

Recent sediment accumulation rates in contrasting lakes in the Carpathians (Romania): impacts of shifts in socio-economic regime

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Abstract Longer-term environmental studies are increasingly used to better understand contemporary ecosystems conditions and for forecasting their future trajectories. Here, we use radiometric measurements and the characterisation of sediment properties from six mountain and a lowland lake in Central Eastern Europe with the aim to assess temporal and spatial variability in sediment accumulation rates (SARs) in relation to three socio-economic regimes: traditional (1840–1948), socialist (1948–1989) and post-socialist (post-1990). We also set out to determine reference conditions for these lakes i.e. conditions before significant human impact. Our results show a trend of increasing SARs from basal sediments (pre 1840) towards the present at only two sites. This contrasts with findings from Western and Central European lakes

where SARs have predominantly increased from 1850 towards the top of cores. We highlight the differential impacts of the traditional, socialist and post-socialist periods on the SARs at these lakes. Lowland and mid-elevations lakes ($n = 2$) were most markedly impacted by the socialist period of land use regime; lakes from the southern Carpathians ($n = 2$) were more impacted in the traditional period (transhumance pastoral activities), whereas those from the north ($n = 3$) in the socialist and post-socialist periods (summer pastoralism). Results from our study show a continuous anthropogenic impact during the entire period considered, even in remote mountain areas. This suggests that a temporal frame of 100–150 years is too short to meaningfully register the reference conditions of these lakes. Furthermore, a predominantly natural state may not have existed for centuries in this region.

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Introduction

Longer-term environmental studies are increasingly used for understanding present-day ecological systems and for forecasting their future trajectories (Willis et al. 2010; Rose et al. 2011; Dearing et al. 2012; Seddon et al. 2014). Results from such studies have been integrated into a number of key environmental reports and initiatives such as the European Union's Water Framework Directive 2005; Millennium Ecosystem Assessment 2005; Intergovernmental Panel on Climate Change 2013.

Sediment accumulation rate (SAR) is a fundamental parameter that can facilitate characterisation of catchment and lake processes. Fluctuations in SAR may also reflect the composition of flora and fauna assemblages as a result of changes in the catchment (Dearing et al. 2006). It is documented that the SAR has increased during the last 100–200 years in many lakes worldwide, reflecting intensification in land use and subsequent soil erosion. Furthermore, the use of fertilisers can lead to lake eutrophication and thereby increase the rate of sediment accumulation via autochthonous material (Dearing et al. 2006, 2012; Rose et al. 2011). A recent review of SAR in Western and Central Europe indicates that 71 % of the lakes assessed showed a higher recent SAR (post-1975) than during the pre-1850 period (Rose et al. 2011). It was therefore concluded that reference conditions, defined as conditions before significant anthropogenic impact, in the majority of these lakes had been altered. The same study also showed that lakes in lowlands have greater rates of sediment accumulation than those in upland areas (Rose et al. 2011). This was potentially related to a more significant modification of their catchments as a consequence of agricultural development. Mountain lakes, away from direct human impact, on the other hand, were found to be more sensitive to the effects of climate change (Catalan et al. 2002; Lami et al. 2000; Rose et al. 2011).

Although it is recognised that much of the present landscape of Europe has a cultural legacy (Willis and Birks 2006), such cultural landscapes are often considered to be open, lowland landscapes. In contrast, forested regions, and in particular those in the mountains of Eastern Europe, are viewed as ancient, despite studies indicating that many forests have undergone significant prehistoric and historic clearance and burning (Tanău et al. 2011, 2014; Fărcaș et al. 2013; Feurdean et al. 2009, 2013a), which may have influenced sediment and nutrient inputs into aquatic ecosystems. Furthermore, more recently Central Eastern Europe has undergone a series of marked socio-economic transitions. These include (i) the socialist period (1948–1989), which brought large-scale, mechanised and state-controlled agriculture, and (ii) the post-socialist period (post-1990), characterised by the collapse of collective

agriculture and the restoration of land ownership back to the private sector; ultimately leading to widespread agricultural land abandonment (Stoate et al. 2009). However, following Romania's membership of the EU in 2007 agriculture in productive areas appears to have been reinforced via EU subsidy payments (Griffiths et al. 2013).

Because these abrupt socio-economic shifts have greatly affected land use management, soil stability and erosion rates in this region, we expect them to have also impacted rates of sediment accumulation in lake basins. However, despite the richness of the region in terms of lakes and peat deposits, assessment of recent changes in SARs in Romania is entirely derived from only two lakes located in the southern (a glacial lake) (Rose et al. 2009) and eastern (a natural barrage lake) Carpathians (Begy et al. 2009). In addition, Akinyemi et al. (2013) provide information on recent sediment characteristics and pollution trends in selected mountain lakes across the Romanian Carpathians.

Here, we present the results of radiometric measurements (^{210}Pb , ^{241}Am and ^{137}Cs) and the characterisation of sediment properties (organic content, mineral magnetism, grain size distribution and geochemical analyses) from six mountain lakes in the Romanian Carpathians and one from the lowlands of the Transylvanian Plain. The aims are to (i) examine past changes in SARs in relation to the three major socio-economic periods: traditional (1840–1948), socialist (1948–1989) and post-socialist (1990 onwards); (ii) determine whether SARs have increased more recently as compared to an earlier period i.e. the nineteenth century; (iii) examine spatial variability in SARs i.e. dissimilarities between lakes in discrete mountain areas in the Carpathians; and between mountain and lowland lakes. This study also sets out to determine whether we can find reference conditions (condition before a significant anthropogenic impact) in these lakes at such short time scale given the lasting human impacts in this region.

Study area

Changes in sediment accumulation rates are inferred in seven lake sediment sequences distributed across Romania (Figs. 1, 2; Table 1). The lakes in the Carpathians Mountains are located in three distinct areas within the country: in the north in the Rodna Mountains (Lake Știol and Lake Buhăiescu Mare) and Maramureș Mountains (Lake Vinderel); in the south in the Făgăraș (Lake Capra) and Retezat Mountains (Lake Negru); and in the east, in the Harghita Mountains (Lake Sfânta Ana) (Figs. 1, 2). The lowland lake (Lake Știucii) lies in the Transylvanian Plain, NW Romania. All of our sites are located in protected areas such as national or natural parks or have been recently designated as Natura 2000 sites. Details of the site

