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Impacts of forest loss in the Eastern Carpathian Mountains: linking remote sensing and sediment changes in a mid-altitude catchment (Red Lake)

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Abstract

Worldwide accelerated forest loss and the associated environmental impacts are important environmental concerns. In this study we integrate evidence from historical maps and a Landsatderived time series of catchment scale forest cover changes with a multi-proxy, palaeolimnological reconstruction spanning the last 150 years from Red Lake (Eastern Carpathians, Romania) to better understand the impact of long-term forest changes on catchment erosion and sediment accumulation. We are able to consider two time windows. Firstly, we show that during the traditional (1840–1948) and socialist (1948–1989) periods, catchment changes and sediment responses, as reflected in the sediment accumulation rate, detrital input and grain size were moderate and likely reflect the combined result of known periods of excessive precipitation and local-scale forest disturbances. Secondly, and in contrast, rapid responses in catchment-scale geomorphological processes to forest loss are evident during the post-socialist land use period (1987-2010). We found that the first land restitution period (1987-1999) and the first part of the second land restitution period (2000-2002) had a greater impact on forest loss and subsequent catchment processes with sediment accumulation rates increasing from 0.5 cm/yr^{-1} to 1.2 cm/yr^{-1}. Finally, environmental impacts of forest changes were strongly dependent on the size of the area deforested, its location within the catchment, susceptibility to erosion and geomorphological thresholds. In a region noted for accelerated recent forest loss, our study highlights the potential of combining historical maps, satellite images and sediment proxies for documenting such changes and highlights the need for more strategic and sustainable environmental management planning.

Keywords: forest change, maps, satellite images, lake in-filling, erosion, Romania

Length of the manuscript:
7659 word (without references and figures)
6 Figures
Total words count 10382

Highlights

- inter-disciplinary approach assesses impacts of forest change on catchment scale geomorphic processes over the last 150 years
- multi-proxy, dated lake sediment profile records forest disturbance catchment impacts
- link between sediment changes and remote sensing reveals the nature and timing of recent catchment process responses to forest disturbances
- catchment-lake environmental management perspective in an environmentally important area

1. Introduction

The Carpathian Mountains are considered to hold some of Europe's last remaining pristine forests (Kuemmerle et al. 2007; Veen et al. 2010; Korn et al. 2012). In particular, the Romanian Carpathian forests are an important conservation hotspot considering the biodiversity and ecosystem services of their old growth forests (Thompson et al. 2009; Potapov et al. 2014). Although forest cover in Romania has undergone remarkable prehistoric and historic transformations through burning, clearing and grazing (Feurdean et al. 2010, 2013; Giosan et al. 2012; Tantau et al. 2014; Haliuc et al. 2016), recent changes are exceptional and unprecedented. Changes in forest cover include removal by natural e.g., wind throws, forest fires, heavy snowfall and insect infestation and/or anthropogenic factors and forest management e.g., harvesting and sanitary logging (Kuemmerle et al. 2007; Anfodillo et al. 2008; Popa 2008; Griffiths et al. 2012; Feurdean et al., 2017a).

One of the major environmental concerns in relation to forest disturbance (please see Section 3.4) are the consequences for geomorphological processes. Examples of forest disturbance impacts on the catchment include changes to litter interception, evapotranspiration, water storage and water movement, which expose the soil to direct rain-drop and thus promote sedimentation downstream (Dearing et al. 1987; Foster et al. 2003; Rogger et al. 2017). This subsequently activates hydro-geomorphological processes including top-soil and deeper soil erosion, and can lead, apart from floods and landslides, to river channel instability, river bed aggradation and lake siltation (Dearing et al. 1987; Foster et al. 2003; Hall et al. 2014).

Whereas the links between forest loss and socio-economic and political regimes have been widely studied in the Carpathian region (e.g., Griffiths et al. 2012; Korn et al. 2012; Munteanu et al. 2014, 2016), the geomorphological impacts of such changes on the catchment dynamics have been less investigated (Begy et al. 2009; Romanescu et al. 2013; Hutchinson et al. 2016; Florescu et al. 2017). These studies show that land cover was most strongly impacted during the socialist period due to industrialisation, the intensification of agriculture, overgrazing and forest harvesting (Hutchinson et al. 2016; Munteanu et al. 2016; Feurdean et al. 2017b).

Over the past decade, using techniques including remote sensing analysis, supported by historical maps, forest statistics and pollen datasets, Muller et al. 2009, Griffiths et al. 2012; Korn et al. 2012; Munteanu et al. 2014, 2016; Feurdean et al. 2017b have reported widespread land cover/use changes in response to political and socio-economic shifts in both the Romanian Carpathians Mountains and the lowlands. Whereas remotely sensed data can provide an objective assessment of land cover changes, the time span over which images are available is generally limited to the last few decades, e.g., the early 1980's onwards, and the impact of such changes on catchment geomorphological processes cannot be quantified. To overcome this limitation, multi-proxy analysis of sediment cores can provide a record of catchment changes and, combined with remotely sensed and map-based images of land/forest changes, can offer a longer-term perspective on the geomorphological consequences of such catchment changes.

The most important land and forest management periods over the last 150 years in CEE Europe are: 1) the traditional period (1840–1948) when the region experienced an expansion of agriculture on more fertile soils; 2) the socialist period (1948–1989) when land was transferred to state ownership and agriculture intensified and became highly mechanised (Sarbu et al. 2004); 3) the post-socialist period (1989-2007) when changes in ownership from the state to the private sector led to extensive land abandonment; 4) accession to EU period (post-2007) when the implementation of macro-economic policies led to both a second agricultural expansion into fertile zones and the abandonment of more marginal land (Kuemmerle et al. 2016).

In this study, we aim to determine the potential of the dual application of palaeolimnological techniques using the sediment record from Red Lake, historical map and remote sensing analysis to assess environmental changes and their impacts on catchment processes over the past 150 years in the Eastern Carpathians. Previous work on Red Lake has focused on the origin, hydro-geology and geomorphology of the lake catchment and region (Mihailescu 1940; Preda and Pelin 1963; Ghenciu and Carausu 1967; Bojoi 1968 a, b; Grasu and Turculet 1980; Pandi 2004; Romanescu et al. 2013) and limnological characteristics of the lake (Pisota and Nastase 1957; Ghenciu 1968 a, b). Here we aim to: i) assess the impacts of forest disturbances and sediment responses on a secular (last 150 years) and a decadal (23 years) time frame, and to identify the links with political, socio-economic developments; ii) evaluate the efficacy of combining a sediment-based approach, historical maps and remotely sensed data.

2. Study area

Red Lake is located in the Eastern Carpathians (north eastern Romania) within the Hăşmaş Massif at an altitude of 983 m a.s.l. (46.47.27°N, 25.47.14°E) (**Fig. 1**). The lake was formed by a landslide which dammed the Bicaz river (Mihailescu 1940; Ghenciu and Carausu 1967; Bojoi 1968 a, b). The triggers of the landslide, either an earthquake or heavy rainfall, and the year of formation (1837 or 1838) are controversial (Mihailescu 1940; Ghenciu and Carausu 1967; Bojoi 1968 a, b). However, the geomorphological features of the lake's surroundings and the presence of in situ standing dead trees in the waterbody, suggest landsliding as the origin of the present lake (Mihailescu 1940; Ghenciu and Carausu, 1967, Bojoi 1968 a, b).

The lake has a surface area of 12 ha and a maximum depth of ~11 m with a catchment area of 41 km^2 (**Fig. 1e**). It has two main limbs; the Oii running in a north-south direction for 960 m and the shorter Suhard heading 380 m northeast-southwest. The northern end of the lake is delineated by the landslide which dammed the valley. Red Lake has formed in a 'bath-like' basin with steep margins and a greater depth at the northern end (near Bicaz outflow) decreasing towards the south-west and north-west deltas (**Fig. 1 e**).

Since 2000 Red Lake has been part of the Hăşmaş-Cheile Bicazului National Park and therefore benefits from some environmental protection. Given the easier road access via the DN12C which passes near the site, Red Lake is one of the most visited attractions of the region. The road was constructed between 1910 and 1937 and was tarmacked in the 1950's. Settlement (mainly associated with tourist facilities) is restricted to the area around the north-eastern shore of the lake reflecting the road access through the catchment (**Fig. 1 d**).

The climate of the Red Lake area is temperate continental. Mean annual temperatures range from +5 °C to +7 °C (winter mean temperatures range from -7 °C to -9 °C and in summer from +14 °C to +16 °C). Mean annual precipitation ranges from 544 mm to 1026 mm.

The geology of the catchment comprises calcareous sandstones, limestone and dolomites in the immediate vicinity of the lake with areas of sandstones and conglomerates to the north and south (in Oii valley), and crystalline schist to the west (Sandulescu 1975, 1984; Grasu and Turculet 1980; Grasu et al. 2012). An area affected by denudational processes (mainly, landslides) is present in the southern, lower part of the catchment, along the Oii valley (Grasu and Turculet, 1980). The underlying geology strongly influences the soils of the catchment; soil types range from podzolic (over the schist) to more widespread rendzinas where the substrate is more calcareous (Romanescu et al. 2013).

The CORINE land cover dataset (reference year 2012) shows that coniferous forest covers 70% of the catchment with transitional woodland-shrubs covering 15% and natural grassland with 12%, while only 2% comprises agricultural land, pastures and sport and leisure facilities (**Fig. 1 d**).

