sciendo
Acta hort regiotec, 27, 2024(1): 42–50
DOI: 10.2478/ahr-2024-0007

Research Article

Response of the Soil Organic Matter to Clear-cutting in the Face of Climate Change – a Report from the East Sudety Mountains, South-West Poland

Elżbieta Jamroz*, Andrzej Kocowicz, Jakub Bekier, Magdalena Dębicka, Irmina Ćwieląg – Piasecka
Wrocław University of Environmental and Life Sciences, Institute of Soil Science, Plant Nutrition and Environmental Protection, Wrocław, Poland

Article Details: Received: 2023-10-10 | Accepted: 2024-01-31 | Available online: 2024-05-31

Licensed under a Creative Commons Attribution 4.0 International License

SCREENED BY iThenticate Professional Plagiarism Prevention

Clear-cutting induces biogeochemical, ecological, and hydrological changes in the soil environment, especially in the conditions of climate change effect. This type of management affects soil carbon sequestration. In this paper, we generalize the effect of clear-cutting in mountainous mixed coniferous forests on the direction of organic matter transformation and the properties of humic substances. Soil samples of dystric Cambisols were taken two and ten years after clear-cutting (CC). Soil profiles located at the same elevation under forest cover without any harvesting were used as references. The contents of total organic carbon, total nitrogen, qualitative and quantitative characteristics of humic substances, as well as the mineralogical composition and the clay-associated C fraction, were analysed. Under mountainous conditions, clear-cutting in the mixed coniferous forest enhanced organic matter decomposition and decreased the low-molecular weight humic fraction. It also caused the accumulation of more stable humic acids, particularly in the upper soil horizons, and resulted in accumulation of humic substances with higher contents of C and O and lower H content in the first years after CC. Clear-cutting in the first two years reduced the aliphacity of humic acids in the topsoil. Ten years after harvesting, a significant increase in aliphacity in the Oa horizon confirmed organic matter recovery. Mixed coniferous forests are more resistant to biotic and abiotic disturbances, which is particularly important in the face of violent weather phenomena related to climate change. Thus, forest management plans should consider the conversion of spruce monocultures to mixed coniferous forests.

Keywords: soil organic matter, humic acids, fulvic acids, clear-cutting

1 Introduction

In recent years, an increase in violent weather phenomena, such as heavy rains followed by longer periods of drought, has been observed. This is the climate change effect, which leads to catastrophic flooding and loss of topsoil due to soil erosion, mainly in mountainous areas where soils are poor in organic matter and without plant cover (Baveye et al., 2020). In Poland mountainous areas are covered mostly by forest ecosystems which store large amounts of carbon in their soils, accounting for almost 50% of the total global C in organic form (Cerli et al., 2008). The size of the C reservoir is the result of organic matter input and loss due to decomposition, leaching, and, especially in mountainous regions, erosion processes (Jamroz et al., 2014; Mayer et al., 2020). Worldwide, clear-cutting is the most common forest harvesting practice, although it negatively affects soil carbon stocks, mainly due to the reduction of plant residues (Mayer et al., 2020; Prescott, 2005). This type of harvesting induces biogeochemical, ecological, and hydrological changes. Some authors found that, following clear-cutting, the accelerated decomposition of soil organic matter (SOM) resulted in the loss of humic substances from the soil and a change in their properties (Jamroz & Jerzykiewicz, 2022; Ussiri & Johnson, 2007). The unprotected soil surface, particularly in mountainous regions, is exposed to erosion and soil loss (Borelli et al., 2017). Understanding the effect of harvesting types, such as clear-cutting, on the soil environment is therefore important for the management of harvested sites.

Over 60% of the global soil organic carbon occurs as humic substances (De Nobili et al., 2020; Loffredo & Senesi, 2006), consisting of three highly reactive fractions: humic acids (HA), fulvic acids (FA), and humins (HU). Each

***Corresponding Author:** Elżbieta Jamroz, Wrocław University of Environmental and Life Sciences, Institute of Soil Science, Plant Nutrition and Environmental Protection, ul. Grunwaldzka 53, 50-357 Wrocław, Poland, https://orcid.org/0000-0003-0130-181X

of them plays an important role in ensuring environmental stability (Amoah-Antwi et al., 2022). Of these, HA and FA can dissociate H^+ ions from functional groups, thus contributing to cation exchange capacity (CEC) in soil (Boguta et al., 2019; Dębicka et al., 2016). High-molecular-weight humic acids play a significant role in many soil processes, such as mineral weathering, soil structure stabilisation and metal binding. In mountainous areas, they are particularly important for the stabilisation of soil aggregates (Bronick & Lal, 2005).

The low-molecular-weight fulvic fraction, more labile in the soil profile and thus easily leaching to the deeper soil horizons, plays a crucial role in sorption processes (Jamroz, 2012). Organic matter in soils undergoes mineralization and humification; these two processes overlap, and the properties of humic substances formed depend on environmental factors such as harvesting practices. Any change in the turnover rate of SOM may alter the atmospheric CO_2 concentration, and consequently, affect the global climate (Lützow et al., 2006).

The study examined the effect of clear-cutting in a mountainous mixed coniferous forest on the organic matter transformation and the properties of humic substances, with the aim of providing recommendations for the maintenance of stable and high-quality SOM in the context of climate change.

2 Materials and methods

2.1 Study site and soil sampling

The study areas were located in the two mountain ranges: A – Zmijowiec Range (50° 14′67.4′′N, 16° 50′17.2′′E), 950 m a.s.l., East Sudety Mountains, South-West Poland; B – Bialskie Mountains (50° 14′.0 55.9″ N, 17° 0′ 2.2″ E), 870 m a.s.l. East Sudety Mountains, South-West Poland (Fig. 1). Table 1 shows the main characteristics of the investigated soils. Soils in both ranges were described as Dystric Cambisols (FAO, 2015), derived from gneiss and schists. The forests habitat was mountainous mixed coniferous forest (MMCF) with the following dominant mature trees: *Picea abies*, *Fagus sylvatica*, *Larix decidua*, *Acer pseudoplatanus*. Soil samples were taken 2 years after clear-cutting (CC) in Site A and after 10 years in Site B. As reference, we used soil profiles from the same elevations under forest cover but without harvesting (F).

