N	15.24805556E	6.9	1100	NW	32	600	Dolomite	Leptosoil
17	SL	46.26083333N	15.32194444E	6.9	1100	NW	26	1070	Dolomite	Leptosoil
18	SP	42.20138889N	2.721944444W	8.3	630	N	30	1430	Granite	Umbrisol
19	SP	42.20083333N	2.718611111W	8.4	630	N	23	1390	Granite	Umbrisol
20	SP	41.77555556N	2.456666667E	10.2	954	S	18	1186	Granite	Umbrisol

Note: BA- Bosnia and Herzegovina, BG-Bulgaria, CZ-Czech Republic, GE-Germany, IT-Italy, PL-Poland, RO-Romania, SRB-Serbia, SK-Slovakia, SI-Slovenia, and SP-Spain; MAT - mean annual temperature (°C); MAP - mean annual precipitation, Soil type is given according to WRB World reference base (IUSS Working Group WRB, 2015). Climate data are taken from: Cornes et al. (2018)

Table 2. Referential values of oxides ratio (∑SiO2/Fe2O3+Al2O3), sodium adsorption ratio (SAR), clay ratio (CR), and modified clay ratio

Indicator	Most applicable soil texture	Benchmark values	Reference
Oxides (Ei=∑SiO2/Fe2O3+Al2O3)	Clay	Range 0.0-4.0	Bennett 1926
		<1 – least resistant to erosion	
		~2 – medium resistant to erosion	
		~4 – very resistant to erosion	
SAR	Loam	Range 0.1 – 3.0	Rengasamy 1984
	Sandy loam	Range 0.9 – 3.0	Rengasamy 1984
	Clay	Range 3.7 – 6.8	Rengasamy 1984
CR	All soil textures	Range 0.52-11.2	Bouyoucos 1935
		< - 1 very resistant to erosion	
		> - 3 poorly resistant to erosion	
	Sandy	10.9-11.6	Bouyoucos 1935
	Loam	3.3	Bouyoucos 1935
MCR	All soil textures	Range 3.28-11.00-	Kusre et al. 2018
		>6.9 – proneness to erosion	

Table 3. Pearson correlation matrix showing relationships between soil erodibility indices (CR-clay ratio, MCR-modified clay ratio, SAR-sodium adsorption ratio, oxides ratio- $\sum SiO_2/(Al_2O_3 + Fe_2O_3)$, and physical and chemical properties (Corg-soil organic C in %, pH values, EC-electric conductivity, Ca^{++} and Na^{+} ion concentration, TWSC-total water-soluble cations, sand content in %).

	C_{org}	pH	EC (µS)	Ca^{++}	Na^{+}	TWSC	sand	MCR	CR	SAR	Oxides
C_{org}	1	0.287*	0.686**	0.515**	0.387**	0.475**	-0.275*	-0.232	-0.054	-0.316*	-0.159
pH		1	.0501**	0.660**	-0.033	0.614**	-0.315*	-0.301*	-0.247	-0.659**	-0.221
EC			1	0.754**	0.237	0.717**	-0.366**	-0.345**	-0.201	0-.634**	-0.131
Ca ion				1	0.293*	0.952**	-0.589**	-0.503**	-0.375**	-0.788**	-0.11
Na ion					1	0.328*	0.003	0.127	0.196	0.281*	-0.198
TWSC						1	-0.647**	-0.536**	-0.401**	-0.751**	-0.084
sand							1	0.924**	0.865**	0.577**	-0.227
MCR								1	0.995**	0.583**	-0.354**
CR									1	0.490**	-0.404**
SAR										1	-0.021
Oxides											1

** Correlation is significant at the 0.01 level (2-tailed); * Correlation is significant at the 0.05 level (2-tailed). N=76 data from all bedrock groups (layer 0-10cm, 10-20cm, 20-40cm, 40-80cm) were included.

Figure 1. Soil sampling sites across pure beech forests in Europe. Numbers refer to site location given in Table 1. We used World Topo Map URL: https://server.arcgisonline.com/ArcGIS/rest/services/World_Topo_Map/MapServer/tile/{z}/{y}/{x} (in July 2019) we imported coordinates representing the sites from Table 1 on World Topo Map in QGIS 2009. Emira Hukić created the map.

Figure 2. Principal component analysis for 75 pure beech forest soils on 5 bedrock types. CR-clay ratio, MCR-modified clay ratio, SAR-sodium adsorption ratio, EC-electrical conductivity Ca av, Mg av, Na av, K av, Fe av, Mn av, where av denotes available (water-soluble) cations. Temperature, precipitation, altitude, slope data are given in Table 1.