3. Methodology

3.1 Sediment coring

Red Lake was sampled using a gravity corer (66 mm internal diameter) in the summer of 2011 when five surface sediment cores were taken along the main limb of the lake. A second coring campaign was undertaken in the winter of 2013 from the ice-covered surface of the lake (water depth 8.9 m); this core was the longest core extruded and represents the main focus of this study. The other cores are used only for the sedimentological description of lake basin and identification of sediment variation along the main limbs.

The location of the core site was logged using a hand-held GPS and lies in the main body of the lake (**Fig. 1 e**). Unlike previous cores taken from Red Lake (Begy et al. 2009), the key core sequence used here was taken from the deepest and flat-bottomed part of the lake and therefore avoids the potential effects of shallow water on marginal sediments and possible subaquatic processes (slumping) on steeper slopes.

3.2 Laboratory analysis

All cores were described in terms of visual characteristics, extruded and sectioned at 0.5 cm intervals, and dried at <40 °C. From the key core subsamples were subjected sequentially to multiple analyses including geochemical analysis via XRF, selected mineral magnetic measurements and physical characterisation; LOI (total organic content) and particle size distribution. Subsamples were also submitted for gamma-based radiometric dating.

The geochemical properties of the sediments were investigated using a Niton XL3t GOLDD X-Ray Fluorescence analyser (fpXRF) mounted in a shield. This is a rapid and sample non-destructive technique widely employed for the geochemical characterisation of soil and sediment samples (Krauskopf and Bird 1994; Kalnicky and Singhvi 2001; Haliuc et al. 2016; Florescu et al. 2017). The accuracy of the technique was corroborated by analyses of a Certified Reference Material (CRM) as part of the measurement sequence; NCS DC73308 (Chinese stream sediment). Only those elements where the relative percent difference between the concentration reported for the reference material and the concentration measured by the fpXRF were <10% are given. The instrument's performance is discussed by Shuttleworth et al. (2014).

A suite of selected mineral magnetic measurements was made. Magnetic susceptibility was determined using a Bartington Instruments Ltd MS2 meter and MS2B sensor at both low and high frequency in order to allow the calculation of both low frequency (χ) and frequency dependent magnetic susceptibility (χfd) (Dearing 1999). Anhysteretic Remanent Magnetisation (ARM) was induced using a Molspin AF Demagnetiser, while for Saturated Isothermal Remanent Magnetisation (SIRM) (magnetic field 1.0 mT) a Molspin Ltd Pulse Magnetiser was employed. A Minispin Fluxgate Magnetometer was used to determine the resultant magnetic remanences at each step (Walden et al. 1999; Akinyemi et al. 2013).

To estimate the total organic matter content of the samples, the loss-on-ignition (LOI) method was used whereby the weight loss of material dried at 105 °C and burned at 550 °C was determined and expressed as a percentage of loss-on-ignition (Heiri et al 2001; Veres 2002; Santisteban 2011).

The particle size distribution of the samples was measured using a Horiba Partica LA-950V2 particle size analyser. The instrument employs a laser diffraction method in order to estimate the particle size range within a sample. Ashed samples (following LOI determination) in an aqueous suspension were analysed employing a protocol to minimise uncertainties (i.e., a common sample circulation time (2 minutes) and period of ultrasonication (2 minutes) making repeat measurements (3) (Haliuc et al. 2016). This instrument complies with ISO 13320 (Particle size analysis - laser diffraction methods) with a documented accuracy of 3% on the median of a broad distribution standards with a precision of 0.1%.

Dried sediment samples were analysed for ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am by direct gamma assay in the Environmental Radiometric Facility at University College London, using an ORTEC HPGe GWL series well-type coaxial low background intrinsic germanium detector following three weeks' storage in sealed containers to allow radioactive equilibration. The absolute efficiencies of the detector were determined using calibrated sources and sediment samples of known activity. Corrections were made for the effect of self-absorption of low energy gamma rays within the sample (Appleby et al. 1986).

3.3 Historical maps

We used two sets of historical (scanned) maps: military plans compiled from 1917 and 1939 surveys and military topographic map from 1983 to estimate the forest changes. These were the oldest maps available for our study area with a suitable resolution and the necessary spatial coverage. Earlier maps, produced under Habsburg Empire surveys (XVIII and early XIX century) for our study area had a very poor resolution and thus could not be used to estimate forest changes.

The difference in forest cover between 1917/1939 and 1983 maps were taken as forest changes. However, overlapping these maps we established three classes of change: 1) non-forest stable areas, which represent areas with non-forest vegetation on both maps which do not change; 2) non-forest extension areas, which represent areas with no forest vegetation on the 1917/1939 maps which were extended on the 1983 map; 3) non-forest retreat areas comprising areas identified with no forest vegetation on the 1917/1939 map which were forested in 1983 map. Using manual digitisation to estimate the deforested area from topographic maps, the resulting values cannot be directly compared with the remotely sensed data. Nevertheless, this information complements the overview of forest changes in the Red lake catchment before the 1980's – the time limit for remote sensing images.

The topographic maps from 1983 provide some information about the structure of the forest which, at the time of mapping, was mainly composed of spruce with a median height between 18 and 25 m and a median diameter between 20 and 30 cm. These maps also provide information about other land-cover types such as recently harvested forest, pastures, pastures with scatter woody vegetation (spruce and junipers) and surfaces without vegetation (classified as barren).

3.4 Remote sensing analysis

A subset of a near-annual collection of Landsat and TM/ETM+ images for the period 1984-2010 of Griffiths et al. (2012) covering central-eastern Romania (Landsat footprint path/row 183/028) was employed in this study (**Fig. 1**). Details on the image pre-processing and time-series segmentation procedure are provide in Griffiths et al. (2012). Their overall accuracy is reported as 95.7%.

For this study, we used that section of the Landsat survey that covers the catchment of Red Lake. The watershed was defined and areas without the lake's drainage were excluded. The data were processed using ArcGIS to calculate the extent of forest loss at twenty-one annual time steps (1987-1989, 1991, 1993-1996, 1998 and 2001- 2010) with missing years in 1990, 1992, 1997 when the condition, cloud cover, prevented image recovery.

The terminology forest disturbance used here, *sensu* Griffiths et al. (2012), refers to intermediate to high intensity canopy disturbances as depicted by satellite image analysis and caused by natural events or forest management activities. However, as stated by Griffiths et al. (2012), most of the recent disturbances identified in central-eastern Romania are due to harvesting activities.

3.5 Statistical analysis

A principal component analysis (PCA) was applied to selected parameters of the four cores that describe the core transect to explore the spatial variation and identify relationships between their parameters. A correlation matrix was calculated for the entire geochemical dataset to examine the relationship between all elements and to select those which hold stronger associations. Principal component analysis was performed on selected elements including geochemical elements (Ti, K, Ca, Zr, Rb, Pb, Fe, Mn) and ratios (Zr/Rb, Zr/Ti, Fe/Mn), organic (OM) and carbonate content, magnetic parameters ($\chi_{fd\%}$, SIRM), particle size (median) to interrogate their variation between the cores.

Statistical analysis was performed using PAST software version 2 and 3 (Hammer et al. 2001). The most relevant principal components were identified with the broken stick model.

4. Results and interpretation

4.1 Palaeolimnological analyses

We present palaeolimnological results including physical and geochemical proprieties, and mineral magnetic characteristics along a longitudinal transect. This transect lies along the main limbs of the lake and includes the undated cores (Core 1, 2, 3 and 5) taken in 2011 and the dated Core 1 from 2013 (**Fig. 1 e**; **Fig. 2**). For the dated core, Core 1 – 2013, we focus on the upper part of the core, above 36 cm, which represents the recent, post-landslide sediment sequence (**Fig. 2**).

4.1.1 Age-depth model

The age-depth sediment profile of Red Lake is based on ^{210}Pb and was calculated using the CRS (constant rate of ^{210}Pb supply) dating model (Appleby and Oldfield 1978). This dating model places the 1986 depth at 15.25 cm and therefore is in good agreement with the depth suggested by the ^{137}Cs record. Details of the age-depth model are presented in Supplementary Material S 1.

Sedimentation rates calculated by the ^{210}Pb data indicate a slowly increasing trend in sedimentation rates into the 1930's followed by variations until around 2000 (Supplementary Material S 1, S 2). There is a small peak in the sedimentation rate around 1960, with a consistent increase from the 1980's and a sharp peak that reached 0.36 g cm^{-2} yr^{-1} in 2002 (Supplementary Material S 1). Subsequently sedimentation rates have declined.

4.1.1 Physical properties

Visual inspection of the dated core taken in 2013 (Core 1 - 2013) revealed a marked transition in sedimentary characteristics in terms of changes in colour and texture at ~36 cm (**Fig. 2; Fig. 5**). The sediments below 36 cm are composed of coarser (sand-silt) material and likely to be of landslide-origin. The interval between 36 cm and 28 cm is composed of dark-grey (clay-silt) while the interval between 28 and 0 cm consists of dark-brown (clay-silt) interrupted by white-grey medium to coarser silt layers. These visual changes are clearly reflected in the physical properties of the core (**Fig. 3**).

Core 1 - 2013, Core 2 – 2011 and Core 3 - 2011 are located near the northern and southern lake edges (**Fig. 1 e**; **Fig. 2**) and consists of medium to coarse silt and sand which seems to characterise the material influx brought in by permanent and temporary streams (**Fig. 2**). Cores 5 - 2011 is located in the central part of the lake and consists of fine sand and silt at the base followed by bands of organic matter intercalated with thin layers of silt (**Fig. 2**).

