The possible role of agricultural land drains in sediment delivery to a small reservoir, Worcestershire, UK: a multiparameter fingerprint study

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Abstract Recent monitoring of a small (1.5 km^2) UK experimental catchment has shown that specific sediment yields are *c.* 100 t km^{-2} $year^{-1}$ and that agricultural land drains contribute >50% of this yield. In an attempt to identify the impact of land drainage on longer term sediment yields and sources, a sedimentary sequence spanning six centuries has been recovered from a nearby reservoir in a catchment of similar soil type and drainage history. A ^{210}Pb chronology has been established for the lake sediments and a range of other gamma emitting radionuclides, physical and mineral magnetic properties have been used to identify sediment sources and the possible impact of drainage history on sediment accumulation rates. The most significant changes in sediment accumulation and sediment properties occurred in the late nineteenth and twentieth centuries. These appear to relate to a short period of arable expansion during the Second World War and to phases of agricultural land drainage installed in the catchment between the 1960s and 1970s.

Key words agricultural land drainage; radionuclides; mineral magnetism; lake sediments

INTRODUCTION

In 1997, a series of experiments were commissioned by the UK Ministry of Agriculture Fisheries and Food (MAFF), now DEFRA (Department for Environment, Food and Rural Affairs), to investigate the potential of subsurface agricultural land drains to contribute sediment and sediment-associated nutrients to receiving rivers. The project established monitoring in the 1.5 km^2 Rosemaund experimental catchment in Herefordshire, UK. Results, which were based on catchment monitoring and sediment fingerprinting techniques, showed that land drains contributed >50% of the sediment load of *c.* 100 t km^2 $year^{-1}$ and that at least 75% of the sediment delivered through the drains came from agricultural topsoils (cf. Chapman, 2001; Russell *et al.*, 2001). An important question not addressed by this research programme was whether land drainage increased or decreased the potential for sediment transfer or whether it reduced surface runoff and, hence, sediment delivery to rivers. This paper provides preliminary results from a project which was undertaken to find out if an analysis of lake sediments could support the hypothesis that agricultural land drainage increased the potential for sediment delivery to rivers in a similar catchment.

SITE SELECTION, MATERIALS AND METHODS

The Kyre Pool catchment (Fig. 1(a) and (b), Table 1) was selected on the basis of its similarity in soil type and drainage history to the Rosemaund catchment and also because Kyre Pool provided a virtually undisturbed sedimentary record spanning six centuries. The catchment is underlain by late Silurian red mudstones and sandstones of