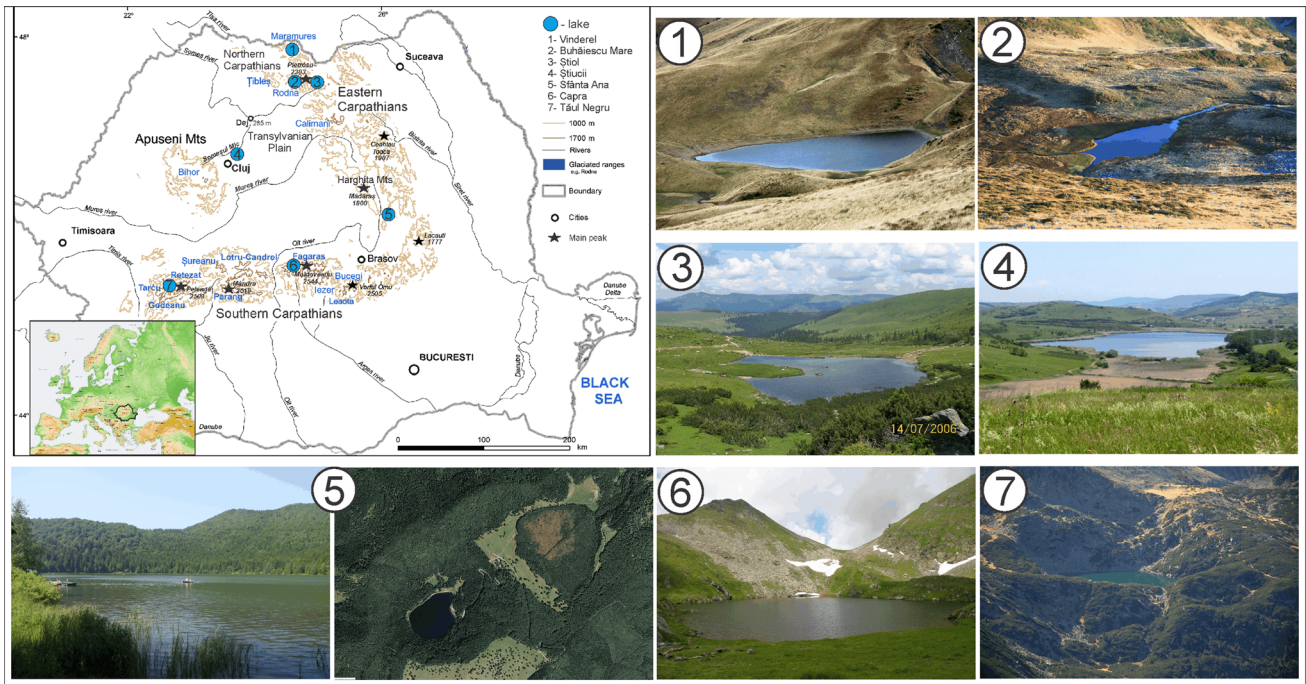


Fig. 1 a Location of the areas of investigation in Europe and Romania. b Photographs of our study sites: (1) Lake Vinderel; (2) Lake Buhăiescu Mare; (3) Lake Știol; (4) Lake Știucii; (5) Lake

Sânta Ana; (6) Lake Capra; (7) Lake Negru. Photograph custody: Marcel Mîndrescu and Nicolae Radoane

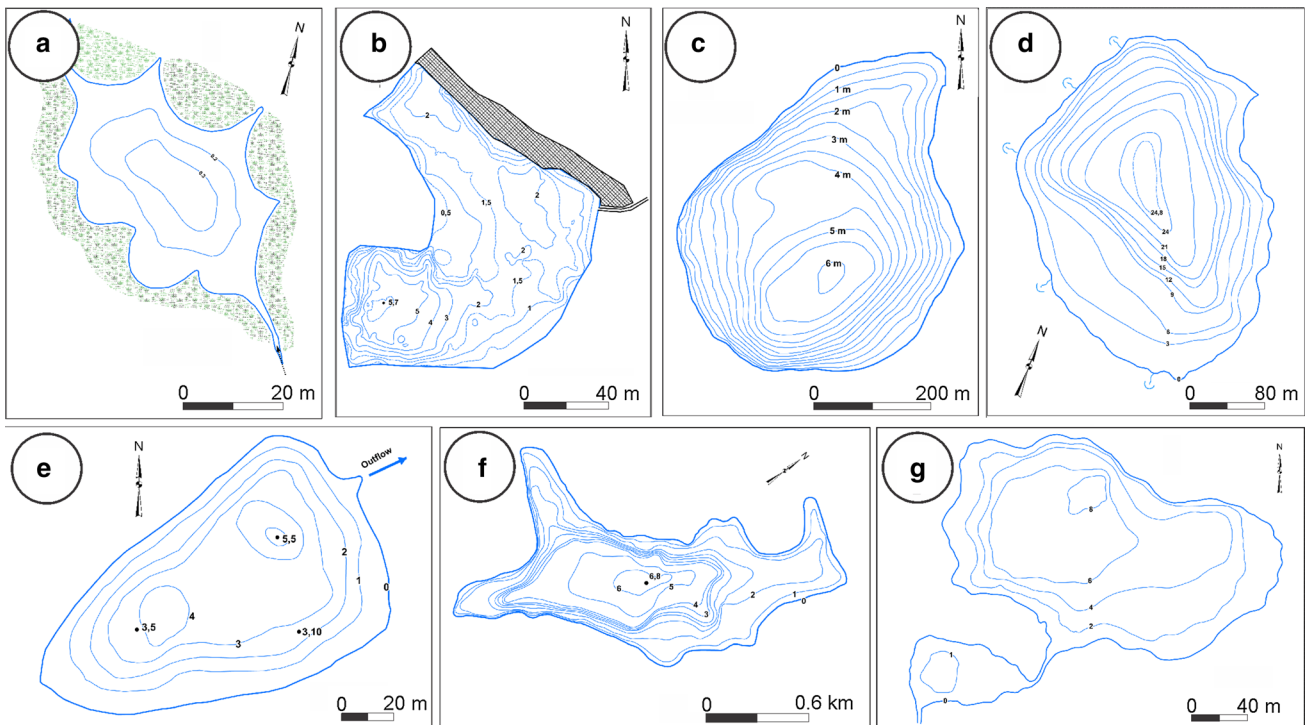


Fig. 2 Bathymetric maps of our study sites: a Lake Vinderel; b Lake Buhăiescu Mare (after Pișota 1968); c Lake Știol (after Mîndrescu et al. 2010); d Lake Sânta Ana (after Pândi and Magyari-Sáska

2007); e Lake Negru (after Pișota 1971); f Lake Știucii (after Șerban and Sorocovschi 2003); g Lake Capra (after Pișota 1971)