In Core 1 - 2013, the lower part of the core (below 36 cm) shows two marked peaks in organic matter content (around 70 cm and 50 cm), but elsewhere it exhibits a low organic content (<5%). Above 36 cm, the LOI variations are less marked, but more frequent than in other parts of the core (**Fig. 2**). LOI values tend to be greater between 36 and 16 cm with a gradual decline towards the surface of the core with a peak in LOI (25%) at 24 cm (**Fig. 2**). In Core 1- 2011, the organic content varies between 10 and 16% with slightly lower values around 30 cm. The organic matter content has similar values in Core 2 – 2011 and higher values in Core 3 – 2011, especially below 20 cm depth. In Core 5 - 2011 the organic matter has a marked change at 40 cm depth with low organic content values (<5%) below 40 cm and increasing values (>10%) above this depth (**Fig. 2**).

Median particle size was selected as a proxy for changes in energy and runoff intensity, and erosion input (Florescu et al. 2017 and references therein). In the upper part of Core 1 – 2013 (top 30 cm) median particle size is relatively low and consists of silt-clay (D50, <60μm) with peaks around 20, 10 and 5 cm depth (**Fig. 2**). A large peak around 36 cm, composed of sand, reaches a similar magnitude to that of the lower part of the core (**Fig. 2**). This marked shift in particle size might indicate the transition between landslide (coarser, sandy) and post-landslide (finer, silt-clay) material deposited (top 36 cm). Core 2 - 2011 presents a slightly increasing trend with and important shift at 25 cm and 17 cm, which marks two inflection points where the values start to decrease (**Fig. 2**). A similar trend is visible in Core 3 – 2011, higher values are present below 40 cm and two large peaks are present around 30 and 20 cm (**Fig. 2**). In Core 5 - 2011 an increasing trend is visible in the first part of the core peaking at 17 cm, after this point the values start to decrease. Comparing the cores along the transect we observe that the central core, Core 1 - 2013, is coarser on the part below 30 cm while Core 5 - 2011 is coarser on interval above 30 cm (**Fig. 2**).

4.1.4. Geochemical properties

Ti, K, Zr/Ti, Zr/Rb are used here as proxies to characterise the erosional input as changes in these proxies reflect the variation in the mineral input from the lake catchment mainly as a result of transport-deposition processes or changes in the source of minerals (Kylander et al. 2011). As Ti, K and Rb are mainly enriched in the finer silt fraction, while Zr tends to increase in the coarse silt and sand fraction we use Zr/Ti and Zr/Rb ratios to highlight the intervals with coarser/finer sediments (Kylander et al. 2011). Our interpretation is also supported by the particle size analysis which show a synchronous variation with the geochemical ratios. For cores along the transect we plot selected elements for ease of comparison.

In Core 1 – 2013, the Ti, K values depict a fluctuating trend in the section below 36 cm, which also attains the highest values from the entire record and indicates a high detrital input (**Fig. 2**; **Fig. 5**). A second increase, although values are moderate compared with the interval below 36 cm depth, is observed above 20 cm while low values characterise the interval between 30 and 20 cm depth. Zr/Ti and Zr/Rb are characterised by high values below 36 cm and a fluctuating trend for the rest of the profile which suggest very coarse material for the bottom part of the profile and finer material for the upper one (**Fig. 5**; Supplementary Material S 3). However, if we consider only the interval above the landslide material, an interesting pattern is depicted with more silt in the interval spanning between 36 and 30 cm and more clay for the interval between 30 and 0 cm, but interrupted by coarser material around 20 cm depth and above 10 cm. In Core 1 – 2011, Ti values depict a decreasing trend with important peaks at 50, 17 and 5 cm depth which suggest a pattern of declining detrital inputs although interrupted by energy events, which is not surprising given the marginal location of this core, near the southern delta (**Fig. 2**). In Core 2 – 2011, Ti exhibits a fluctuating trend with an increase between 30 and 15 cm, but does not show important changes in detrital inputs at this location. In Core 3 – 2011, Ti values depict a rather monotonous pattern, slightly increasing towards the upper part of the core which indicate a consistent detrital input which is typical given the marginal location of the core (**Fig. 2**). In Core 5 – 2011, Ti shows high values below 30 cm depth followed by a rather stable trend until 10 cm and a second increase towards the top of the core which suggests an increased detrital input in the bottom (below 30 cm depth) and upper (above 10 cm depth) parts of the profile. Although the resolution is relatively low, for Core 5 -2011 the Ti pattern is comparable to changes in this lithogenic element observed in Core 1 – 2013, both characterise sediments taken from the deepest part of the lake (**Fig. 2**).

4.1.3 Mineral magnetic characteristics

In the Core 1 – 2013, the presence of finer mineral magnetic grains in the upper part of the core is indicated by the χ_{fd} values which, although highly variable throughout the entire profile, are greater above 36 cm (Supplementary Material S 3). Within the upper 36 cm of the core there also appears to be a decline in the representation of SSD (stable single domain size) magnetic minerals toward the top of the profile with the highest values of ARM/χ and SIRM/χ between 36 and 20 cm input (Supplementary Material S 3). χ_{fd} values, indicative of fine, ‘viscous’ (FV) magnetic grains (Mullins 1977), are most consistently elevated above this (e.g., between 15 and 5 cm). The uppermost sample appears to indicate a reversal of this feature and a sediment richer in SSD size mineral magnetic grains. The magnetic grain size sensitive parameters and ratios show a shift in magnetic grain size between the pre- and post-landslide material; the marked changes in ARM/χ, SIRM/χ, and mirrored variation in SIRM/ARM, indicate a greater proportion of finer mineral magnetic grains (SSD) in the sediments above 36 cm (Banerjee et al. 1981, King et al. 1982) (Supplementary Material S 3).

In Core 1 – 2011 the SIRM values do not depict any marked change. Core 2 – 2011 has a similar trend with Core 1 - 2011 with the exception of a slightly higher values between 40 and 30 cm. The magnetic concentration of Core 5 – 2011 shows an increasing trend peaking at almost 40 cm and 30 cm followed by a sharp decrease (**Fig. 2**). Core 3 – 2011 the SIRM values show an increasing trend peaking at almost 20 cm followed by a decrease and a second increase around 40 and 33 cm (**Fig. 2**).

4.1.4 Sediment spatial and temporal changes

Multi-proxy analysis of a longitudinal transect of undated 2011 and dated 2013 cores, supported by the principal component analysis, reveals important spatial sediment variations across the lake basin (**Fig. 3**). Our multi-proxy investigation show that sediment cores display considerable variation which is unsurprising considering the basin characteristics with narrow edges, shallow water and short history.

The first two components, PC1 and PC2, explain 57% of the total variance. PC1 captures 37% of the total variance and is representative of variations in Zr/Rb, Zr/Ti, Ca and the carbonate content. PC2 explains 20% and reflects variations in χ_{fd}, organic matter and SIRM. Samples belonging to Core 1 - 2011 and Core 2 - 2011, located at the southern end of the lake, are grouped together and share common physical characteristics which suggests that sedimentation here may be regulated by the influx of material from southern sub-catchment of the Oii and Licas brooks (**Fig. 1**). Core 1 – 2013 samples are discriminated from the other cores with top (above 30 cm) and bottom (below 30 cm) samples showing distinctive characteristics. In the top samples there is an association between organic matter content, SIRM while in the bottom samples there is an association with Ti, K and median particle size, which show the different characteristics of bottom, coarser material, sandy deposit and the upper, finer material, clay-silt lacustrine sediments. As the lithogenic parameters display their highest concentrations in the lower part of the core (below 40 cm), early in-filling of the newly-formed lake basin, immediately after the landslide, is implied.

Samples from Core 3 are clearly discriminated by their χ_{fd} and exhibits different proprieties compared to cores located along the main limb of the lake (Cores 1, 2 and 5) which may indicate a different sediment input from Suhard brook (see **Fig. 1 e**). Samples from Core 5 exhibit the highest variance; the samples from the bottom of this core are clearly differentiated from the uppermost samples e.g., Zr/Ti, Ca, carbonate content and Fe, SIRM. These discriminating characteristics of the top and bottom proprieties of Core 5 sediments may indicate a basal, possible flood deposit, with overlying lake sediments. The physical proprieties of the cores suggest that the southern limb of the lake (Core 1, 2) has received less alluvial material than the northern limb (Core 3) (**Fig. 2**). The physical characteristics of the five cores (**Fig. 2 a**) show that both cores located along northern and southern limbs (Cores 1, 2, 3) and cores located in the central part of the lake (Core 5 and Core 1-2013) do not become finer over the bed of the lake, probably reflecting higher energy in-lake sediment transport with a possible turbidity effect.

4.2 Historical maps and remote sensing data

During the traditional and socialist periods, the temporal and spatial evolution of forest area is analysed at reference points in time, 1917/1939 and 1983 (**Fig. 4 a**). In 1917/1939 the total non-forest area was ca. 394 ha represented by small patches in the central, south-eastern and eastern areas of the catchment (**Fig. 4 c**). Comparing the 1917/1939 and 1983 maps we observe a ca. 165 ha stable non-forest area, represented by pastures, which remained unchanged. In 1983, the total non-forest increased to ca. 519 ha and the disturbed patches tended to be found in the southern, central (Oii valley) and also west of the catchment (**Fig. 4 c**).