Four soil profiles were located on each site (A and B), two soil profiles after clear-cutting, and two in the undisturbed forests. Investigated objects, both in the sites A and B, were located on the same soil type derived from the same parent material. Soil profiles were located at the same altitude, the same aspect, to avoid the influence of slope processes. Samples, each approximately of 200 g, from each soil horizon were prepared for chemical analysis. Texture and mineralogical composition were determined only in mineral horizons. Soil samples from Oa and Ah soil horizons were taken for the detailed analysis of humic substances.

Figure 1 Study area, East Sudety Mts., south-west Poland

2.2 Soil analysis

All samples were air-dried, and mineral samples were sieved through a 2-mm mesh. Soil texture was analysed using the sedimentation-sieve method according to Bouyoucos, with Casagrande and Prószyński modifications (Gee & Bauder, 1986). The composition of the clay fraction (<2 μm) was analysed with an X-ray diffractometer with CuKα radiation (λ for CuKα1 = 1.54056) in the range of 5–30° 2θ. The clay fraction (<2.0 μm) under study was separated by centrifugation (1,000 rpm × 4 min). The samples were treated with 30% H_2O_2 to remove organic matter in surface horizons. The free and amorphic forms of Al and Fe were removed via the dithionite-citrite-bicarbonate method according to Jackson's method. The samples were air-dried (N-natural), saturated with ethylene glycol (Gl) and heated at 550 °C for 2 hours (550 °C) prior to measurements. The data obtained were analysed with XPowder, a software package for powder *X*-ray diffraction analysis (Martin, 2016).

Table 1 Basic properties of the soils (values are means) under mountain mixed coniferous forest (MMCF) after clear cutting (CC) and without harvesting (F). A – Zmijowiec Range; B – Bialskie Mts

Object	Soil horizon	Depth (cm)	pH 1M KCl	TOC (g.kg^{-1})	NT (g.kg^{-1})	CEC (cmol(+) kg^{-1})	Silt + clay (%)
MMCF A CC	Oa	4	2.7	203.98^{a}	10.30^{a}	43.18	n.d.
	A	21	2.9	37.99^{a}	1.62^{a}	6.80	41
	Bw	20	3.6	44.65^{a}	2.04^{a}	5.45	27
	C	29	3.9	9.77	0.45	n.d.	19
MMCF A F	Oa	4	2.7	309.28^{b}	14.88^{b}	47.13	n.d.
	A	10	3.5	69.62^{b}	2.83^{b}	5.92	33
	Bw	20	4.0	48.50^{a}	1.81^{a}	6.74	35
	C	20	4.0	29.24	1.50	n.d.	32
MMCF B CC	Oa	12	4.1	184.50^{a}	11.10^{a}	n.d.	n.d.
	A	10	3.3	113.40^{a}	2.60^{a}	18.90	9
	Bw	30	3.9	71.00^{a}	2.60^{a}	17.95	19
	C	>	4.1	61.80	2.00	14.48	15
MMCF B F	Oa	10	3.0	202.00^{b}	10.40^{a}	n.d.	n.d.
	A	15	3.7	104.00^{b}	7.20^{b}	19.82	19
	Bw	20	4.1	44.20^{b}	2.30^{a}	19.03	21
	C	>	4.0	30.50	1.50	13.40	22

n.d. – not determined; a, b, c... – values following the same letters (upper index) are not significantly different according test t, p <0,05; the same soil horizons were compared, differences were checked between object CC and F within object A and B separately

The pH was measured potentiometrically in 1 M KCl. Total organic carbon (TOC) was determined via a CSMAT 5500 analyser (Strohlein GmbH & Co., Kaarst, Germany, currently Bruker AXS Inc., Madison, WI, USA) and total nitrogen (TN) by the Kjeldahl method using a Buchi Labortechnik GmbH N analyser.

2.3 *Extraction and purification of humic and fulvic acids*

Humic fractions were extracted from the genetic horizons using the procedure described by Swift (1996), recommended by the International Humic Substances Society (Swift, 1996).

Elemental analysis of HA and FA was performed with a Perkin-Elmer 2,000 instrument. The O was calculated via mass balance.

2.4 *Statistical analysis*

The normal distribution of the data was checked using the Shapiro-Wilk test. Means were compared using the *t*-test (p <0.05). The effect of the clear-cutting on the SOM properties of soils in various soil horizons was defined with cluster analysis. The groups of similar treatments are presented in a form of dendrogram. The smaller the Euclidean distance, the more similar the objects. Data clustering was performed with the Ward method. All the data were processed using the software package Statistica 13.3 TIBCO Software Inc.

3 Results and discussion

3.1 *TOC and content of humic substances*

In coniferous forests, most of the organic carbon is stored in the O horizons. Vegetation type and plant residue amount affected the pH, which was lowest in undisturbed Oa horizons (Table 1). In the Zmijowiec Range, two years after harvesting, we observed a significant decrease in TOC as an effect of clear-cutting (Table 1), both in organic and mineral soil horizons. In the Oa horizon, a TOC decrease of 34% was found, whereas in the Ah horizon, this decrease was 66%. Two years after clear-cutting, SOM was still under the strong influence of decomposition. In the Bialskie Mountains, at 10 years after clear-cutting, there was a significant decrease in TOC (Fig. 2) in the Oa horizon (9%). In the deeper mineral soil horizons, a significant increase in TOC was observed as a result of intensively developing grass species. In the Ah horizon, the content of TOC increased by 9%, and in the Bw horizon, by 60%.