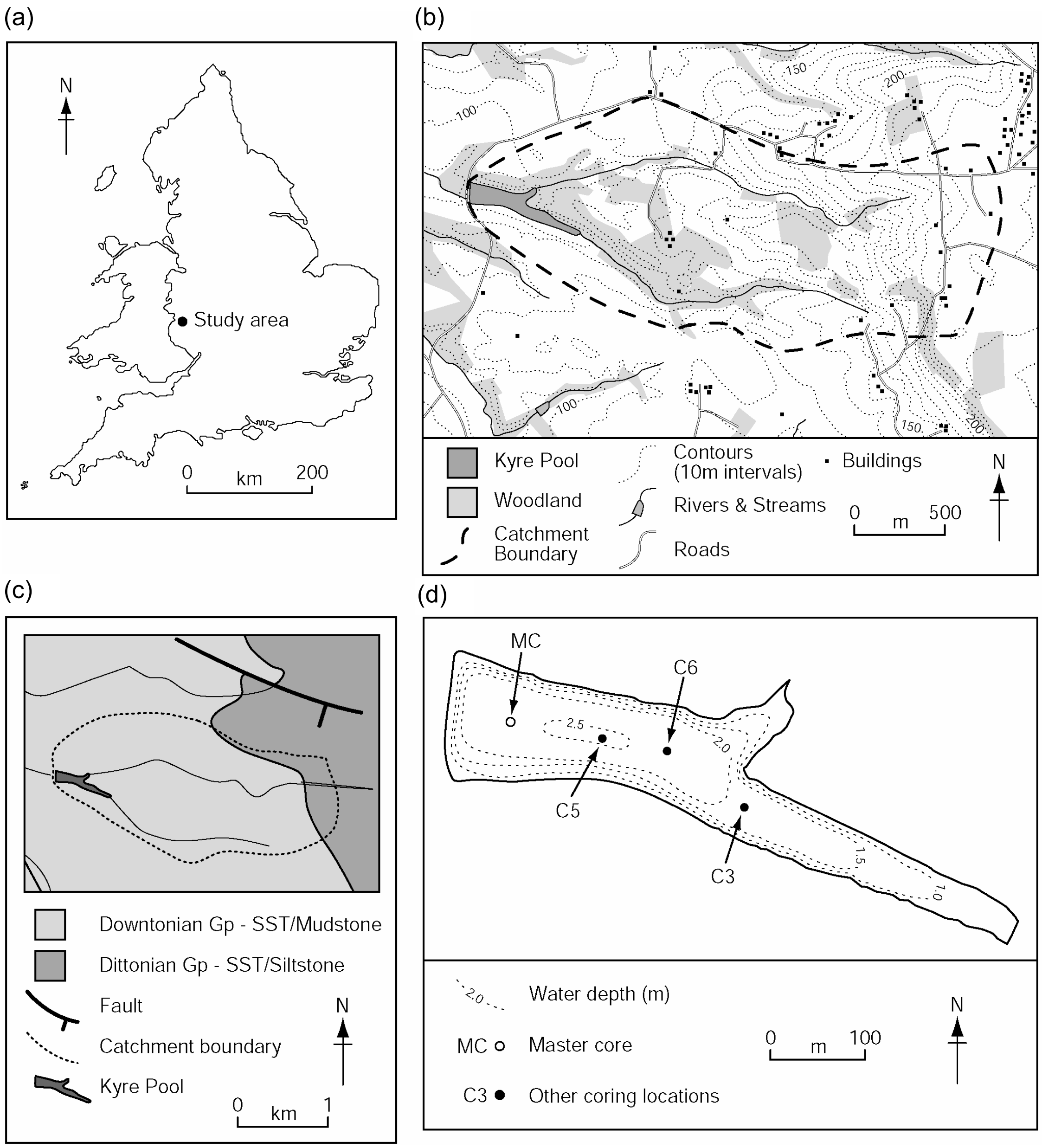

Fig. 1 Location (a) and details (b) of the Kyre Pool catchment with geology (c), pool bathymetry and coring locations (d). (Sedimentation limits approximately follow the 1 m isobath.)

the Downtonian Group which in part are overlain by Devonian fine-grained sandstones and siltstones of the Dittonian Group. The latter forms a prominent escarpment in the east of the catchment (Fig. 1(c) and (b)). Soils are dominated by Brown Earth's (Bromyard series) which are of a fine silty texture, exhibit significant cracking at times of water stress, and are known to have made a significant contribution to drainflow losses at the Rosemaund catchment (cf. Chapman *et al*., 2001).

Table 1 Kyre Pool summary information.

Characteristic	Value	Characteristic	Value
Year impounded	1584	Lake volume (m^3)	133 000
Lake area (ha)	5.34	Contemporary land use (%):	
Catchment area (km^2)	2.73	pasture	49
Lake:catchment area ratio	52:1	woodland	33
Maximum altitude (m)	262	arable	18
Minimum altitude (m)	90	Mean annual rainfall (1970–1999) (mm)	762
Relative relief (m)	172	Recorded partial reservoir drawdown (repair/maintenance)	1760, 1789, 1940, 1995
Maximum water depth (m)	2.5		

Kyre Pool and its catchment have a well documented history. The pool was built as a water supply reservoir for Kyre Manor in 1584. Timber was removed from the catchment for renovations to the Manor until 1615 and oak woodland has been felled on a variable scale since Elizabethan (I) times for shipbuilding. In 1789, a major conifer plantation was created on the north bank of the lake and, between 1840 and 1902, large areas of the catchment adjacent to the inflowing streams and lake were planted with oak woodland. During the agricultural revolution, >50% of the catchment was arable and by 1839 even the steepest valley-side slopes were cultivated. By 1935, most land in the catchment was pasture (Table 1) although a short period of more intensive arable production occurred during the Second World War (SWW). Today, limited cereal growing is concentrated on the flatter interfluves and pasture mostly occupies the steeper slopes (Table 1).