Between 1987 and 2010 the area of forest disturbance around Red Lake is analysed at roughly twenty-one annual time steps (**Fig. 4 b**). The forest disturbance area was lowest in 1991 and 1993 (0.54 and 0.71 ha respectively) and highest in 2000 and 2002 at 59.67 and 58.51 ha respectively. The disturbed areas tend to be found in the south west of the catchment, relatively distant from the lake; probably reflecting road access (**Fig. 4 b**). From 1995 the disturbed areas become more widespread, but still tend to favour the west of the catchment (**Fig. 4 b**). In 1996 a significant block of forest loss was detected within a 1000 m of the lake with further increased from 1998 to 2001 (**Fig. 4 b**). In 1996 the first extensive disturbed area in the southern part of the catchment becomes apparent, but become more marked in 1999 and 2000 in the Oii sub-catchment (**Fig. 4 b**). From 2001 to 2005 the forest disturbance areas are relatively scattered although in 2004, forest disturbance occurs immediately upstream from the lake (**Fig. 4 b**). In 2006 disturbed areas relatively close the southern end of the lake begin to be detected although the levels of annual disturbance start to fall from 2008 (**Fig. 4 b**).

The total number of forest disturbance patches closely resembles the total disturbance area registered per year (**Fig. 4 d**). However, we found a higher number of disturbance patches than the total area disturbed for 1989 and lower for 2002 and 2010. For the recent periods discussed, the highest number of disturbance patches is registered between 2000 and 2004 (second restitution period) and the lowest number of disturbance patches between 1987 and 1989 (late socialist period) (**Fig. 4 d**).

5. Discussion

In the first sub-section we evaluate the impact of natural and anthropogenic activities on forest cover, as determined from historical mapping, and sediment/catchment responses determined from geochemical and mineral magnetics properties, over the last 150 years. In the second sub-section, we focus on a 23-year window (1987-2010) with more dynamic and better-documented socio-economic events, and discuss the catchment responses to forest disturbances established through remotely sensed data.

5.1 Longer-term natural and anthropogenic disturbances and catchment responses

The impact of human activities on forest over the last millennia in the Carpathian region is well known (Feurdean et al. 2010, 2013a; Tantau et al. 2011, 2014; Giosan et al. 2012). However, only a few studies have focused on investigating the catchment response to more recent human intervention (Begy et al. 2009; Enea and Romanescu 2012; Hutchinson et al. 2016; Florescu et al. 2017). These studies show key hydro-geomorphic changes, especially erosion and lake in-filling, in response to human disturbances and extreme climatic events.

5.1.1 Catchment responses to forest changes during the traditional period (1840-1948)

During the traditional period, Red Lake's catchment was characterised by moderate instability. This is highlighted by moderate, but generally increasing trends in sediment core Ti values (peaking around 1925), mineral magnetic concentrations (e.g., SIRM) median particle size and SAR (**Fig. 5**). Around this time, the map-based forest estimates (1917/1939), showed reduced forest loss (**Fig. 4 a, c**). However, work on road construction and localised forest disturbances throughout the catchment started (e.g., 1910). These changes in forest area seem to have had a limited impact on catchment stability and detrital input to the lake via soil erosion. Interestingly, the peak in Ti, SIRM and SAR around 1925, overlap an interval characterised by heavy precipitation across Romania (1910-1919) (Topor 1964; Dragota 2006) (**Fig. 5**) which may have contributed to sediment input. Our inferred moderate changes in forest cover, and their impacts on the catchment stability, over the traditional period are in line with results inferred from other mid- and high-altitude lakes from the Carpathians (Hutchinson et al., 2016). Furthermore, documentary evidence indicates that Harghita County, where Red Lake catchment is located, experienced lower forest loss rates at this time compared to the southern and eastern parts of Romania, where deforestation for agricultural expansion was the result of 1872 and 1921 privatisation events (Munteanu et al. 2014; 2016 and references therein). Also, levels of seasonal pastoralism, an important activity generally in the Romanian Carpathians, were relatively low in the Red Lake catchment in comparison to the Southern Carpathians (Constantin 2004).

5.1.2 Catchment responses to forest changes during the socialist period (1948-1986)

During the socialist period, the characteristics of the lake's sediments e.g., an increase in Ti, K concentrations, SAR, oscillating values of SIRM, and a decrease in organic matter content suggest slope destabilisation (**Fig. 5**). These sedimentological changes are coincident with a forest cover reduction, as depicted by our map-based estimates (**Fig. 4 a, c**). This suggests that forest losses during socialist period led to increased catchment inputs to the lake via surface runoff. Indeed, comparison of the two historical maps from 1917/1939 with 1983, show that the deforested area in 1917/1939 (traditional period) was represented by small, isolated patches of disturbed forest spread across the catchment. On the other hand, the 1983 (socialist period) map show a significant increase in the extent of the deforested area, which concentrates on the central and southern part of the catchment, especially across the Oii brook (**Fig. 4 a**). The Oii Valley was characterised by Grasu and Turculet, (1980) as denuded. It is clear that areas with lower slope angles, e.g., Oii brook valley, were preferred for wood cutting given the easier access to the site and for wood removal (via forest roads or waterways) (**Fig. 4 a**). From 1960 to 1962, concerns regarding lake infilling led to installation of sediment traps on the Oii and Vereschiu brooks (P.N.C.B.-H., 2016). Around 1967, extensive forest harvesting is documented in the catchment, especially along the Suhard and Oii valleys due to the opening of forest roads (Ghenciu and Carausu 1967). Consequently, forestry operations here are likely to have exacerbated any landscape instability and enhanced erosion processes. However, changes observed in geochemistry (e.g., Ti, K, Zr/Ti, Zr/Rb), median particle size and sediment accumulation rate around 1960’s and 1970’s also overlap a decade of excessive precipitation in Romania (spanning between 1966 and 1975), which may also have contributed to the observed catchment instability. We suggest that the increases in soil instability and lake sedimentation post-1960’s, are primarily the effect of forest losses, exposing catchments surfaces. Nevertheless, the period of excessive precipitation between 1966-1975 may have enhanced erosion.

5.2 Integrating remotely sensed and palaeolimnological data to assess short-term forest changes and environmental impacts

The level of forest loss in the catchment varies dramatically over the time period for which Landsat data is available for the region (1987-2010). We use four periods (as defined by Griffiths et al. 2012) of forest loss: 1987-1989, 1991-1999, 2000-2004, 2005-2010 alongside our palaeolimnological data to discuss catchment responses to changes in forest. These periods reflect the implementation of land ownership restitution laws (18/1991, 1/2000 and 247/2005) (Ioras and Abrudan 2006) re-privatising formerly collectivised forest and agricultural land (pre-1948) following the collapse of the socialist system in 1989.

5.2.1 Catchment responses to forest changes during late-socialist period (1987-1989)

During the late socialist period (1987-1989) the forest loss in the Red lake catchment is rather reduced when compared with the 1987-2010 period (**Fig. 4 b, d**). The geochemical parameters (e.g., Ti, K), sediment particle size characteristics and SAR indicate changes in the catchment that started as early as the 1970's. It appears that the sediment changes observed during this time reflect the on-going geomorphological impacts of the earlier socialist period on forest losses.

5.2.2 First land restitution period (1991-1999)

The first increase in forest loss is evident between 1993 and 1995, following the first land restitution law (Law 18/1991) (**Fig. 4 b, d**). Although this law was adopted in 1991, the process of forest restitution to private owners was slow and its implementation delayed (Abrudan et al. 2009; Griffiths et al. 2012). The Red Lake record shows marked sediment changes i.e., high values of lithogenic elements such as Ti, K, SIRM, median particle size and SAR, between 1994 and the early 2000's, which suggest an increase in soil instability in the catchment (**Fig. 6**). The high rates of forest loss appear to have destabilised the catchment, increasing the detrital input to lake via erosion. In 1996, a considerable disturbed area is observed very close to the lake (<1000 m), followed by a second peak of forest loss between 1998 and 2001. This forest disturbance is perfectly mirrored in the sediment proprieties and shows a rapid catchment geomorphological response to forest disturbances (**Fig. 6**).

5.2.3 Second land restitution period (2000-2004)

The forest loss registered between 2000 and 2004 represents the highest forest area lost between 1986-2010 with two isolated peaks placed around 2000 and 2002 (**Fig. 4 b, d**). Changes in the forest cover are closely reflected in the sediment proprieties of Red Lake e.g., a decreasing trend in Ti concentrations, SIRM, median particle size, organic matter content and SAR (**Fig. 6**). However, the isolated peak in forest disturbance registered around 2002 is coincident with singular peaks in the sediment accumulation rate values and other erosion-related parameters, which show the impact of forest area reduction on the slopes. As most of the disturbances are located in the Oii valley, in an area already destabilised by erosion processes (Grasu and Turculet 1980), the location of the forest disturbance may help account for the unprecedented size of the peak in the sediment accumulation rate.

The greater relative significance of forest cover changes around the first restitution period (1991-1999) and the first part of the second restitution period (2000-2002) on catchment processes, is in agreement with the observations of Griffiths et al. (2012) of forest loss across the entire central-eastern region of Romania. It reflects private owners' empowerment after the law implementation, illegal timber exploitation, loopholes, weaker forest law and the emergence of the black market in the forest industry (Kuemmerle et al. 2009a; Grozavu et al. 2012). This highlights the impact of institutional instability on forest cover and subsequent environmental disturbances.