Figure 3. Textural characteristics of beech forest soils.

Figure 4. Mean values (±SE) of soil erodibility indices (CR-clay ratio, MCR-modified clay ratio, SAR-sodium adsorption ratio, oxides ratio-$SiO_2/(Al_2O_3 + Fe_2O_3)$) and soil factors (proportion of sand%-content of sand, C_{org}(%)-the content of soil organic carbon, pH value, TWSC-water-soluble cation capacity) concerning soil depth (1:0-10cm, 2:10-20cm, 3:20-40cm, 4:40-80cm) and different bedrock material (G-granites; A-andesite; S-sandstone; Q-quartzite and L-limestone and dolostone). Gray marked surface represents all average values.

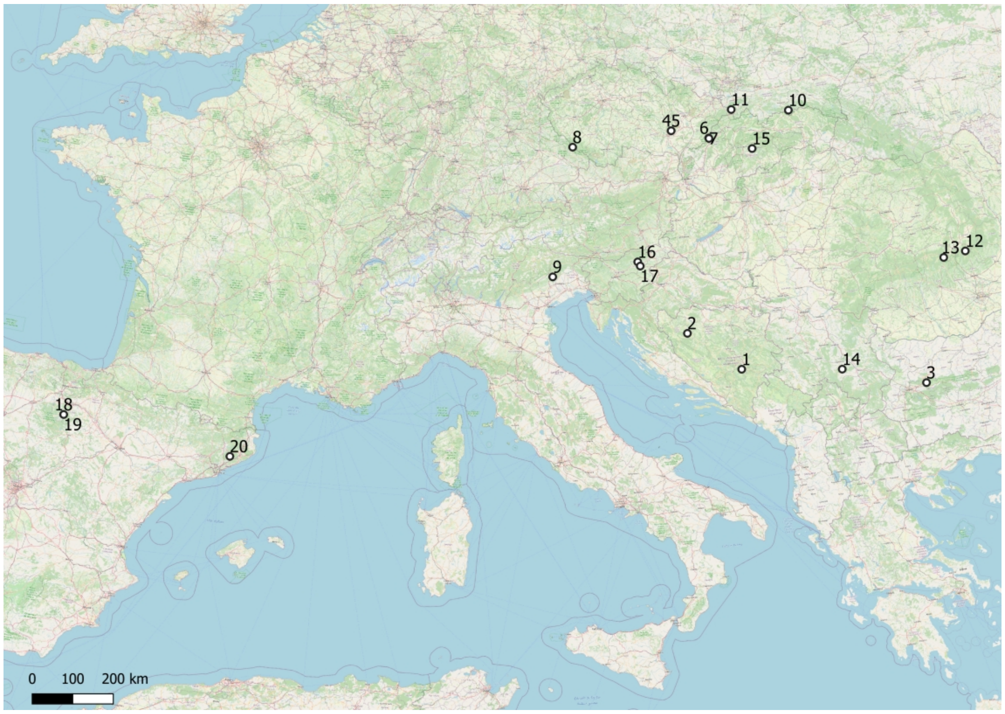

Figure 1. Soil sampling sites across pure beech forests in Europe. Numbers refer to site location given in Table 1. We used World Topo Map URL: https://server.arcgisonline.com/ArcGIS/rest/services/World_Topo_Map/MapServer/tile/{z}/{y}/{x} (in July 2019) we imported coordinates representing the sites from Table 1 on World Topo Map in QGIS 2009. Emira Hukić created the map.