Table 1 Key catchment and lake characteristics of study sites

	Lake Țiucii	Lake Sfânta Ana	Lake Țiol	Lake Vinderel	Lake Buhăiescu Mare	Lake Negru	Lake Capra
Position	46° 57' 60" N 23° 54' 07" E	46° 07' 34" N 25° 53' 18" E	47° 34' 30" N 24° 48' 55" E	47° 54' 36" N 24° 27' 26" E	47° 34' 26" N 24° 38' 36" E	45° 21' 34" N 22° 49' 45" E	45° 36' 03" N 24° 37' 46" E
Location	Transilvanian Plain	Harghita Mts.	Rodna Mts.	Maramureș Mts.	Rodna Mts.	Retezat Mts.	Făgăraș Mts.
Elevation (m)	239	950	1,670	1,680	1,918	2,000	2,300
Area (ha)	38	19.56	1.06	0.68	0.09	4.05	1.87
Depth (max) (m)	6.8	6.6	5.0	5.5	0.5	25	1.87
Slope aspect	NE	–	N	V	N	N	S
Climatic parameters	$[T_{\text{ann}}] = 8.5 \text{ } ^\circ\text{C}$ $[P_{\text{ann}}] = 550\text{--}700 \text{ mm}$	$[T_{\text{ann}}] = 5 \text{ } ^\circ\text{C}$ $[P_{\text{ann}}] = 650\text{--}700 \text{ mm}$	$[T_{\text{ann}}] = 1.2 \text{ } ^\circ\text{C}$ $[P_{\text{ann}}] = 1,300 \text{ mm}$	$[T_{\text{ann}}] = 1.2 \text{ } ^\circ\text{C}$ $[P_{\text{ann}}] = 1,300 \text{ mm}$	$[T_{\text{ann}}] = 1.2\text{--}0 \text{ } ^\circ\text{C}$ $[P_{\text{ann}}] = 1,300 \text{ mm}$	$[T_{\text{ann}}] = -2 \text{ } ^\circ\text{C}$ $[P_{\text{ann}}] = 1,000\text{--}1,100 \text{ mm}$	$[T_{\text{ann}}] = -1 \text{ to } 0.8 \text{ } ^\circ\text{C}$ $[P_{\text{ann}}] = 1,000\text{--}1,100 \text{ mm}$
Catchment Geomorphology (origin & position of lake)	Pseudokarst/floodplain	Volcano carter	Glacial cirque	Landslide depression	Glacial cirque	Glacial cirque	Glacial cirque
Catchment area (ha)	18.1	201.8	156	5.1	14.4	58.2	29.7
Land cover (% surface area)	Pasture and arable land (75 %) Forest (18 %) Village area (3 %)	Forest (86.8 %) Water (9.7 %) Pasture (7.01 %)	Grass (60) Scrub (20) Scree (14) Rock (5) Water (5 %)	Grass (99) Scrub (0) Scree (0) Rock (0) Water (1)	Grass (60) Scree (37) Scrub (1) Water (2)	Scrub (33 %) Grass (33 %) Scree and rock (33)	Grass (65) Scree (20) Rock (9) Water (6) Scrub (0)
Catchment: lake ratio	–	10.31	147.2	85.0	698.9	12.53	8.0

locations, climate conditions and the physical characteristics of basins are provided below and summarised in Table 1.

Lakes in the northern Carpathians

Lake Buhăiescu Mare (1,918 m asl) and Lake Știol (1,670 m asl) are located in the Rodna Mountains the northern part of the eastern Carpathians. Lake Buhăiescu Mare is remnant (0.1 ha) of a previously larger glacial lake (1.2 ha), the basin of which is now largely in-filled by peat bog (Pisota 1968). The geology of this region comprises crystalline rocks such as epimetamorphic schist and mica schist. The vegetation surrounding the site is composed of alpine pasture and shrubs (*Ericaceae*, *Vaccinium* spp., *Juniperus*). Lake Știol (1,670 m asl) is described as a glacial lake that was illegally dammed in 2002. This significantly enlarged the lake surface and augmented the catchment area, but is thought to have left deeper water zone of the original lake basin intact (Table 1; Mîndrescu et al. 2010). Lake Știol is located at the treeline transition with vegetation dominated by *Pinus mugo* and scattered *Picea abies* trees.

Lake Vinderel (1,680 m asl) situated in the Maramureș Mountains, was formed about 1,000 years ago (Feurdean in prep.) as a result of hill-slope movement. The geology of this region comprises epimetamorphic schist and flysch, and the vegetation comprises high mountain pasture and shrubs. Unlike the two other lakes, Lake Vinderel has no discernable inflow or outlet stream.

Lakes in the eastern Carpathians

Lake Sfânta Ana (950 m asl) is a volcanic crater lake located in the Harghita Mountains in the eastern Carpathians (Pándi and Magyari-Sáska 2007). The geology of this region comprises andesite. The slopes surrounding the lake are covered by mixed forest of *Betula pendula*, *Picea abies* and *Fagus sylvatica*.

Lakes in the southern Carpathians

Lake Capra (2,300 m asl) is a glacial lake, located in the Făgăraș Mountains in the southern Carpathians (Fig. 1). The geology comprises predominantly crystalline rocks and metamorphic strata such as paragneiss and mica schists (Pană 1990). The vegetation of the Lake Capra catchment comprises alpine pasture (Table 1). Lake Negru (2,000 m asl) is a glacial lake situated in the Retezat Mountains in the western part of the southern Carpathians. The geology is dominated by granites, and the surrounding slopes are covered by mountain pasture with *Pinus mugo*, *Vaccinium* spp., *Ericaceae* and scattered *P. cembra* (Rose et al. 2009).

Lakes in the Transylvanian Plain

Lake Știucii (239 m asl) lies in a depression in the Pîrțot river valley in the Transylvanian Plain, NW Romania. The lake is fed by run-off and from surface and subsurface springs (Serban and Sorocovschi 2003). The geology comprises sedimentary strata such as marls, clay, sands and salt deposits. The vegetation consists of a mosaic forest steppe patches, pastures, meadows and arable fields, mostly in an abandoned state (Feurdean et al. 2013b; 2015).

Materials and methods

Fieldwork

Coring in the upland sites was undertaken from summer from 2007 to 2012 (Table 1) from small inflatable boat using a short gravity corer following a survey of each lake bed with a hand-held depth sensor. Lake Știucii was also gravity cored but in the winter of 2012 directly from the ice. Sediment cores were sliced at 0.25-, 0.5- and 1-cm intervals in the field.