5.2.4 Third land restitution period and EU accession (2005-2010)

During the third land restitution period (2005-2010) forest loss peaks between 2006 and 2008 and mainly localised in the area close to the southern end of the lake. The disturbed area represents the second highest forest loss in 23 years (**Fig. 4 b, d**) which is in line with changes seen across the wider central-eastern region of Romania. The impact of this forest disturbance is reflected in the increased detrital input to the lake, as depicted by high values of Ti, SIRM, median particle size and organic matter content of the sediments. Despite the significant change in forest cover, the sediment accumulation rate shows a decreasing trend, which might suggest that, although there was some erosion (as shown by other parameters), a significant part of sediment might have been stored in the catchment and/or the sediment supply was exhausted (**Fig. 6**).

Results from this study show that the impacts of forest loss following restitution laws over the past 23 years appears to have had differential catchment responses dependent on the size of the area deforested, the location of deforested area within the catchment, its susceptibility to erosion and geomorphological thresholds. We found that the impact of first land restitution law on the catchment (soil erosion and increasing siltation) was gradual (**Fig. 6**). This is because the implementation of the law and thus forest disturbance was delayed, although the first land restitution law facilitated the return of greatest forest area to its former owners (Abrudan et al. 2009).

Marked change in sediment accumulation rates followed the implementation of the second land restitution law. This response in sediment accumulation may reflect the highest forest loss registered at this time, which occurred in an already disturbed catchment (**Fig. 6**). Furthermore, the location of the deforested area was also closer to the lake (**Fig. 6**) thus, facilitating rapid sediment transport to the lake. However, after this increase, the SAR values show a decreasing trend, which was also maintained after the third land restitution law when forest loss and subsequent erosion increased. It is possible that the decreasing SAR, despite the forest loss increases, might be due to geomorphological threshold or an exhaustion of sediment supply, as forest disturbances took place in the same area over a number of years (south-west and central parts of the catchment).

6. Conclusions

Our analysis provides an overview of forest changes and the subsequent catchment impacts over the past 150 years with the greatest focus over the most dynamic period of the last 23 years; a key period of major political upheaval in CE Europe fuelling potentially deleterious land cover changes. The strength of our analysis lies in the evaluation of the impact of forest loss on the local environment through a combination of palaeolimnogical analysis, historical maps and a Landsat dataset.

The long-term forest changes and associated environmental impacts observed in our catchment were driven by a suite of factors including natural, political and socio-economic factors, whereas the short-term changes are more a reflection of institutional instability. Catchment-scale changes following local/regional events (road construction/improvement and localised harvesting) were enhanced by known periods of exceptional precipitation. There was also a differential impact of forest disturbances on the sedimentation changes according to catchment conditions and the size and location of the area affected by tree removal.

Over the last 23 years (1987-2010), we show that changes in forest ownership, following the implementation of land restitution laws, impacted upon catchment-scale geomorphological processes, manifested as increases in erosion and sediment accumulation rates. The exceptional downstream sedimentation impacts of recent forest loss are important environmental issues for catchment management as increased sedimentation can affect aquatic populations and alter water resources. These impacts highlight the need for integrated environmental management planning that effectively considers both causes (forest disturbance) and effects (sedimentation) and which should be a priority for environmental decision making in the Red Lake Natural Reserve.

As remotely sensed data covers the wider Carpathians and this study highlights localised forest changes and catchment responses, this site might serve as a model for other studies across the region to evaluate changes in land cover and the subsequent environmental disturbances in other settings.

Acknowledgements

AH and AF acknowledge ERASMUS Program for facilitating access to laboratory facilities and AF from FE-1969/4_1. Patrick Griffiths and Richard Armitage are gratefully acknowledged for providing the remotely sensed dataset and for its preliminary GIS processing. We wish to thank Gabriela Florescu, Andrei Zamosteanu and Daniel Forgaci for their assistance in the field. The editor and two anonymous reviewers helped to improve a previous version of this manuscript.

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Figure captions:

Fig. 1 a) Location of the study area within Europe (upper left panel), b) aerial photo (Esri, DigitalGlobe) and topographic map (1:25000) of Red lake catchment including the Hăşmaş-Cheile Bicazului National Park and Natural reserve perimeters, c) relief, d) land cover (CORINE Land

Cover 2012), e) the bathymetry of Red Lake and location of sediment cores taken during field campaigns in 2011(red dots) and 2013 (yellow dot)

Fig. 2 The transect of sediment cores taken in 2011 and 2013 showing the water depth at each coring point and the main sediment proprieties for each core. The dashed line in Core 1 – 2013 marks the lithological change between sandy (landslide material) and silty-clay (lacustrine) sediments. The parameters are expressed as it follows: Ti (mg kg^{-1}), SIRM (10^{-5} Am^2 kg^{-1}), LOI (%), median particle size (μm)

Fig. 3 PCA bi-plot for selected sedimentological, geochemical and magnetic proxies plotted on the first two components (Component 1 and Component 2) with symbols and points coloured according to core numbers. The red line of the scree plot represents the broken stick model

Fig. 4 Forest change evolution from available cartographical resources (upper panel). a) Forest change evolution from 1917/1939 military and 1983 topographical maps. b) Forest change evolution from satellite images (1987-2010) over land restitution periods. c) Total non-forest area (ha) from all cartographical resources. d) Total number of disturbance patches and forest disturbance (ha) between 1987-2010

Fig. 5 The physical, geochemical and magnetic proprieties of the Red Lake sediment record (Core 1 – 2013) spanning the last 150 years (1860-2010). The annual precipitation curve (bottom, light blue from Pauling et al., 2006 and upper, dark blue – CRU Dataset, Harris et al., 2014) and regional wet decades are marked in blue (Topor, 1964, Dragota, 2006). The key political, socio-economic and ownership changes, and local events are marked in the right panel. The dashed lines delineate the three political, socio-economic (traditional, socialist, post-socialist) periods discussed in text

Fig. 6 The physical, geochemical and magnetic proprieties of the Red Lake sediment record (Core 1 – 2013) spanning the last 23 years (1987-2010). The green-coloured zones and the red arrows (left panel) mark the intervals with the higher forest loss in the catchment. The timing of each forest restitution law release is marked by dashed arrows. Intervals of wider high forest disturbance i.e., across the Carpathians are marked with continuous lines and identified in italics