In our study, forest floor carbon declined following clear-cutting in the first 10 years, but in the deeper mineral soil horizons, SOM started to recover after this period; this is in line with the findings of other authors (James & Harrison, 2016). Besides the reduced C inputs after removing stems in mountainous regions, other factors can affect soil C stocks, such as accelerated erosion or the leaching of low-molecular humic substances. The total nitrogen content was lower in the soils after CC (Table

1) and, similar to TOC, on Site B at 10 years after harvesting, it started to recover. In forest soils, the main source of nitrogen is SOM, particular HA and HU, and the qualitative and quantitative changes observed in SOM directly affect the nitrogen content.

Changes in the plant community toward the development of grass species are commonly observed after stem removal. This type of organic matter source is characterised by a low C/N ratio, promoting microbial growth and enhancing N mineralisation (Fukuzawa et al., 2006; Jasińska et al., 2019).

The contribution of humic substances to SOM was the effect of harvesting (Fig. 3). In mineral horizons, the share of fulvic acids in SOM was significantly lower (11.75% of TOC in the A horizon) compared to the forest site without harvesting (30.75% of TOC respectively). In the Bialskie Mts., 10 years after CC, a slight increase in the fulvic fraction in mineral soil horizons was observed, although this was not statistically significant (Fig. 4). In the soils from Site A, 2 years after CC, a significant increase in humic acids in Oa and A horizons was observed. 10 years after CC, in soils from Site B, the contribution of HA to organic matter was still significantly higher (40.3% of TOC) compared to that in the site without harvesting (24.80%). The contribution of humins in the Oa horizon, 2 years after CC, was significantly lower (49.29% of TOC) compared to the 54.36% of TOC from the forest site without harvesting. In the first mineral horizon, the HU share was significantly higher (62.14% of TOC) in comparison to the uncut forest (42.38%). The share of HU in the Oa horizon in the Bialskie Mts., 10 years after clear-cutting, was also significantly lower, and in Bw horizon, a significant increase of this fraction was observed.

Fulvic acids represent the most labile fraction among all humic substances, and thus, the distribution in the soil profiles point to enhanced leaching of these low-molecular organic compounds under the influence of harvesting (Falsone et al., 2012; Jamroz et al., 2014). Intensive forest management affects the decomposition of SOM and diminishes the low-molecular humic fraction. However, it also causes the transformation of SOM towards more stable humic acids, particularly in the upper soil horizons (Oa and A). The transformation of organic matter towards HA formation could be the effect of biological synthesis from phenolic precursors. In the ground plant community in coniferous forests next to common grasses, perennial shrubs such as *Vaccinium myrtillus*, rich in phenolic compounds (Kukla & Kuklova, 2018), are often found.

Phenols and other humic-like substances can be generated by

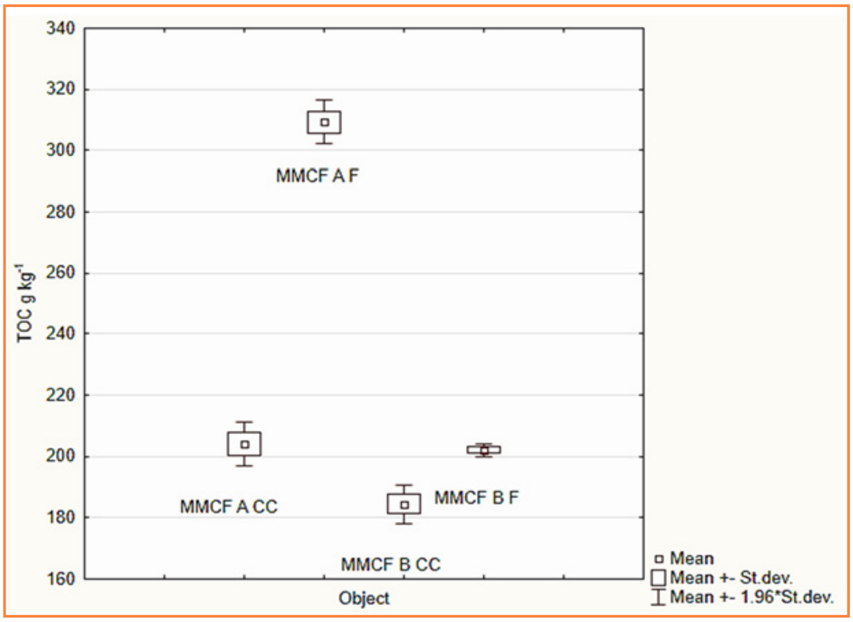

Figure 2 Total organic carbon (TOC) in Oa horizon of the soils under mountain mixed coniferous forest: undisturbed (MMCF F) and after clear-cutting (MMCF CC)
A – Zmijowiec range, B – Bialskie Mts

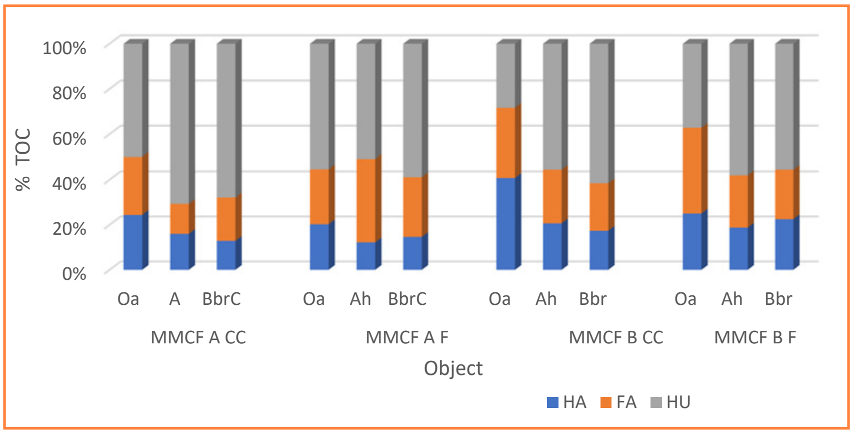

Figure 3 The content of humic (HA), fulvic acids (FA), and humins (HU) in soil profile under mountain mixed forest without harvesting practice (F) and after clear-cutting (CC) in the East Sudety Mountains

fungi even though no aromatic materials are present in the starting substrates (Hayes & Swift, 2020). The contribution of humins significantly decreased after clear-cutting in Oa horizons in both sites (Fig. 3). In the Zmijowiec Range, 2 years after CC, the share of this humic fraction was at the level of 49.29% and was significantly lower compared to the uncut site (54.36%). In the upper mineral horizon, a significant increase in HU was observed after stem removal (from 42.38% of TOC to 62.14%). The high contribution of humins to TOC confirms that this fraction is the major contributor to soil carbon sequestration (Hayes et al., 2017).