Laboratory analysis

To characterise the physical properties of the sediments (wet and dry bulk density), samples were weighed, dried at 40 °C and re-weighed (see Last and Smol 2001). Saturation isothermal remanent magnetisation (SIRM) measurements were taken with a Molspin pulse discharge magnetiser. The resultant magnetic remanences were measured using a Molspin Minispin fluxgate magnetometer (Walden et al. 1999). The geochemical analyses were undertaken with a field portable Niton XL3t 900 XRF analyser mounted in a laboratory-based shield. The sediment samples were ground, and the powder pressed into cups fitted with a 6-μm-thick polyester film (Shuttleworth et al. 2014). NCS DC73308 was employed as a certified reference material (CRM). To assess the organic matter content, subsamples were dried at 105 °C overnight, combusted for 5 h at 550 °C, and the resultant weight loss expressed as percentage loss of the dry weight (LOI; Heiri et al. 2001). The particle size distribution characteristics of the sediments were determined using a Horiba LA-950 Laser Scattering Particle Size Analyzer.

In order to determine the age of the sediments, samples were analysed for lead-210 (^{210}Pb), radon-226 (^{226}Ra), caesium-137 (^{137}Cs) and americium-241 (^{241}Am) by gamma spectroscopy (Appleby et al. 1986, 1992; Appleby 2001). For Lake Știucii, Sfânta Ana, Vinderel, Tăul Negru and Capra, the radiometric

analyses were performed using facilities at University College London (UCL), UK. Dried sediment samples were analysed by direct gamma assay in the Bloomsbury Environmental Isotope Facility (BEIF) at UCL, using an ORTEC HPGe GWL series well-type coaxial low background intrinsic germanium detector (Supplementary Material S1). For Lake Buhăiescu Mare and Ştiol, measurements of radioisotope concentrations were taken at the Faculty of Environmental Science, University of Babeş Bolyai Cluj, Romania, using an ORTEC DigiDart spectrometer with a HpGe detector, Gamma-X (GMX) type (Supplementary Material S1).

Results

Age-depth models

The determination of age-depth sediment profiles via ^{210}Pb generally follows two models: the constant initial concentration (CIC model) provided that the sediment accumulates constantly and constant rate of supply (CRS model) where sediment accumulation is not constant through time (Appleby 2001). Given the prevalence of nonlinear sediment accumulation rates in this study, all our chronologies were constructed using the CRS model (Fig. 3). Details on the determination of an age-depth profile at each site are given in the Supplementary Material S1.

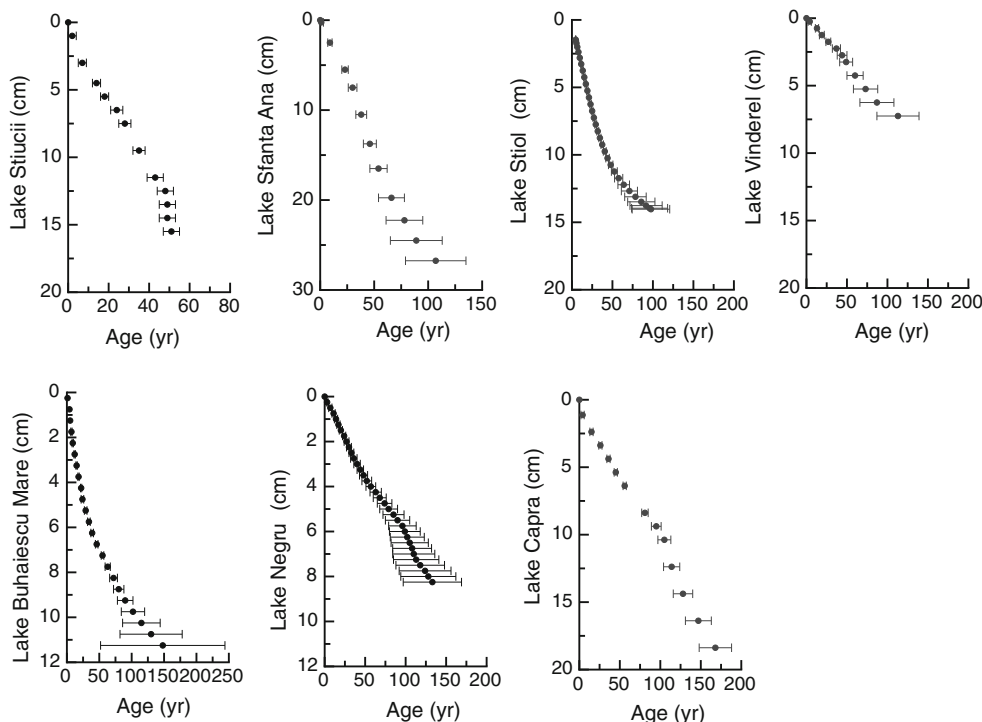
Changes in the sediment accumulation rates and of sediment properties

At Lake Ştiucii, SAR varied moderately during the period 1964 to 1988 (from 0.04 to $0.11 \text{ g cm}^{-2} \text{ year}^{-1}$) and decreased from 1984 onwards (Fig. 4; Supplementary Material S1). Ti and SIRM concentrations, as well as particle size values, largely followed similar trends to the SAR (Fig. 4). Between 13.5 and 14.5 cm (~ 1961 – 1963), there was a sharp peak in the sedimentation rate from 0.08 to $0.33 \text{ g cm}^{-2} \text{ year}^{-1}$ associated with a peak in SIRM. However, due to the unusual equilibrium of total ^{210}Pb activity with supporting ^{210}Pb , probably a result of a more impacted catchment, little confidence can be attached to the high sedimentation rates at depths below 13 cm (Supplementary Material S1).

At Lake Sfânta Ana, there was an overall increase in the SAR from 1900 to 1970 from 0.012 to $0.07 \text{ g cm}^{-2} \text{ year}^{-1}$ (Fig. 4; Supplementary Material S1). Except for the Ti concentrations, there is little association between the increase in SAR and the SIRM and particle size values (Fig. 4). SAR declined from 1970 to 2000, but re-increased at the sediment surface (2007) to about $0.06 \text{ g cm}^{-2} \text{ year}^{-1}$.

At Lake Ştiol, there is an increasing trend in the SAR from 1840 to 1965, followed by two clear episodes of high sediment accumulation: one around 1965 (from 0.04 to $0.06 \text{ g cm}^{-2} \text{ year}^{-1}$) and the second and more marked one after 2003 (from 0.06 to $0.09 \text{ g cm}^{-2} \text{ year}^{-1}$; Fig. 4). The general rise in SAR at this site corresponded most closely to an increase particle size (Fig. 4).