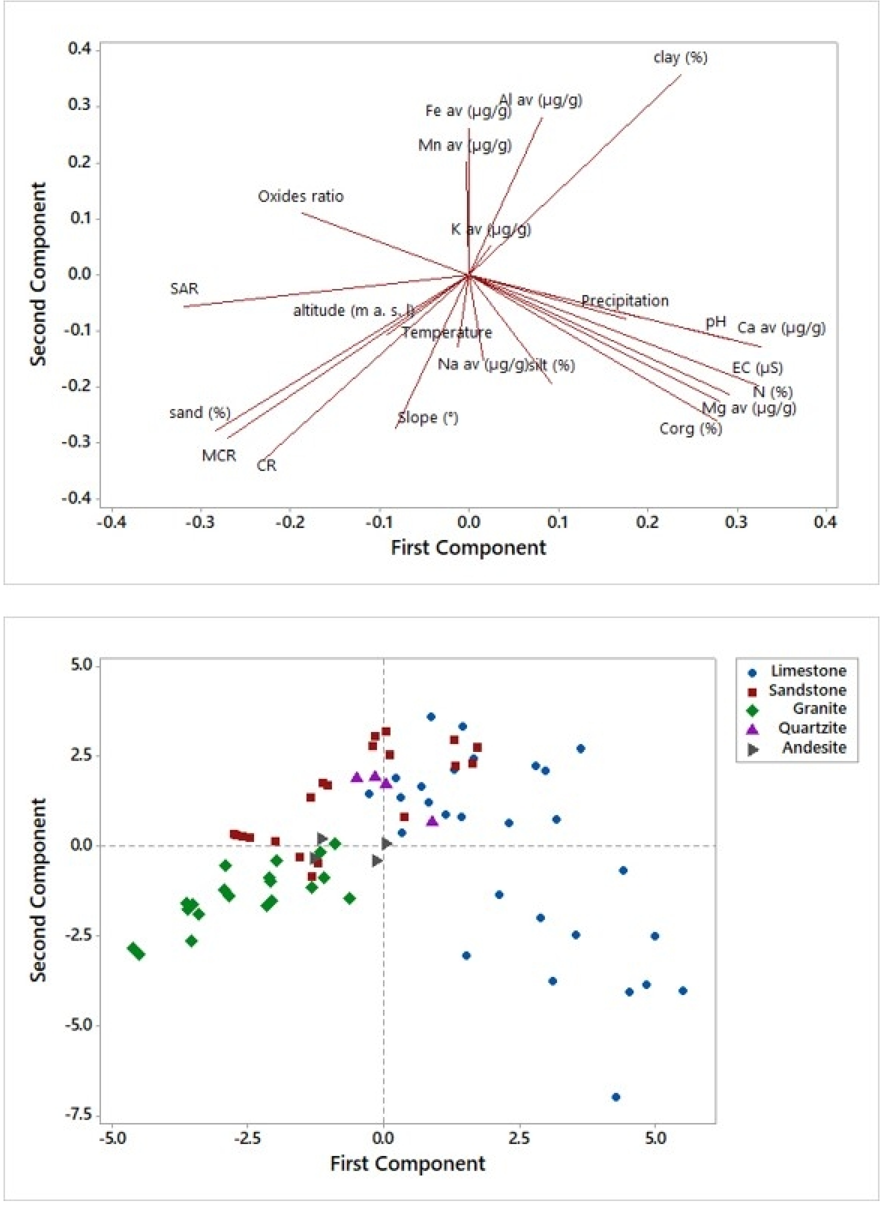

Figure 2. Principal component analysis for 75 pure beech forest soils on 5 bedrock types. CR-clay ratio, MCR-modified clay ratio, SAR-sodium adsorption ratio, EC-electrical conductivity Ca av, Mg av, Na av, K av, Fe av, Mn av, where av denotes available (water-soluble) cations. Temperature, precipitation, altitude, slope data are given in Table 1.

98x135mm (150 x 150 DPI)

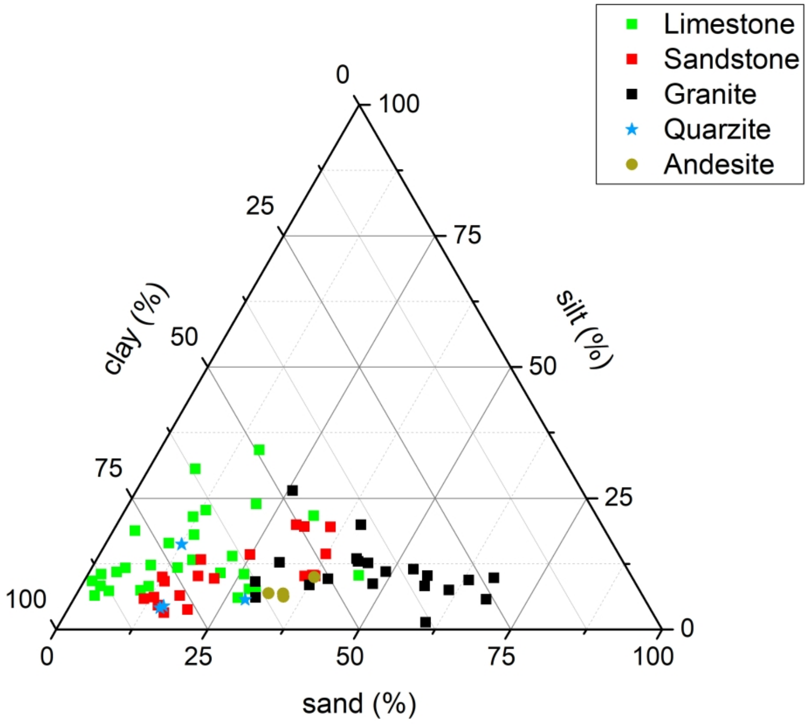

Figure 3. Textural characteristics of beech forest soils.