More labile components, such as peptides, nucleic acids and other low-molecular compounds, are metabolised by microorganisms unless they are protected by other mechanisms, such as clay inclusion (Hayes & Swift, 2020; De Nobili et al., 2020). In our study, the contribution of C bounded with clays increased 2 years after clear-cutting, from 6.81 to 9.13% in the A horizon (Table 2), which is in agreement with this theory. As humic acids and humins are considered highly stable products of humification and with a degree of recalcitrance, they can be important for the carbon budget in soils (Barancikova et al., 2018; Brunetti et al., 2016; Jerzykiewicz et al., Designations of soil horizons based on WRB, 2015 2019; Rice & MacCarthy, 1991).

3.2 Elemental composition of humic and fulvic acids

The elemental composition of humic and fulvic acids is shown in Tables 3 and 4. A significant influence of CC on the chemical composition of HA and FA molecules, mostly in the Oa horizons, of the investigated soils was observed. The HA molecules from the Zmijowiec Range, 2 years after CC, were characterised by significantly higher contents of carbon and lower contents of hydrogen compared to the uncut forest site. In the humic acid molecules from Bialskie Mts., the hydrogen content in the Oa horizon was significantly higher (46.33%) compared to that in the undisturbed forest sites (43.52%). No other significant differences in elemental composition of HA as a result of clear-cutting were found. The content of C in fulvic acids from the A soil horizon 2 years after CC was significantly lower, along with a higher content of hydrogen, in comparison to the uncut forest. In the Bialskie Mts., FA molecules from the Oa horizon were characterised by lower carbon and nitrogen levels in comparison to the undisturbed forest site.

The atomic ratio, as a consequence of elemental composition, is often used to define the degree of condensation or to provide structural information or formula weights of the HS (Tan, 2014). In particular, the H/C ratio, as an indicator of aliphacity (Rice & MacCarthy, 1991), is often use in humic matter characteristics. Overall, humic acids from the Zmijowiec Range were more aliphatic in nature in comparison to those from the Bialskie Mts. In the first 2 years after clear-cutting, aliphacity (lower H/C ratio) of humic acids in Oa and A horizons was reduced, whereas in the Bialskie Mts., 10 years after harvesting, a significant increase in this parameter in the Oa horizon was found. Barancikova et al. (2018) and Jerzykiewicz et al. (2019) reported higher values of the H/C ratio for humic acids from forest windthrow-affected mountainous areas and after clear-cutting, indicating a low degree of SOM humification. Results of the cluster analysis (Fig. 4) point that clear-cutting in the first 2 years affected organic matter properties in the topsoil of mountain mixed coniferous forest by lowering TOC content in the forest floor and decreasing share of FA in the mineral soil horizons as well as increasing share of HA, HU and contribution of C bounded with clays in Ah horizon.

Table 2 Effect of clear-cutting on mineralogical composition of clay fraction and clay-associated C concentration (values are means). MMCF – mountain mixed coniferous forest; (CC) after clear cutting; (F) – without harvesting. A – Zmijowiec Range; B – Bialskie Mts

Object	Soil horizon	Clay type*	Clay C (g.kg^{-1})	Clay C % of TOC
MMCF A CC	A	V-I, I, K, Q	3.47	9.13[a]
	BC	I, V-I, K, Q	4.10	9.18[a]
MMCF A F	A	V, I, K, Q	4.74	6.81[b]
	BC	V, V-I, I, K, Q	6.29	12.97[b]
MMCF B CC	A	V-I, K, Q	0.79	0.70[a]
	BC	V, I, K, Q	1.06	1.49[a]
MMCF B F	A	V-I, I, K, Q	1.59	1.53[b]
	BC	V-I, I, K, Q	2.56	8.39[b]

* V-I – vermiculite-illite, I – illite, K – kaolinite, Q – quartz, V – vermiculite; a,b,c.. – explanation: – values following the same letters (upper index) are not significantly different according test t, *p* <0,05; the same soil horizons were compared, differences were checked between object CC and F within object A and BC separately

Table 3 Elemental composition of humic acids from the soils under clear cut and undisturbed forests (values are means)

Object	Soil horizon	C	H	N	O	H/C	O/C
		(atomic %)					
MMCF A CC	Oa	31.80[a]	49.42[a]	1.82[a]	16.96	1.55	0.53
	A	32.22[a]	44.37[a]	2.31[a]	21.10	1.38	0.66
MMCF A F	Oa	31.33[b]	50.54[b]	1.82[a]	16.31	1.61	0.52
	A	30.54[a]	44.37[a]	2.65[a]	22.43	1.45	0.73
MMCF B CC	Oa	33.23[a]	46.33[a]	1.93[a]	18.51	1.39	0.56
	A	35.66[a]	37.67[a]	2.51[a]	24.16	1.06	0.68
MMCF B F	Oa	34.62[a]	43.52[b]	2.14[a]	19.72	1.26	0.57
	A	35.12[a]	37.09[a]	2.47[a]	25.32	1.06	0.72