Fig. 3 Age-depth models (including the error bars) of the seven cores investigated employing CRS model ^{210}Pb dates



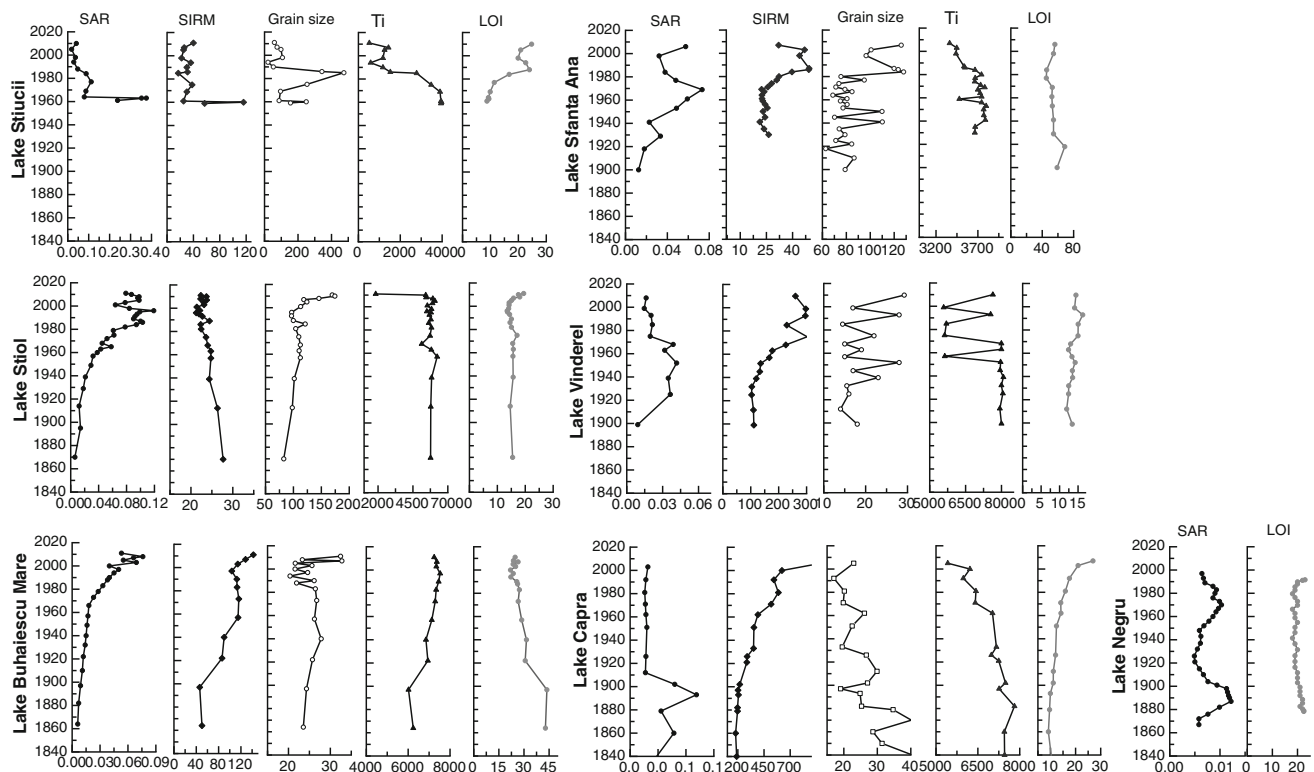


Fig. 4 Sediment accumulation rate (SAR) ($\text{g cm}^{-2} \text{ year}^{-1}$), saturation isothermal remanent magnetisation (SIRM; $10^{-5} \text{ Am}^2 \text{ kg}^{-1}$), median grain size (micron), Ti content (mg kg^{-1}) and organic matter content (%) for the seven study sites

At Lake Vinderel, the SAR values are higher between 1920 and 1970 and declined markedly thereafter (Fig. 4; Supplementary Material S1). Ti concentrations, median particle size and SIRM fluctuated strongly during most of this period, but there is a little co-variation among these parameters (Fig. 4).

Lake Buhăiescu Mare shows a progressive increase in the SAR from 1870 to 1966, followed by clear rise from 1966 to the present from 0.02 to $0.08 \text{ g cm}^{-2} \text{ year}^{-1}$ (Fig. 4; Supplementary Material S1). The SAR increase coincides well with a rise in Ti, SIRM and an coarsening of sediment particle size (Fig. 4).

At Lake Capra, the SAR varied greatly between 1860 and 1900 from 0.05 to $0.12 \text{ g cm}^{-2} \text{ year}^{-1}$ (Fig. 4; Supplementary Material S1). However, SARs were relatively uniform (average rate of $0.03 \text{ g cm}^{-2} \text{ year}^{-1}$) in the last 100 years (1900–2007), with only a slightly rise between 1990 and 2007. The high values in SAR are closely mirrored in the particle size values (Fig. 4).

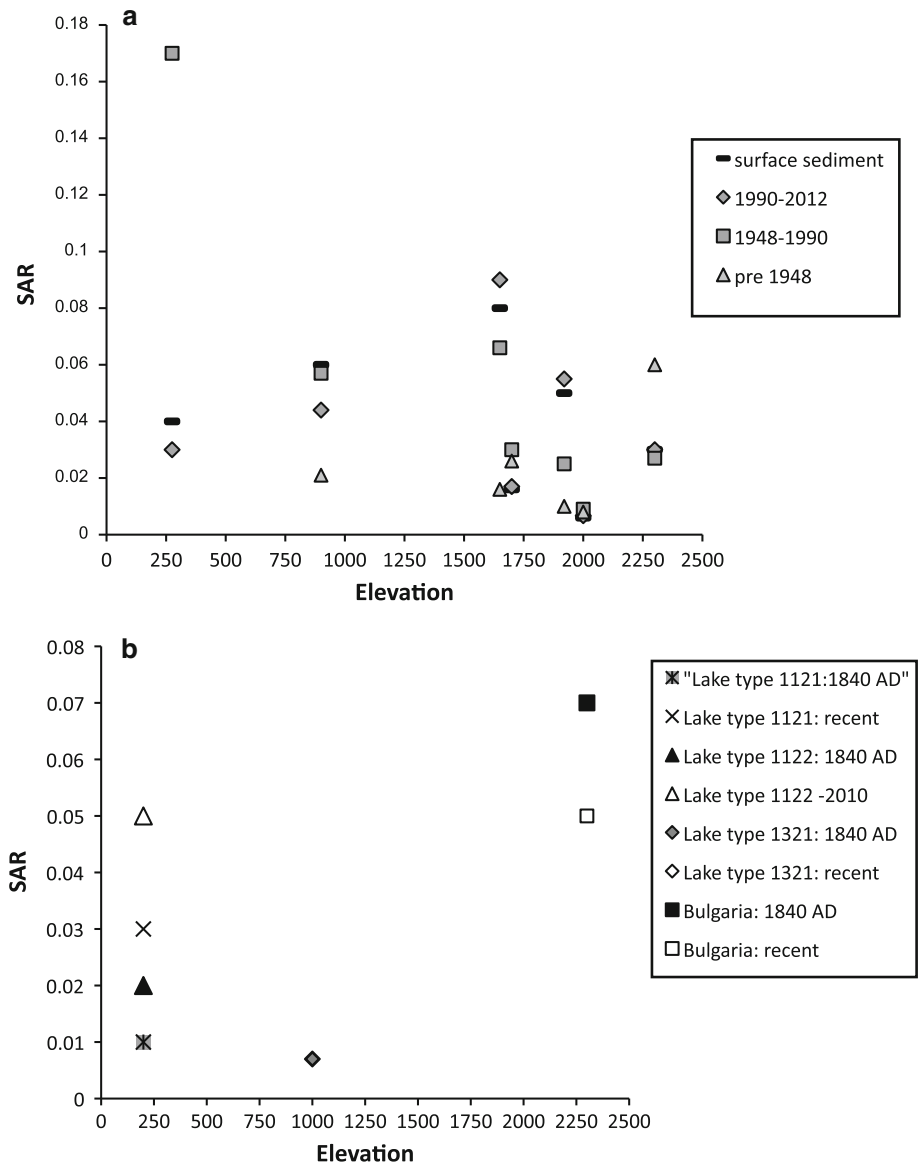
The age-depth model at Lake Negru suggests small fluctuations in the mean SAR over the period 1867–2009. The mean sedimentation rate was $0.007 \text{ g cm}^{-2} \text{ year}^{-1}$ with slightly higher values between 1880 and 1900 ($0.01 \text{ g cm}^{-2} \text{ year}^{-1}$) and between 1970 and 1985 ($0.009 \text{ g cm}^{-2} \text{ year}^{-1}$), respectively (Fig. 4; Supplementary Material S1).