List of figures

Fig. 1

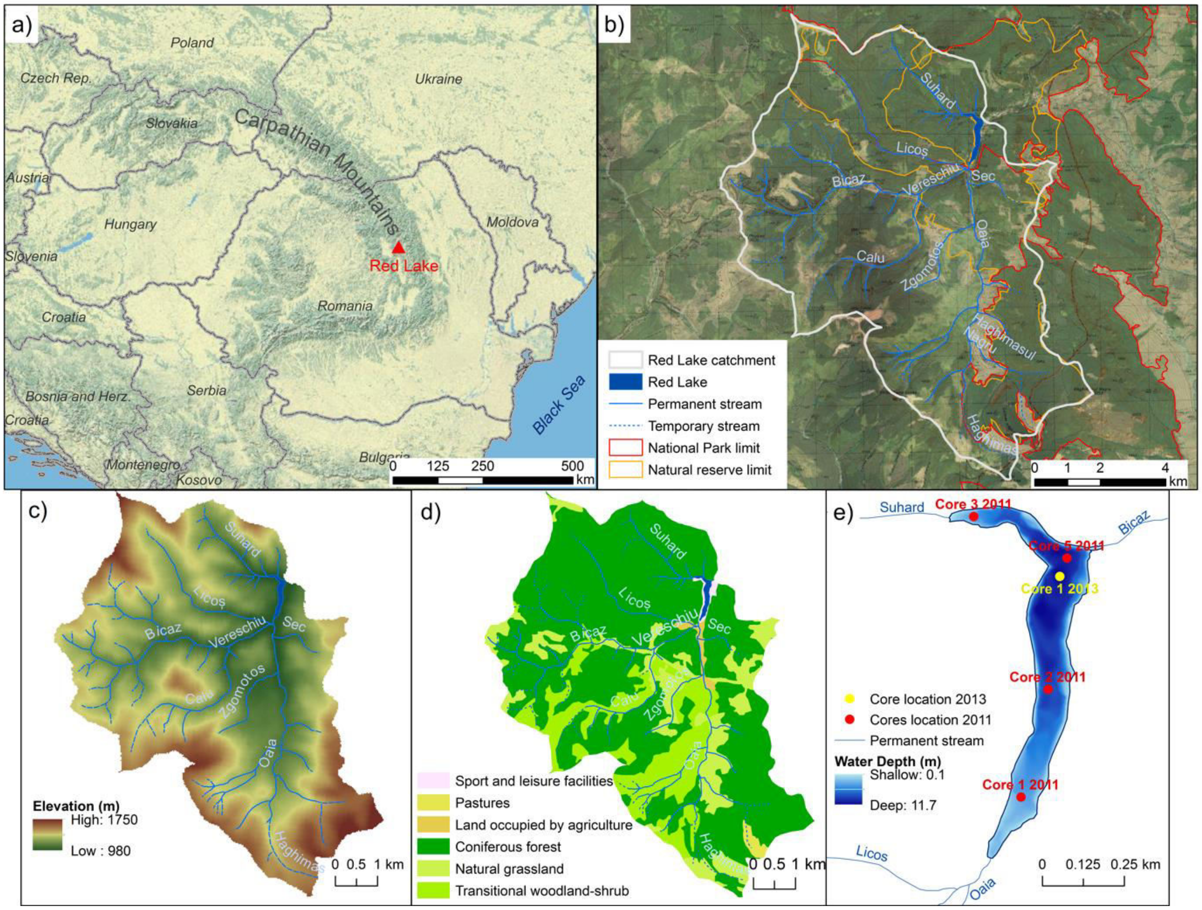


Fig. 2

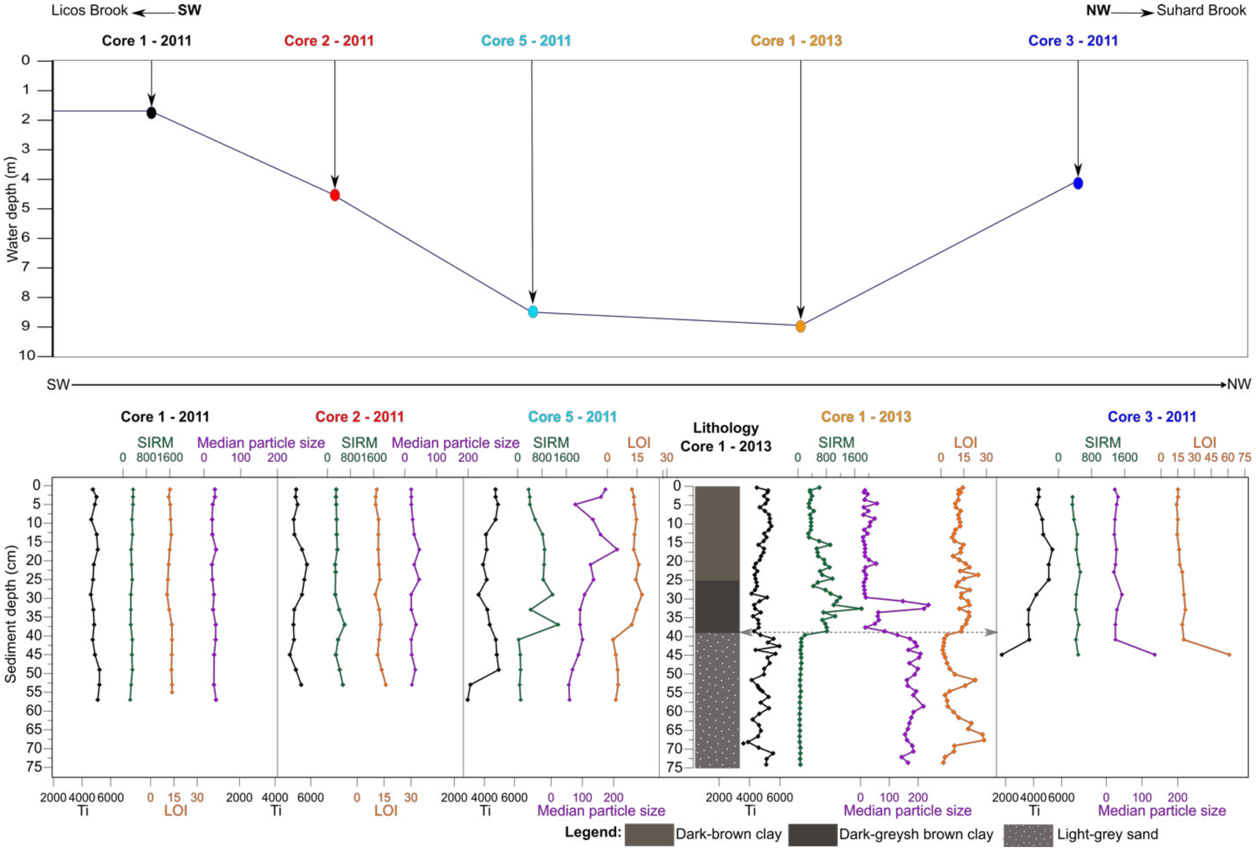

Licos Brook ← SW
NW → Suhard Brook
Core 1 - 2011
Core 2 - 2011
Core 5 - 2011
Core 1 - 2013
Core 3 - 2011
Water depth (m)
0
1
2
3
4
5
6
7
8
9
10
SW
NW
SIRM
Median particle size
LOI
Lithology
Core 1 - 2013
Sediment depth (cm)
Ti
Legend:
Dark-brown clay
Dark-greysh brown clay
Light-grey sand

Fig. 3

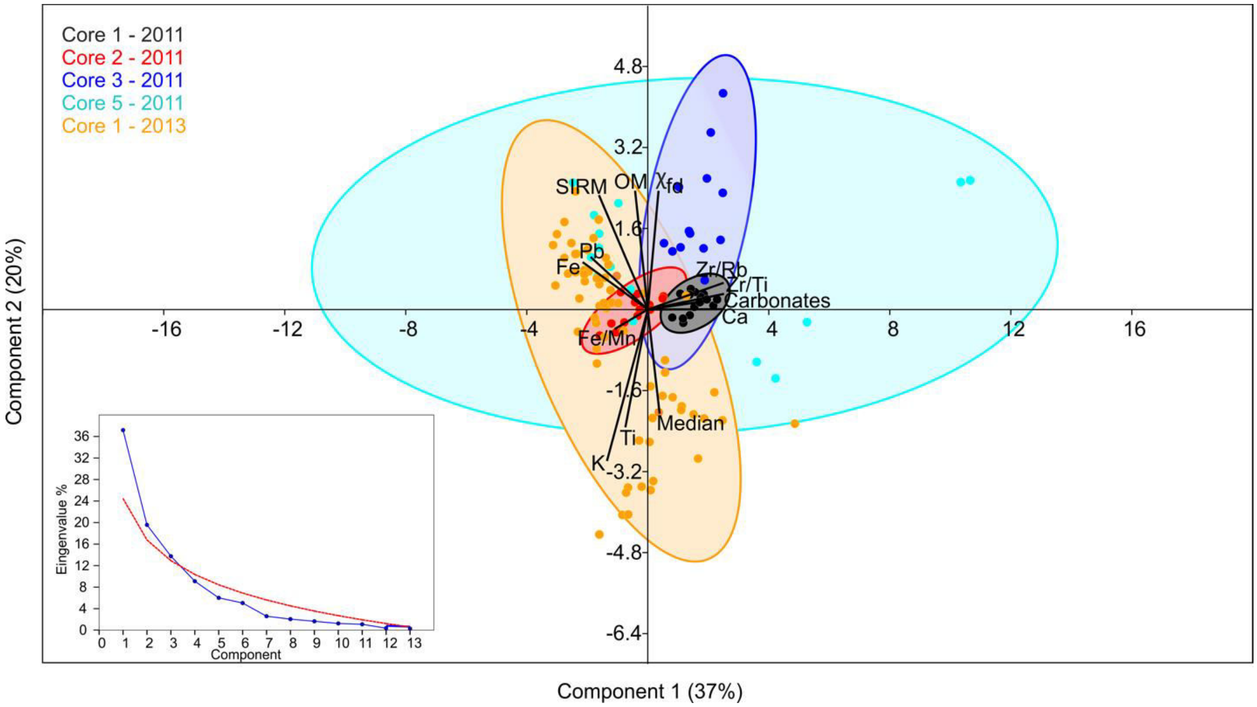

Core 1 - 2011
Core 2 - 2011
Core 3 - 2011
Core 5 - 2011
Core 1 - 2013
4.8
3.2
1.6
-1.6
-3.2
-4.8
-6.4
-16
-12
-8
-4
4
8
12
16
SIRM
OM
χ_{fd}
Pb
Fe
Zr/Rb
Zr/Ti
Carbonates
Ca
Fe/Mn
Ti
K
Median
Component 2 (20%)
Component 1 (37%)
36
32
28
24
20
16
12
8
4
0
Eingenvalue %
0 1 2 3 4 5 6 7 8 9 10 11 12 13
Component