MMCF – mountain mixed coniferous forest; (CC) after clear cutting; (F) – without harvesting; A – Zmijowiec Range; B – Bialskie Mts
a, b, c... – explanation: – values following the same letters (upper index) are not significantly different according test *t*, *p* <0,05; the same soil horizons were compared, differences were checked between object CC and F within object A and Oa separately

Table 4 Elemental composition of fulvic acids from the soils under clear cut and undisturbed forests (values are means)

Object	Soil horizon	C	H	N	O	H/C	O/C
		(atomic %)					
MMCF A CC	Oa	33.23[a]	36.86[a]	0.76[a]	29.14	1.11	0.88
	A	38.53[a]	20.92[a]	0.77[a]	39.78	0.54	1.03
MMCF A F	Oa	32.55[a]	37.24[a]	0.85[a]	29.36	1.14	0.90
	A	41.91[b]	15.36[b]	0.74[a]	41.99	0.37	1.00
MMCF B CC	Oa	33.70[a]	35.80[a]	0.70[a]	29.80	1.06	0.88
	A	33.93[a]	35.19[a]	0.61[a]	30.27	1.04	0.89
MMCF B F	Oa	34.01[b]	36.51[a]	1.01[b]	28.48	1.07	0.84
	A	32.54[a]	35.60[a]	0.81[a]	31.05	1.09	0.95

MMCF – mountain mixed coniferous forest; (CC) after clear cutting; (F) – without harvesting; A – Zmijowiec Range; B – Bialskie Mts
a, b, c... – explanation: – values following the same letters (upper index) are not significantly different according test *t*, *p* <0,05; the same soil horizons were compared, differences were checked between object CC and F within object A and Oa separately

Two years after CC aliphaticity of humic substances was reduced as a consequence of forest removing. Ten years after harvesting, direction of SOM transformation in Oa horizon confirmed organic matter recovery.

3.3 Silt-clay protected C

Many studies have described the correlation between mineralogical composition and stabilisation of organic carbon or soil properties in soils (Lützow et al., 2006; Polláková et al., 2018; Weber et al., 2012). Besides the clay content, the type of clay (1 : 1, 2 : 1) also affects C stabilisation in soils. It is of a great importance because it determines the properties of individual group of clay minerals, and thus their chemical and physicochemical activity depending on environmental conditions. In our studies in all investigated soil horizons, the dominant clay type was 2 : 1 (Table 2). The mineralogical composition of the soil clay fraction in the soils from Zmijowiec Range 2 years after clear-cutting in the A horizon (Fig. 5A) was dominated by mixed-layered minerals of vermiculite-illite (V-I), kaolinite (K) and highly dispersive quartz (Q).

At the deepest soil horizon of this site, the mineral composition was similar (Fig. 5B). However, a higher share of illite (I) in relation to V-I minerals, as well as high dispersion of quartz, could be observed. In the soils from undisturbed forest, vermiculite was the dominant clay mineral in the <2-μm fraction of the A horizon (Fig. 6A). Further, I, K, and Q were present in smaller amounts. At the deepest soil horizon, the mineralogical composition was similar, but the amount of V-I type of mixed-layered minerals accompanying vermiculite increased, and the share of highly dispersed quartz (Q) also increased (Fig. 6B).

In the soils from Bialskie Mts., 10 years after CC, in the mineral composition of the <2 μm fraction of the Ah horizon, the minerals of mixed, disordered packages of vermiculite and illite (V-I) occurred, as well as kaolinite (K) and quartz (Q), as representatives of primary minerals.

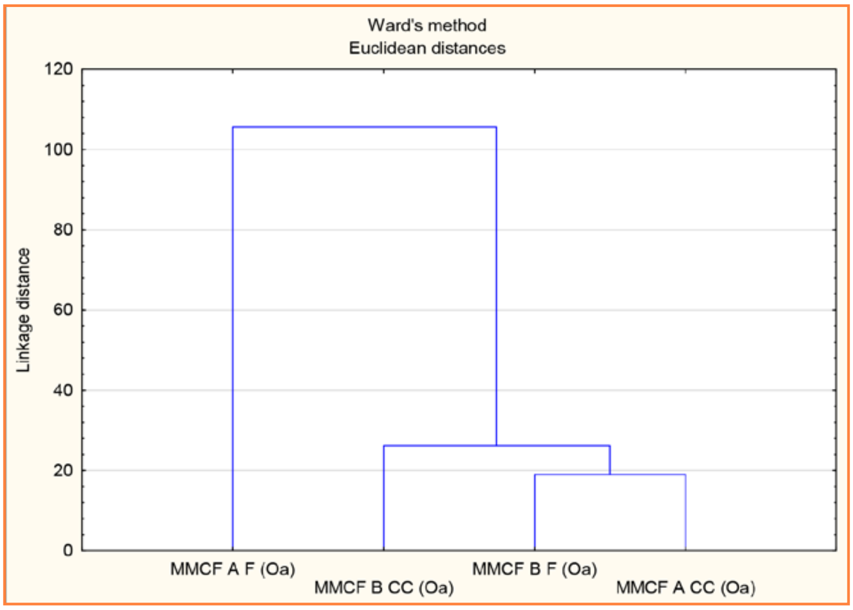

Figure 4 Results of cluster analysis for Oa horizons of the soils from clear-cut (CC) and undisturbed forest (F) in the Zmijowiec Range (A) and Bialskie Mts. (B). Overall properties taken