Discussion

Results from this study do not reveal a consistent temporal pattern in sediment accumulation rates across sites during the three socio-economic periods of interest in this region. This indicates the differential impact of land use change during the traditional (1840–1948), socialist (1948–1989) and post-socialist (post-1990) periods on the SARs in these lakes (Figs. 4, 5). However, although at the lowland site (Lake Știucii) a reliable SAR record only starts after 1963, similarities in trends are more apparent at sites located at a comparable elevation; (a) the lowland (Lake Știucii) and (b) mid-elevation lake (Lake Sfânta Ana) showed higher SARs during the socialist period (Figs. 4, 5a). Sites in the uplands displayed a more variable and contrasting north-south pattern; those from the southern Carpathians (Lake Negru and Lake Capra) show the highest SARs in the traditional period, whereas two of the three sites in the northern Carpathians (Lake Buhăiescu Mare and Știol) displayed their highest SARs during the post-socialist period (Figs. 4, 5a).

Below, we discuss the influence of local factors as well as the effects of land use regimes of the three socio-economic periods on the SARs of the seven lakes in our study.

Fig. 5 a Mean sediment accumulation rates ($\text{g cm}^{-2} \text{ year}^{-1}$) at the six sites corresponding to the three distinct socio-economic periods arranged along an elevation gradient (m asl). **b** Comparison with the SAR in other European lakes (Rose et al. 2011) (see text for coding)



The influence of local site conditions on changes in SARs

Although we have analysed only one core at each site, we assume that the use of single core from each lake will give a reliable estimation of the sediment accumulation rate since the lakes sampled are relatively small. An assessment of within lake variation of sediment properties, however, was also made by taking multiple cores (Akinyemi et al. 2013). Consequently, the key core in each case was taken at a location, which avoided the potentially deleterious effects on the sediments of shallow water (disturbance by wave action) and an uneven lake bed (slumping).

Except for Lake Ştiol whose water depth was artificially raised by a dam wall in 2002, the lakes in the northern

Carpathians are considerably smaller and shallower than those in the south (Table 1). The catchment size of lakes in the north Carpathians is not significantly different to those in the south (Table 1), but their catchment to lake ratio is larger.

The degree of shrub cover at the subalpine sites is greater around Tăul Negru (33 %) and Ştiol (20 %) than at the other upland lakes (Lake Vinderel, Capra, and Buhăiescu Mare) and therefore might be expected to provide better protection against surface soil erosion and slope instability (Table 1; Fig. 4). Lakes from the south have steeper slopes (Lake Capra and Lake Negru) with more scree and moraine in their catchments, which could make these sites more susceptible to erosion. Indeed, the combined effect of lower vegetation cover and higher scree/moraine cover at Lake

Capra may have enhanced a tendency towards in-wash from a steep and rocky catchment at this site.

In the case of Vinderel, the catchment geology is more variable and includes flysch in the proximity of the lake. This is reflected in this lake's formation as a function of slope movement and may also be significant in terms of the erosional inputs into the lake.

The influence of changes in socio-economic regimes on SARs

Traditional period (1840–1948)

There is no available SAR for the lowland site during this period. Three out of the six upland sites (1,670–2,300 m asl) show higher SAR in the traditional period, albeit not simultaneously (Fig. 4). These are Lake Capra and Lake Negru located in the south Carpathians with highest SARs between 1840 and 1910, and Lake Vinderel located in the north Carpathians with greater SAR post-1920 (Figs. 4, 5a). Historically, in the south Carpathians, the practice of seasonal grazing was much more developed compared to other regions in Romania (Constantin 2004). This practice reached its peak in the first half of the nineteenth century and declined markedly around 1900 (Constantin 2004). Subalpine woody vegetation (*Pinus mugo* and *Juniperus*) was also removed to enlarge land for grazing (Urushibara-Yoshino 2010; Feurdean et al. 2011). The temporal correlation between highest SARs at lakes in the southern Carpathians and documentary evidence of more developed seasonal grazing suggest that soil erosion connected to shrub removal, intensive pastoral activities and the resultant trampling by livestock might be responsible for the high SARs at these sites. Support for this interpretation is provided by a coarser median grain size values at Lake Capra (no such data are available for Lake Negru) in this steep-sloped and scree-covered glacial cirque (Figs. 4, 5a). Conversely, the SARs and median particle size declined after 1910 at sites in the south, parallel to a reduction in grazing pressure, possibly indicating subsequent slope stabilisation as the catchment vegetation cover recovered (Fig. 4).