Fig. 4

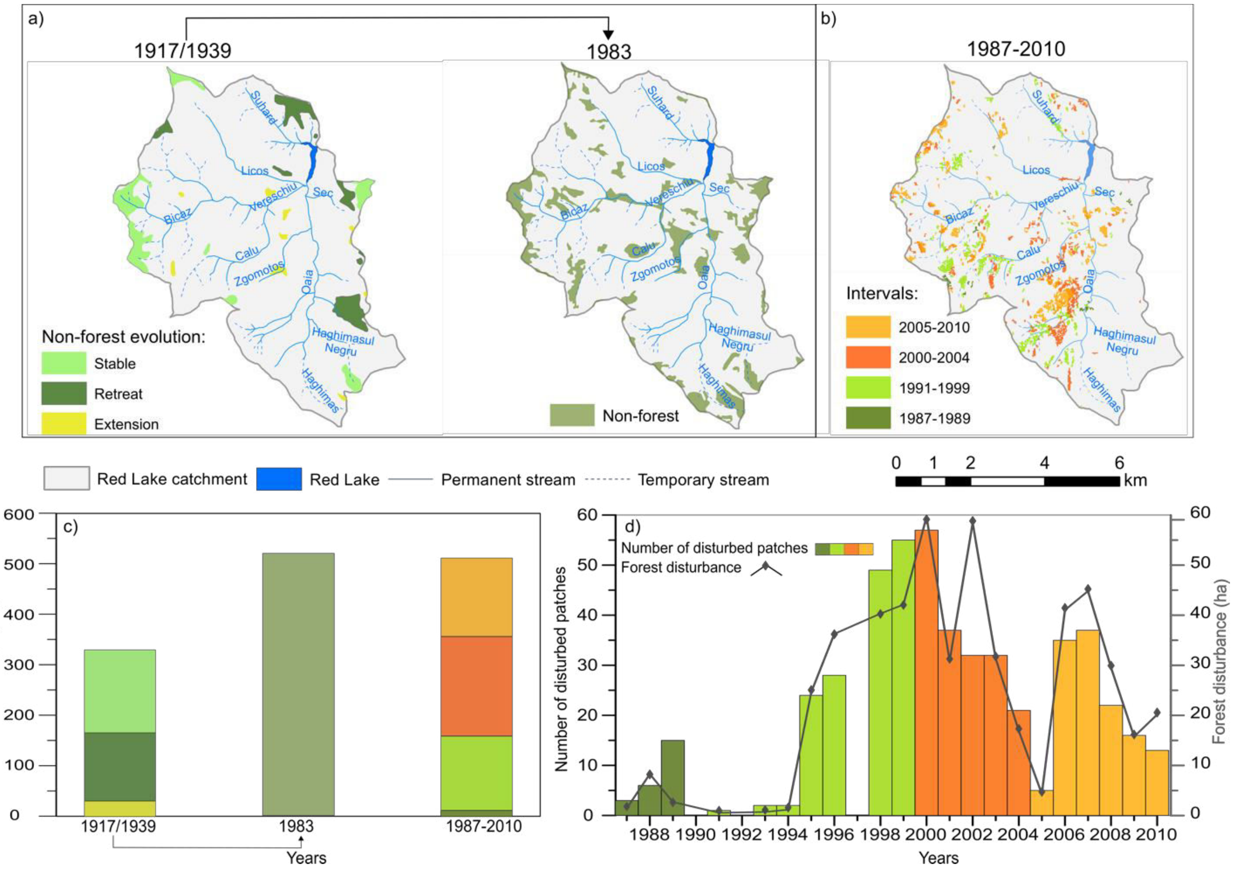

a)
1917/1939
1983
b)
1987-2010
Suhard
Licos
Sec
Vereschiu
Bicaz
Calu
Zgomotos
Oaia
Haghimasul Negru
Haghimas
Non-forest evolution:
Stable
Retreat
Extension
Non-forest
Intervals:
2005-2010
2000-2004
1991-1999
1987-1989
Red Lake catchment
Red Lake
Permanent stream
Temporary stream
0 1 2 4 6 km
c)
Changes (ha)
0 100 200 300 400 500 600
1917/1939
1983
1987-2010
Years
d)
Number of disturbed patches
Forest disturbance
Number of disturbed patches
0 10 20 30 40 50 60
Forest disturbance (ha)
1988 1990 1992 1994 1996 1998 2000 2002 2004 2006 2008 2010
Years

Fig. 5

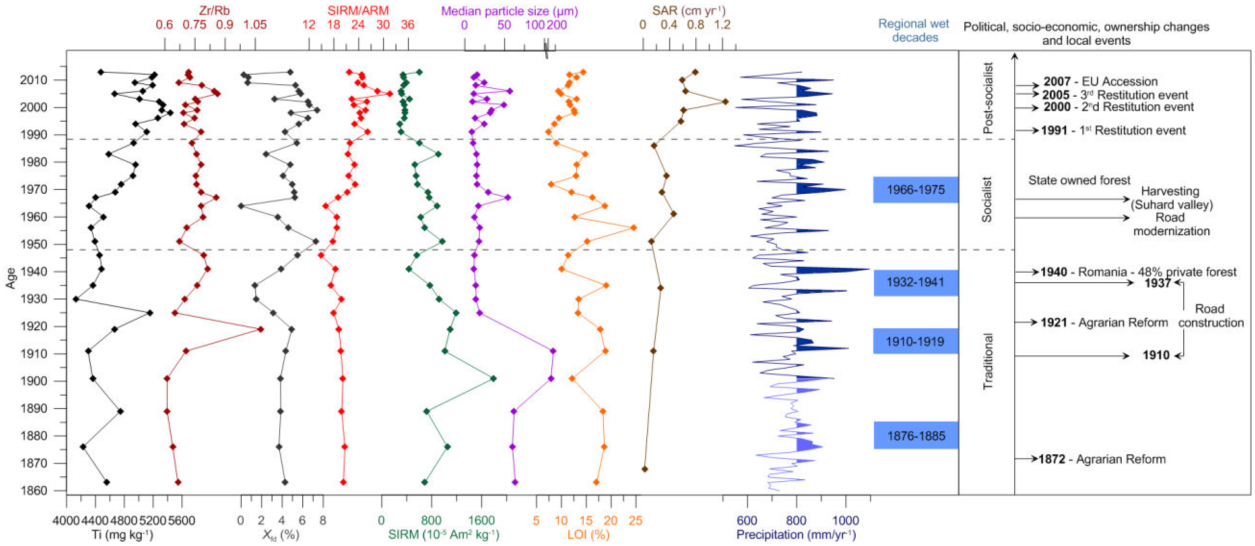
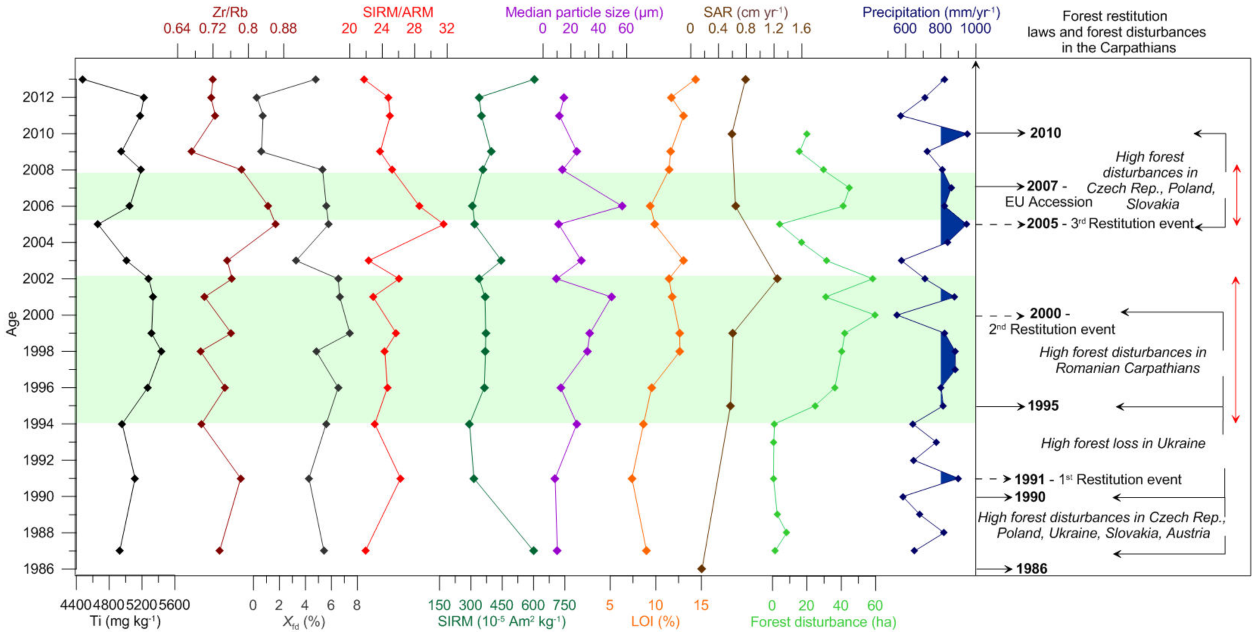

Zr/Rb
0.6 0.75 0.9 1.05
SIRM/ARM
12 18 24 30 36
Median particle size (µm)
0 50 100 200
SAR (cm yr⁻¹)
0 0.4 0.8 1.2
Regional wet decades
Political, socio-economic, ownership changes and local events
Age
1860 1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010
Post-socialist
Socialist
Traditional
2007 - EU Accession
2005 - 3rd Restitution event
2000 - 2nd Restitution event
1991 - 1st Restitution event
State owned forest
Harvesting (Suhard valley)
Road modernization
1940 - Romania - 48% private forest
1937
Road construction
1921 - Agrarian Reform
1910
1872 - Agrarian Reform
1966-1975
1932-1941
1910-1919
1876-1885
4000 4400 4800 5200 5600
Ti (mg kg⁻¹)
0 2 4 6 8
Xlf (%)
0 800 1600
SIRM (10⁻⁵ Am² kg⁻¹)
5 10 15 20 25
LOI (%)
600 800 1000
Precipitation (mm/yr⁻¹)

Fig. 6


Zr/Rb
0.64 0.72 0.8 0.88
SIRM/ARM
20 24 28 32
Median particle size (µm)
0 20 40 60
SAR (cm yr-1)
0 0.4 0.8 1.2 1.6
Precipitation (mm/yr-1)
600 800 1000
Forest restitution laws and forest disturbances in the Carpathians
Age
2012
2010
2008
2006
2004
2002
2000
1998
1996
1994
1992
1990
1988
1986
4400 4800 5200 5600
Ti (mg kg-1)
0 2 4 6 8
Xfd (%)
150 300 450 600 750
SIRM (10-5 Am2 kg-1)
5 10 15
LOI (%)
0 20 40 60
Forest disturbance (ha)
2010
High forest disturbances in Czech Rep., Poland, Slovakia
2007 - EU Accession
2005 - 3rd Restitution event
2000 - 2nd Restitution event
High forest disturbances in Romanian Carpathians
1995
High forest loss in Ukraine
1991 - 1st Restitution event
1990
High forest disturbances in Czech Rep., Poland, Ukraine, Slovakia, Austria
1986