Illite occurred in the deepest soil horizon from the clear-cut sites. The mineralogical composition of the soils from uncut forest was similar to that previously described. However, a higher intensity of reflections, indicating the presence of mixed-layered minerals of vermiculite-illite type and illite, was observed in the Ah horizon, accompanied by kaolinite and highly dispersed quartz, as in other cases. The qualitative composition of clay minerals was also similar in the deepest soil horizon, but also a slightly higher amount of illite and worse order in structure of vermiculite is observed, than in the BC horizon in the clear-cut area. Table 2 shows the content of clay-associated C and its contribution to TOC. Two years after clear-cutting, a significant increase (9.13% of TOC) of clay-associated C was observed in the A horizon compared to the uncut forest site (6.81%). In other investigated soil horizons, a significantly lower share of this fraction was found compared to the undisturbed forest sites. This interesting phenomenon might be related to an increase in the silt + clay fraction in the same A horizon (by 24%) in the first 2 years after harvesting, even though the quantity of clay-associated C was lower by 27% compared to that of the uncut forest site. Consequently, the CEC of the A horizon in the clear-cut areas was significantly higher (by 14%) in comparison to the control object (Table 1). The possible mechanism of this humic fraction stabilisation could be intercalation of organic matter within phyllosilicates, which is typical for acidic soils (Lützow et al., 2006) however, occlusion within clay microstructures or organo-mineral interactions is also possible. Changes in the forest cover in the investigated mountainous conditions in the first years have cause the temporary accumulation of clay-associated carbon in the first mineral soil horizon, but the interactions seem to be rather weak. Pollakova et al. (2018) found that in the forest soils, more humified, e.g. clay-associated fractions, highly enhanced the

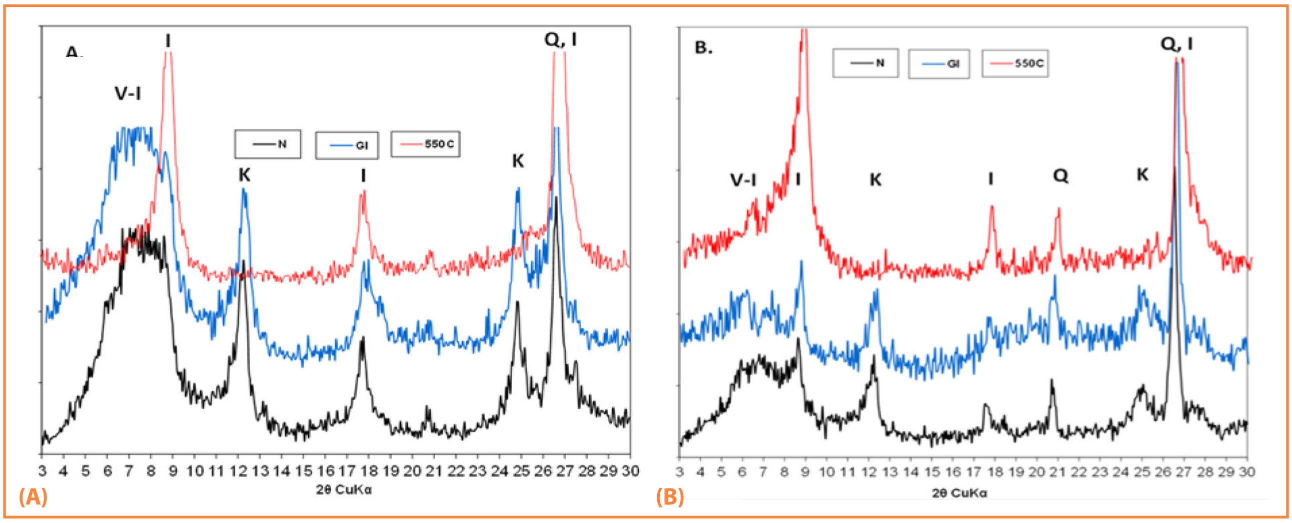

Figure 5 XRD patterns of clay fraction (<2 µm) in MMCF A CC object: (A) A horizon, (B) BC horizon
Symbols for sample pretreatments: N – natural air-dried; Gl – saturated with ethylene glycol, 550 °C – heated at 550 °C for 2 hours.
Mineral designations: V-I – vermiculite-illite, I – illite, K – kaolinite, Q – quartz, V – vermiculite

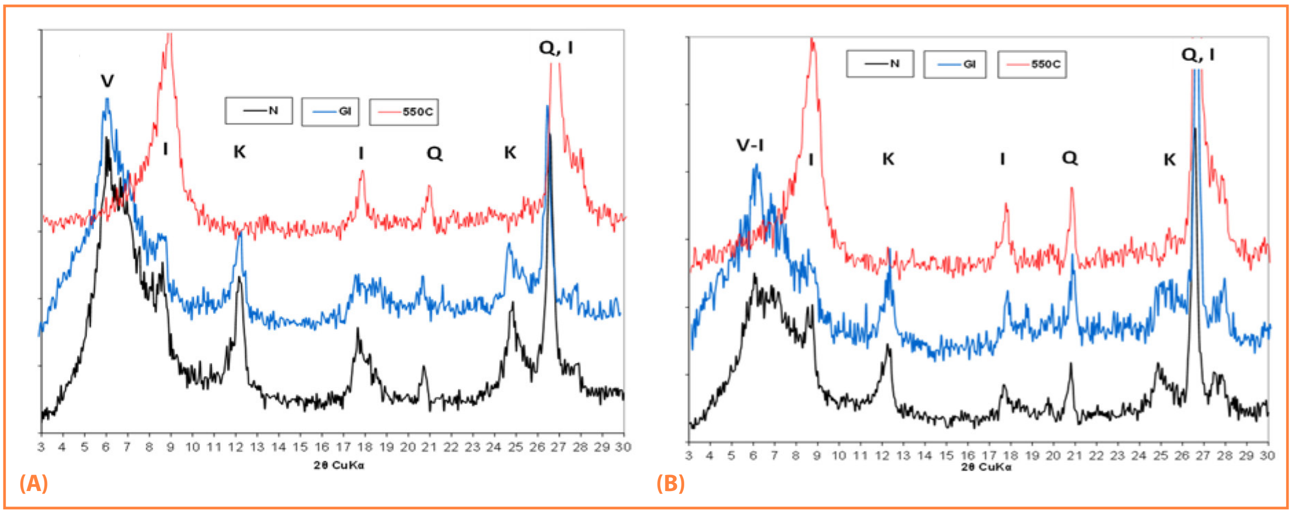

Figure 6 XRD patterns of clay fraction (<2 µm) in MMCF A F object: A) A horizon, B) BC horizon. Symbols for sample pretreatments: N – natural air-dried; Gl – saturated with ethylene glycol, 550 °C – heated at 550 °C for 2 hours. Mineral designations: V-I – vermiculite-illite, I – illite, K – kaolinite, Q – quartz, V – vermiculite

stability of soil aggregates, which is particularly important in mountainous conditions to prevent erosion and soil loss.