Lake Vinderel, in the northern Carpathians (Maramureş Mountain), showed higher values of SAR from 1920 onwards. This SAR increase matches higher values of T_i , variable median particle size and lower SIRM values (Fig. 4). Documentary records show an intensification of forest and shrub clearance in the Maramureş Mountains due to the expansion of mountain pastures at this time (Idu 1999). This was a specifically local phenomenon as Maramureş County was then the only region in Europe where the Jewish population was permitted to lease land (Kubijovič 1932). Overgrazing with heavy animals (cattle)

alongside sheep and goats on pastures immediately surrounding the lake and the use of Lake Vinderel for water for animals may have led to localised slope erosion and a degradation of the lake's margins, thereby elevating SARs at this time.

Socialist period (1948–1989)

At the lowland site (Lake Ştiucii), high values in SARs during the socialist period paralleled elevated values of T_i , fluctuating, but overall a coarser particle size and a peak in SIRM (Fig. 4). The pollen record at this site indicates a marked expansion of grasslands and cultivated fields between 1950 and 1990 (Feurdean et al. 2015). Agriculture intensification appears to have increased allochthonous, minerogenic inputs to Lake Ştiucii via run-off and/or wind erosion. These findings are in line with the widespread intensification of arable agricultural production, dependent on heavy mechanisation and intensive grazing practices, across Central Eastern Europe (Stoate et al. 2009; Faostat 2012). However, due to its low productivity, this part of the Transylvanian Plain was considered marginal for agriculture (Ruprecht et al. 2010). The synchronous peak in SAR and SIRM along with the deposition of clay rich sediments around 1963 suggests the impact of a marked catchment land use or channel change related to agriculture (Serban and Sorocovschi 2003). However, the following peak in SAR (at 1970) is synchronous with the extreme rainfall event and catastrophic flooding in spring 1970 in Romania (Mustăţea 2005), which may have increased the supply of allochthonous material in Lake Ştiucii (Fig. 4). A rise in the rates of soil erosion in the agricultural landscapes of central Transylvania between 1950 and 1990, reflecting unsustainable ploughing techniques used in the agricultural systems of this period, has also been reported (Iurian et al. 2013). A contemporaneous increase in the proportion of herbs and cultivated plants reflecting intensive agricultural land use is further suggested by a pollen record from the NW Transylvanian Plateau (Geantă et al. 2012).

At Lake Sfânta Ana, our mid-elevation sediment record (900 m) SAR increased between 1953 and 1977 (Fig. 4). This lake lies outside the area that was predominantly developed for arable agriculture during the socialist period, but is important for recreation (Pándi 2008). The topmost pollen record from the adjacent crater (Mohoş) shows a marked decline in *F. sylvatica* and a corresponding increase in conifers and herbaceous species about 60 years ago, which has been attributed to forest clearance (Tanţău et al. 2003). Photographic evidence documents a forest fire in the catchment in the 1962 (http://4.bp.blogspot.com/-rX2VE_B94n8/VB2p7OBHfI/AAAAAAAAABIDg/nCLMBMHFT48/s1600/IMG.jpg). This fire episode matches a peak in SAR and an increase in T_i content of this

core, but it is not mirrored in SIRM (Fig. 4). Disturbance by fire, in addition to deforestation, most probably accelerated surface soil erosion and contributed to the SAR increase (Fig. 4). The SAR peak around 1970 is not reflected in any coarsening of sediment grain size, or change in organic matter content, implying that sources of sediment infilling remained constant at this time (Fig. 4). This peak in SAR is also synchronous with the extreme rainfall event and catastrophic flooding in spring 1970 in Romania (Mustătea 2005).

Moving to the high elevation areas, with the shift to a socialist collective system of land use and the increase in urban industrialisation, many mountain villages were abandoned (Pandrea 1993). However, mountain lakes in the northern Carpathians (Lake Buhăiescu Mare and Știol) show higher SARs in the socialist and post-socialist periods i.e. 1960 onwards (Fig. 4). At Lake Buhăiescu Mare, the SAR increase is coincident with a slight rise in Ti, SIRM and coarser particles suggestive of an increasing minerogenic input (Fig. 4). On the contrary, at Lake Știol, there is only a particle size and LOI increase, whereas Ti and SIRM decline slightly, which suggests a more organic input into the sediment or increase in aquatic productivity. Documentary records of livestock in the Rodna Mountains indicate that their number was greater in the socialist, and immediately post-socialist period (until 1993), than in the pre-socialist period (Faostat 2012). Intensification of summer grazing and trampling appears to have affected slope stability. The pollen records from Lake Buhăiescu Mare (Geantă et al. 2014) and Poiana Știol peat bog (close to Lake Știol) (Tanțău et al. 2011) show that grazing has been sustained in the past 200 years. Contrary to the trends in SAR at Lake Buhăiescu Mare and Știol, Lake Vinderel in Maramureș Mountains shows higher values in SAR until 1970 and a continuous decline thereafter (Fig. 4). This decline in SARs from 1970 parallels an increase in SIRM and highly variable values in particle size and Ti concentration. This contrasting result may reflect an unstable lake catchment bringing coarser, mineral magnetically enhanced particles into the lake. It should be noted that this lake was formed by recent, ongoing slope movement.

Lakes in the south Carpathians such as Tăul Negru record a re-increase in sediment accumulation rate between 1960 and 1990 despite the removal of livestock from the Retezat National Park within which Lake Negru is located (Fig. 4). Chironomid, cladoceran, elemental (C, N, S) and pigment analyses all point to enriched autochthonous production and modification in the trophic status of the lake (Rose et al. 2009). It is therefore possible that eutrophication at Lake Negru may explain the increase in SAR after 1960. At Lake Capra, on the other hand, grazing, recreational activities, enhanced by the construction of the nearby Trans-Făgăraș Highway

improving access, remained unrestricted. Such activities, however, appear to have resulted in only a minor rise in SAR around 1950 and between 1990 and 2007, supported by a coarsening of sediment grain size and increased SIRM concentrations (Fig. 4). What could explain a low SAR after 1920, and throughout the socialist period, is the continuous decrease in grazing pressure, first as a response to a decline in seasonal grazing pressure and then the wider rural depopulation of the high mountain area, which allowed vegetation recovery and slopes stabilisation.

Post-socialist (post-1990)

Low values or a decline in SARs in the post-socialist period is visible at several of the investigated sites (Lake Știucii, Sfânta Ana, Vinderel, Lake Negru and Capra). This is coincident with the disappearance of state control of agriculture and guaranteed markets for farm products, and the consequent widespread abandonment of agricultural land (Stoate et al. 2009; Faostat 2012). The post-socialist decline in SAR at our lowland site (Lake Știucii) is mirrored in the Ti content, grain size characteristics and LOI (Fig. 4). The hypothesis of post-1990 agricultural land abandonment leading to slope stabilisation and a decrease in soil erosion and SAR is also supported by the decline in pollen indicative of agro-pastoral activities (Feurdean et al. 2013b).