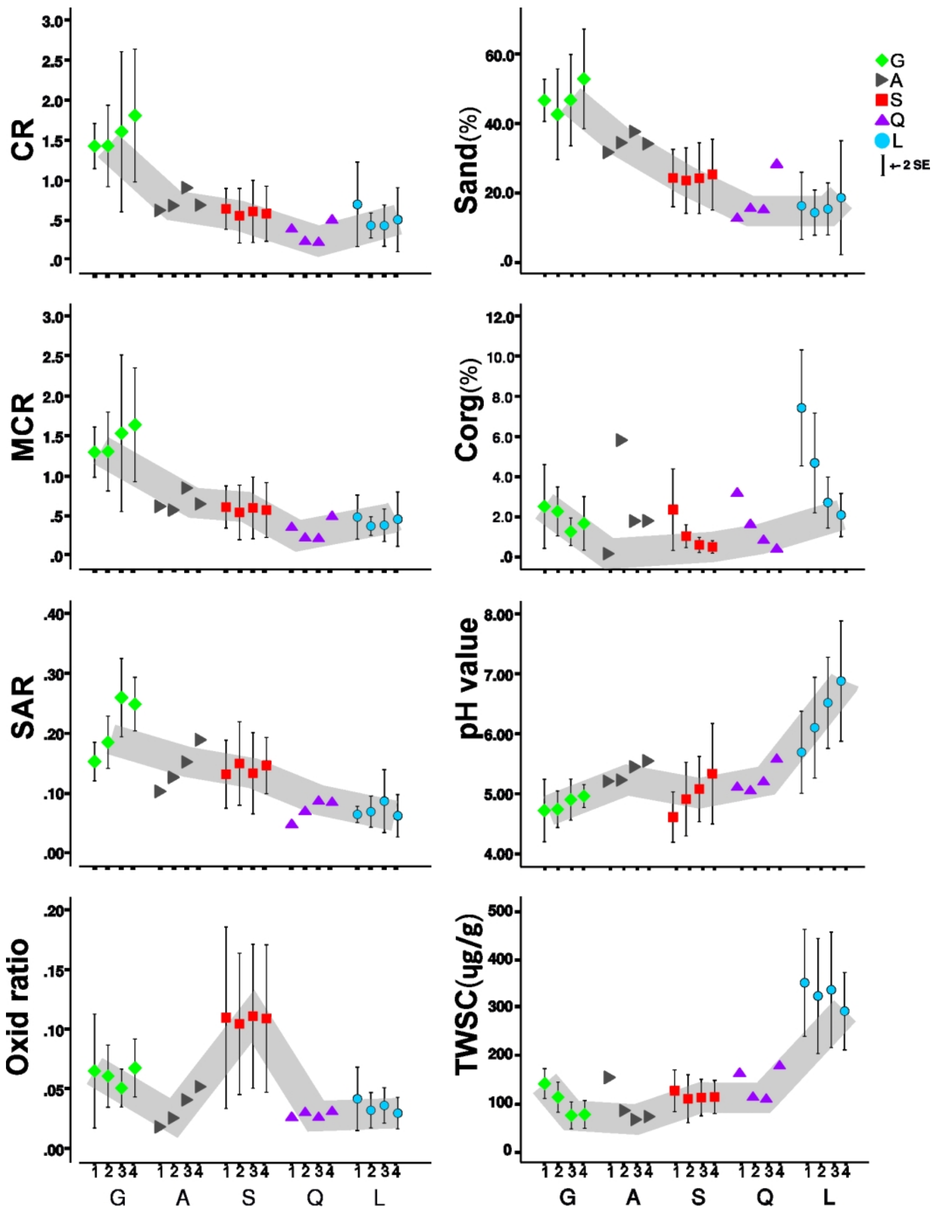

Figure 4. Mean values (±SE) of soil erodibility indices (CR-clay ratio, MCR-modified clay ratio, SAR-sodium adsorption ratio, oxides ratio-SiO2/(Al2O3 + Fe2O3)) and soil factors (proportion of sand%-content of sand, Corg(%)-the content of soil organic carbon, pH value, TWSC-water-soluble cation capacity) concerning soil depth (1:0-10cm, 2:10-20cm, 3:20-40cm, 4:40-80cm) and different bedrock material (G-granites; A-andesite; S-sandstone; Q-quartzite and L-limestone and dolostone). Gray marked surface represents all average values.