4 Conclusions

In mountainous conditions, clear-cutting in the mixed coniferous forest enhanced organic matter decomposition. Forest floor carbon declined following clear-cutting in the first 10 years, but after this period, in the deeper mineral soil horizons, SOM started to recover. Clear-cutting also diminished the low-molecular humic fraction, which could be leached from the soil profile, especially during heavy rainfall, or can partially be transformed into clay-associated organic matter. Although clay-associated C is a relatively small contribution to the total C budget, it might be interesting to investigate whether the mechanism and rate of carbon turnover depend more on the amount of clay minerals or on the time elapsed after clear-cutting. Clear-cutting in the mountainous mixed coniferous forests caused the accumulation of more stable humic acids, particularly in the upper soil horizons (Oa and A). The process of humification, the biological transformation of plant residues, resulted in the formation of humic substances with increasing contents of carbon and oxygen and a decrease in hydrogen in the first years after CC. Humic acids and humins are considered highly stable products of humification and with a high degree of recalcitrance. Therefore, they might be important for the carbon budget in soils. Clear-cutting in the first 2 years reduced the aliphacity of humic acids in the Oa and A horizons. Vegetation type, an acidic soil environment, as well as drought-flood abrupt alternations observed lately favor the formation of humic substances with an aliphatic nature. Ten years after harvesting, a significant increase in aliphacity in the Oa horizon confirmed organic matter recovery. Mixed coniferous forests are more resistant to biotic and abiotic disturbances, which is particularly important in the face of violent weather phenomena related to climate change. Thus, forest management plans should consider the conversion of spruce monocultures to mixed coniferous forests.

References

Amoah-Antwi, C., Kwiatkowska-Malina, J., Szara, E., Fenton, O., Thornton, S. F., & Malina, G. (2022). Assessing factors controlling structural changes of humic acids in soils amended with organic materials to improve soil functionality. *Agronomy*, 12(2), 283.
https://doi.org/10.3390/agronomy12020283

Barancikova, G., Jerzykiewicz, M., Gomoryova, E., Tobiasova, E., & Litavec, T. (2018). Changes in forest soil organic matter quality affected by windstorm and wildfire. *J Soils Sediments,* 18, 2738–2747. https://doi.org/10.1007/s11368-018-1942-2

Baveye, C. P., Schnee, L. S., Boivin, P., Laba, M., & Radulovich, R. (2020). Soil organic matter research and climate change: merely re-storing carbon versus restoring soil functions. *Front. Environ. Sci*., 8, 579904. https://doi: 10.3389/fenvs.2020.579904

Boguta, P., D'Orazio, V., Senesi, N., Sokołowska, Z., & Szewczuk-Karpisz, K. (2019). Insight into the interaction mechanism of iron ions with soil humic acids. The effect of the pH and chemical properties of humic acids. *J. Environ. Manag.*, 245, 367–374. https://doi.org/10.1016/j.jenvman.2019.05.098

Borelli, P., Panagos, P., Märker, M., Modugno, S., & Schütt, B. (2017). Assessment of the impacts of clear-cutting on soil loss bywater erosion in Italian forests: First comprehensive monitoring and modelling approach. *Catena*, 149 (3), 770–781.
https://doi.org/10.1016/j.catena.2016.02.017

Bronick, C. J., & Lal, R. (2005). Soil structure and land managemend: a review. *Geoderma*, 124, 3–22.
https://doi.org/10.1016/j.geoderma.2004.03.005

Brunetti, G., Mezzapesa, G. N., Traversa A., Bonifacio, E., Farrag, K., Senesi, N., & D'Orazio V. (2016). Characterization of Clay- and Silt-Sized Fractions and Corresponding Humic Acids Along a Terra Rossa Soil Profile. *Clean Soil Air Water*, 44(10), 1375–1384. https://doi.org/10.1002/clen.201500857

Cerli, C., Celi, L., Kaiser, K., Guggenberger, G., Johansson, M.-B., Cignetti, A., & Zanini, E. (2008). Changes in humic substances along an age sequence of spruce stands planted on former agricultural land. *Organic Geochemistry,* 39, 1269–1280. https://doi.org/10.1016/j.orggeochem.2008.06.001

Dębicka, M., Kocowicz, A., Weber, J., & Jamroz, E. (2016). Organic matter effects on phosphorus sorption in sandy soils. *Archives of Agronomy and Soil Science*, 62, (6), 840–855. https://doi.org/10.1080/03650340.2015.1083981

De Nobili, M., Bravo, C., & Chen, Y. (2020). The spontaneous secondary synthesis of soil organic matter components: A critical examination of the soil continuum model theory. *Applied Soil Ecology*,154, 103655. https://doi.org/10.1016/j.apsoil.2020.103655

Falsone, G., Celi, L., Capimi, A., Simonov, G., & Bonifacio, E. (2012). The effect of clear cutting on podzolisation and soil karbon dynamice in Boral forests (Middle Taiga zone, Russia). *Geoderma*, 177–178, 27–38. https://doi.org/10.1016/j.geoderma.2012.01.036

FAO (2015). USS Working Group WRB, World Reference Base for Soil Resources 2014, Update 2015. *International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*. World Soil Resources Reports No. 106, Rome.