Our mid-elevation site, Lake Sfânta Ana (900 m) shows steady SARs in the post 1990 period. This is in agreement with the forest inventory of the region, which indicates only a small decline in the forest cover from 175.23 ha (87 % of land cover) in 1984 to 173.42 ha (86 %) in 2005. The increase in SAR from 2000 to 2007 is associated with a grain size and LOI increase and a decline in Ti and SIRM, indicating a change in sediment sources. A higher organic content would imply more autochthonous sediment in this part of the core. The extension of moss vegetation and sedges from shore and the impact of tourism on Lake Sfânta Ana sedimentation were noted by Pándi (2008) and could explain our estimated increase in organic content of the sediment.

Among the high elevation lakes examined, only two lakes in the northern Carpathians show a higher SAR in the post-socialist period (Fig. 4). At Lake Știol, the high values in SAR post-1990 are only associated with high values in Ti (Fig. 4). However, an increase in SIRM, coarsening of the grain size and elevated LOI values occurred post-2002, following a dam construction. The rise in the water level of the lake has perhaps caused riparian erosion increasing organic content of the sediment. As at Lake Știol, the increase in SAR at Lake Buhăiescu Mare is only mirrored in SIRM and grain size coarsening after 2000. This may

reflect either an erosion feature or a mineral magnetic input of atmospheric origin. Support for the latter is provided by elevated Pb concentrations close to the sediment surface (Akinyemi et al. 2013). In recent years, tourism-related activities may have further contributed to the increase in SAR via development of walking trails, mountain huts and the ski industry in the Rodna Mountains. Upland grazing also increased after 2007 encouraged by EU subsidy payments to support agricultural production (Urushibara-Yoshino 2010).

Comparisons with SARs in other European lakes

Sediment accumulation rates in Central and Western Europe show that for small, deep, lowland lakes (<50 ha, >5 m–<200 m asl, lake-type 1121) and therefore the closest in characteristics to Lake Știucii; there is a large temporal variability from 1850 to the present (Rose et al. 2011). Mean SAR in these lakes is $0.01 \text{ g cm}^{-2} \text{ year}^{-1}$ for 1850 with a gradual increase from 1925 to the top of each core (Fig. 5b). A rise in mean SAR from $0.02 \text{ g cm}^{-2} \text{ year}^{-1}$ at 1850 to values varying between 0.008 and $0.03 \text{ g cm}^{-2} \text{ year}^{-1}$ towards present (in particular in the post-1975 period) is also evident in larger, deep lowlands lakes (>50 ha, >5 m deep; type 1122). The core from our lowland site does not provide a record of SAR prior to 1960 (Fig. 5a). However, in contrast to Central and Western European sites, for the overlapping period, the highest SARs were observed between ~1960 and 1988 and there is a declining trend thereafter i.e. in the post-socialist period (Fig. 5a, b).

For small, deep mountain lakes (<50 ha, >5 m, lake-type 1321) in Central and Western Europe, SARs were found to be lower in the 1850 period ($0.005\text{--}0.007 \text{ g cm}^{-2} \text{ year}^{-1}$) and increased modestly towards the surface (Fig. 5b). In many of these lakes, however, SARs have remained constant through the entire period (Rose et al. 2011). In contrast to Central and Western European lakes, our small, deep mountain lakes (e.g. Lake Capra and Tăul Negru in the southern Carpathians) show highest SARs ($0.05\text{--}0.10 \text{ g cm}^{-2} \text{ year}^{-1}$) in the 1850–1920 period (Fig. 5b). However, this pattern is similar to other lakes in SE Europe such as the Rila Mountains, Bulgaria (Ognjanova-Rumenova et al. 2009). Results from our study were also comparable to remote arctic and alpine lakes in North America and Greenland, which indicates a stronger imprint of human impact on sediment properties in their geochemistry and biota response between 1950 and 1970, and again after AD 1980 (Wolfe et al. 2013). Over this period, reservoir lakes in Romania also show a significant increase in sediment inputs leading to severe silting problems (Radoane and Radoane 2005).

Concluding remarks and future prospects

Although the number sites are relatively limited ($n = 7$), our study presents the first preliminary results on the temporal and spatial variability of sediment accumulation rates from a previously under studied region (the Romanian Carpathians in Central Eastern Europe). Our key findings include the following points:

1. Sediment accumulation rates show an increase from basal (i.e. pre 1840) sediments towards the top of cores at only two sites. This trend contradicts wider findings from Western and Central European lakes, where sediment accumulation rates have predominantly increased over the last 150-year period.
2. Results from this study do not reveal a common temporal pattern in sediment accumulation rates across the range of sites during the three socio-economic periods of interest. This indicates the differential impact of changing land use in the traditional (1840–1948), socialist (1948–1989) and post-socialist (post-1990) periods on SARs at these lakes.
3. Lowland and mid-elevations lakes were most markedly impacted by the socialist land use regime i.e. intensive land use with industrialised agriculture and deforestation. The higher elevation lakes from the southern Carpathians ($n = 2$) were more impacted by the intensification of summer pastoralist and shrub layer removal of the traditional period (1840–1920); whilst lakes from the northern Carpathians ($n = 2$) responded more strongly to the impact of the socialist and post-socialist land use regimes.
4. Results from this study, combined with other sources of evidence (pollen, documentary records), highlight the sustained impact of anthropogenic activities throughout the entire period considered and even in relatively remote mountain areas. This suggests that a temporal frame of 100–150 years is too short to register reference conditions of these lakes i.e. conditions before significant human impact. Therefore, a predominantly natural state may not have existed in these catchments for centuries. This is an important consideration if such reference conditions are anticipated as providing a ‘baseline’ against which environmental quality can be assessed.
5. Superimposed on the changes in socio-economic regimes, climatic conditions can affect the trajectory of SARs. Mountain lakes in particular are regarded to be sensitive to climate change through both the direct effects of climate conditions on lake water temperature and the growing season of aquatic flora (Ramstack et al. 2004; Kernan et al. 2009) and indirectly through climate change-related

consequences for land cover and thereby catchment erosion processes (Guilizzoni et al. 2006). However, to examine the effect of climate warming, and to disentangle the effect of climate from other environmental drivers of lake productivity and autochthonous material changes to the sediment column, further analyses (e.g. C, N isotopes, pigment and biotic indicators such as diatoms, chironomid, cladoceran), together with independent measures of land cover change such as remotely sensed images (e.g. Landsat), are needed. Given the known recent land use change history of the region, and the availability of instrumental records showing ongoing, changing climatic conditions (Dragotă and Kucsicsa 2011), such integrated analyses must be a priority for the effective environmental management of the Carpathian Mountains.

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