Regional Environmental Change

SUPPORTING INFORMATION

Impacts of forest loss in the Eastern Carpathian Mountains: linking remote sensing and sediment changes in a mid-altitude catchment (Red Lake)

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Radiometric characteristics, sedimentation rates and chronology

Equilibrium of total ^{210}Pb activity with supported ^{210}Pb occurs at a depth of 36 cm in the core while unsupported ^{210}Pb activities (calculated by subtracting ^{226}Ra activity (as supported ^{210}Pb) from total ^{210}Pb activity) decline irregularly with depth (Fig. S. 1) suggesting that sedimentation rates have changed through time with a marked dip in unsupported ^{210}Pb activity at 7.75 cm indicating an increased sedimentation rate. ^{137}Cs activity versus depth shows a sharp peak with extraordinary high activity at 15.25 cm. This well resolved peak will reflect fallout from the 1986 Chernobyl accident **(Fig. S. 1).**

Use of the CIC (constant initial concentration) model is precluded by the non-monotonic variation in unsupported ^{210}Pb activities. ^{210}Pb chronologies were therefore calculated using the CRS (constant rate of ^{210}Pb supply) dating model (Appleby and Oldfield, 1978). This dating model places the 1986 depth at 15.25 cm and therefore in good agreement with the depth suggested by the ^{137}Cs record **(Fig. S. 1).** Sedimentation rates calculated by the ^{210}Pb data indicate a slowly increasing trend in sedimentation rates into the 1930s followed by variations until around 2000 **(Fig. S. 2).** There is a small peak in sedimentation rate around 1960, with consistent increase from the 1980's and a sharp peak that reached 0.36 g cm^{-2} yr^{-1} in 2002 (Fig. S. 2). Subsequently sedimentation rates have declined.

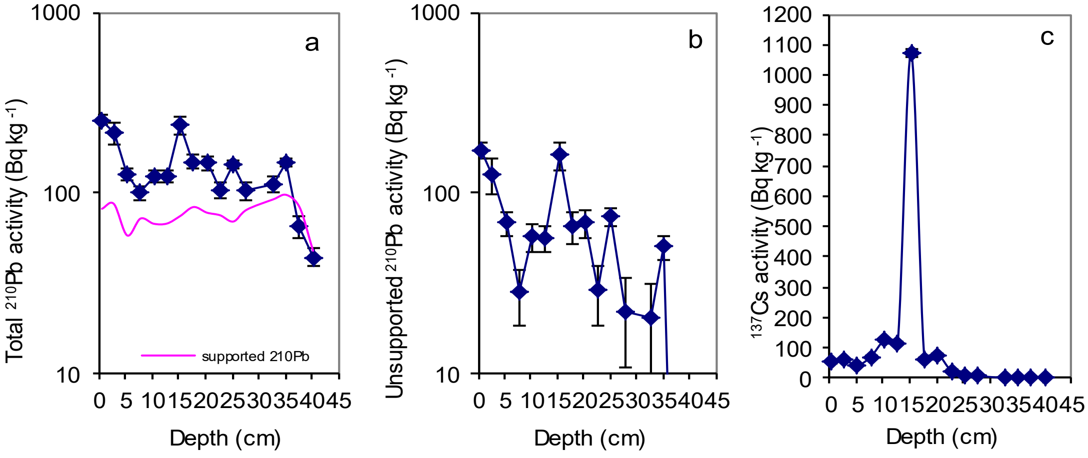


Fig. S. 1 The fallout radionuclide concentrations in Core 1 - 2013 showing (a) total ^{210}Pb, (b) unsupported ^{210}Pb and (c) ^{137}Cs concentrations versus depth

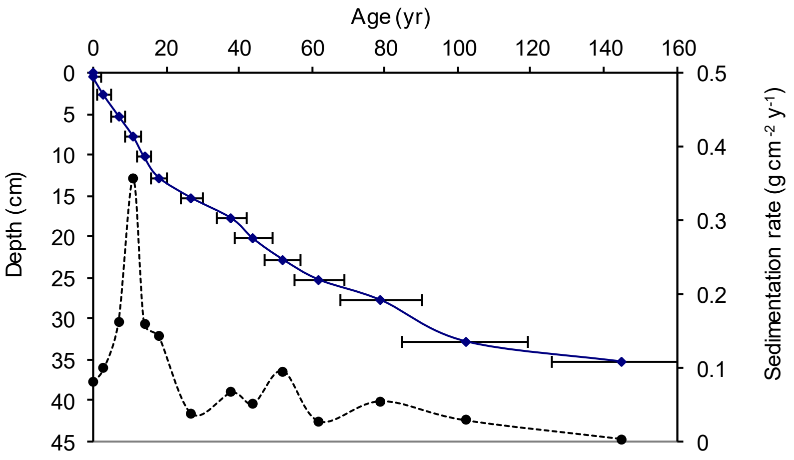
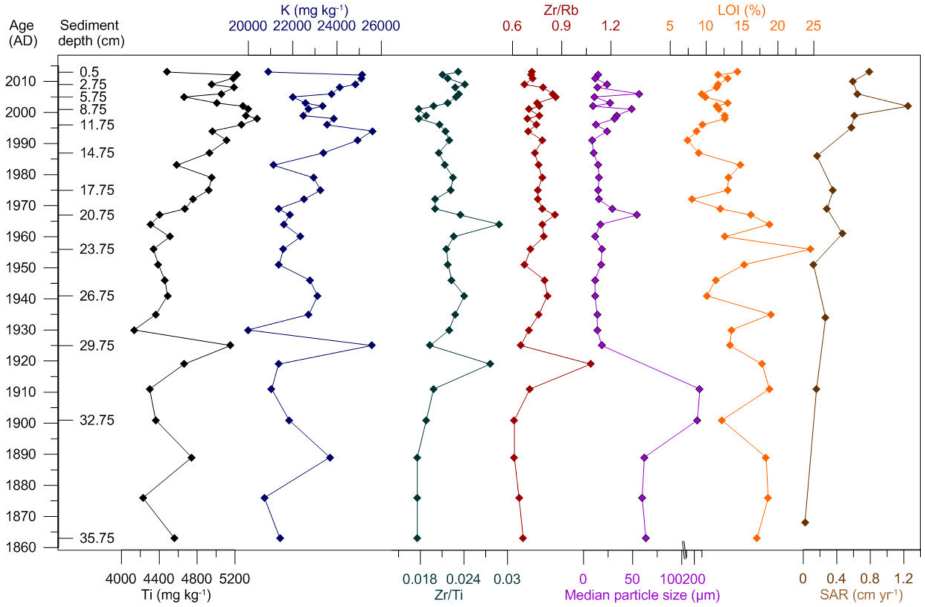


Fig. S. 2 The radiometric chronology of Core 1 – 2013 from Red Lake showing the CRS model ^{210}Pb dates and sedimentation rates. The solid line shows age while the dashed line indicates sedimentation rate

Geochemical and mineral magnetic characteristics



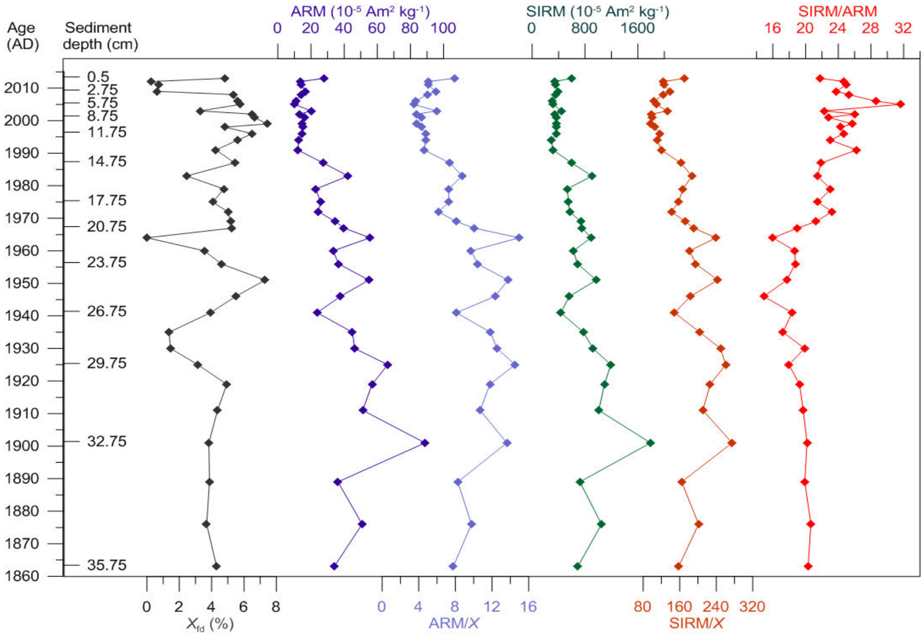


Fig. S. 3 The main geochemical (upper panel) and magnetic proprieties (lower panel) of the dated sediment profile (Core 1 – 2013) plotted against the age-depth model