Fukuzawa, K., Shibata, H., Takagi, K., Nomura, M., Kurima, N., Fukazawa, T., Satoh, F., & Sasa, K. (2006). Effects of clear-cutting on nitrogen leaching and fine root dynamics in a cool-temperate forested watershed in northern Japan. *For. Ecol. Manag.*, 225, 257–261. https://doi.org/10.1016/j.foreco.2006.01.001

Gee, G., & Bauder, J. W. (1986). Particle-size analysis. In: Klute A (ed). Methods of analysis. Part I Agronomy series 9. *Am. Soc. Agronomy Soil Sci.* Am. Inc. Publ, Madison.

Hayes, M. H. B., Mylotte, R., & Swift, R. S. (2017). Humin: its composition and importance in soil organic matter. *Adv. Agron.,* 143, 47–138. https://doi.org/10.1016/bs.agron.2017.01.001

Hayes, M. H. B., & Swift, R. S. (2020). Vindication of humic substances as a key component of organic matter in soil and water. *Adv. Agron.,* 163, 1–37. https://doi.org/10.1016/bs.agron.2020.05.001

James, J., & Harrison, R. (2016). The effect of harvest on forest soil carbon: A meta-analysis. *Forests,* 7, 308. https://doi.org/10.3390/f7120308

Jamroz, E. (2012). Properties of soil organic matter in the forest soils under mountain dwarf pine in the Snieznik Klodzki Reserve. *Sylwan*, 156 (11), 825–832.

Jamroz, E., & Jerzykiewicz, M. (2022). Humic fractions as indicators of soil organic matter responses to clear-cutting in mountain and lowland conditions of southwestern Poland. *Land Degrad Dev*., 33 (2), 368–378. https://doi.org/10.1002/ldr.4158

Jamroz, E., Kocowicz, A., Bekier, J., & Weber, J. (2014). Properties of soil organic matter in Podzols under mountain dwarf pine (*Pinus mugo* Turra.) and Norway spruce (*Picea abies* (L.) Karst.) in various stages of dieback in the East Sudety Mountains, Poland. *For. Ecol. Manag.,* 330, 261–270. https://doi.org/10.1016/j.foreco.2014.07.020

Jasińska, J., Sewerniak, P., & Markiewicz, M. (2019). Links between slope aspect and rate of litter decomposition on inland dunes. *Catena*, 172, 501–508. https://doi.org/10.1016/j.catena.2018.09.025

Jerzykiewicz, M., Barancikova, G., Jamroz, E., & Kałuza-Haladyn, A. (2019). Application of EPR Spectroscopy in Studies of Soils from Destroyed Forests. *Appl Magn Reson* 50, 753–760. https://doi.org/10.1007/s00723-018-1055-5

Kukla, J., & Kuklova, M. (2008). Growth of *Vaccinium myrtillus* L. (Ericaceae) in spruce forests damaged by air pollution. *Polish Journal of Ecology*, 56 (1), 149–155.

Loffredo, E., & Senesi, N. (2006). The role of humic substances in the fate of anthropogenic organic pollutants in soil with emphasis on endocrine disruptor compounds. In I. Twardowska et al. (eds.) *Soil and Water Pollution Monitoring, Protection and Remediation*, Springer (pp. 3–23).

Lützow, M. V., Kögel – Knabner, I., Ekschmitt, K., Matzner, E., Guggenberger, G., Marschner, B., & Flessa, H. (2006). Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions – a review. *European Journal of Soil Science*, 57, 426–445. https://doi.org/10.1111/j.1365-2389.2006.00809.x

Martin, D. (2016). *XPowderX™ (XPowder, XPowder12)*: A software package for powder x-ray diffraction analysis. Qualitative, quantitative and microtexture.

Mayer, M., Prescott, C. E., Abakerd, W. E. A, Augustoe, L., Cécillon, L., Ferreirah, G. W. D., Jamesi, J., Jandl, R., Katzensteinera, K., Laclau, J. P., Laganièrem, J., Nouvellonk, Y., Parém, D., Stanturf, J. A., Vanguelovao, E. I., & Vesterdalp, L. (2020). Tamm Review: Influence of forest management activities on soil organic carbon stocks: A knowledge synthesis. *For. Ecol. Manag*., 466, 118127. https://doi.org/10.1016/j.foreco.2020.118127

Polláková, N., Šimanský, V., & Kravka, M. (2018). The influence of soil organic matter fractions on aggregates stabilization in agricultural and forest soils of selected Slovak and Czech hilly lands. *J Soils Sediments,* 18, 2790–2800. https://doi.org/10.1007/s11368-017-1842-x

Prescott, C. E. (2005). Do rates of litter decomposition tell us anything we really need to know? *Forest Ecology and Management*, 220, 66–74. https://doi.org/10.1016/j.foreco.2005.08.005

Rice, J. A., & MacCarthy, P. (1991). Statistical evaluation of the elemental composition of humic substances. *Organic Geochemistry*, 17, (5), 635–648. https://doi.org/10.1016/0146-6380(91)90006-6

Swift, R. S. (1996). Organic matter characterization. In: *Methods of soil analysis. Part 3. Chemical methods – SSSA Book Series no. 5.* Soil Science Society of America and American Society of Agronomy (pp. 1011–1068).

Tan, K. H. (2014). *Humic Matter in Soil and the Environment*: Principles and Controversies (2nd ed.), CRC Press.

Ussiri, D. A. N., & Johnson, C. E. (2007). Organic matter composition and dynamics in a northern hardwood forest ecosystem 15 years after clear-cutting. *For. Ecol. Manag.,* 240, 131–142. https://doi.org/10.1016/j.foreco.2006.12.017

Weber, J., Tyszka, R., Kocowicz, A., Szadorski, J., Debicka, M., & Jamroz, E. (2012). Mineralogical composition of the clay fraction of soils derived from granitoids of the Sudetes and Fore-Sudetic Block, southwest Poland. *European Journal of Soil Science*, 63, 762–772. https://doi.org/10.1111/j.1365-2389.2012.01482.x