While the exact distribution of agricultural land drainage in the catchment is not known, records suggest that drains may have been installed at some time between the mid nineteenth century and the late 1930s and that many drains were replaced, or new ones installed, from the 1960s to the 1970s (Briggs & Courtney, 1985; Robinson, 1986; Robinson & Armstrong, 1988). Drainage systems (traditionally clay "tiles" but, since the 1960s, slotted or perforated plastic pipes of 10–30 cm diameter, backfilled with gravel) are usually installed at depths of 70–120 cm with a spacing of 10–20 m between drainage lines. These permanent drainage lines are usually connected to secondary drainage systems with a spacing of 1–3 m by using a bullet shaped plough (mole) to create small tunnels 5–20 cm in diameter at depths of between 30 and 60 cm in the soil profile.

Potential source samples (arable and pasture topsoils and subsoils, woodland topsoils and channel banks) were collected in July 2000. (Numbers of samples collected from each potential source is given in Table 2.) At the same time, four short (*c.* 1.5 m) Mackereth cores were recovered from the pool and, at one location (MC Fig. (d)), the sequence was extended to a depth of >4 m using a rod-operated gouge auger.

Table 2 Characteristics of potential source materials and the average of the upper 39 lake sediment samples (post-1923) and sources (*n* = 8 except pasture topsoil *n* = 4, and arable/pasture subsoil *n* = 12).

Mean	^{226}Ra (Bq kg^{-1})	^{228}Ac (Bq kg^{-1})	^{40}K (Bq kg^{-1})	^{234}Th (Bq kg^{-1})	^{235}U (Bq kg^{-1})	X_{lf} (10^{-6} m^3 kg^{-1})	Xarm (10^{-6} m^3 kg^{-1})	IRM$_{(0.8T)}$ (mAm^2 kg^{-1})	S ratio	IRM$_{(-0.1T)}$ (mAm^2 kg^{-1})	HIRM (mAm^2 kg^{-1})
Arable topsoil	44.43	45.28	992.91	34.15*	3.09	0.147	2.499	3.087	0.015	–0.400	1.230
Arable/pasture subsoil	45.66	42.24	949.97	28.12*	2.72*	0.127	2.376	2.998	–0.140	–0.184	1.294
Woodland topsoil	43.10	40.87	967.65	28.18*	2.63*	0.151	2.413	3.894	–0.047	–0.144	1.760
Pasture topsoil	59.70	43.00	883.77	35.72	3.90	0.155	3.187	4.412	0.120	–0.578	1.767
Channel bank	47.17	44.99	986.60	26.28*	3.20	0.159	2.376	3.687	–0.058	–0.140	1.664
Lake sediment	49.55	42.76	885.13	33.76*	3.84	0.169	4.305	4.620	0.163	–1.171	1.520
Standard deviation	^{226}Ra (Bq kg^{-1})	^{228}Ac (Bq kg^{-1})	^{40}K (Bq kg^{-1})	^{234}Th (Bq kg^{-1})	^{235}U (Bq kg^{-1})	X_{lf} (10^{-6} m^3 kg^{-1})	Xarm (10^{-6} m^3 kg^{-1})	IRM$_{(0.8T)}$ (mAm^2 kg^{-1})		IRM$_{(-0.1T)}$ (mAm^2 kg^{-1})	HIRM (mAm^2 kg^{-1})
Arable topsoil	3.27	3.23	28.52	7.78	0.56	0.007	0.497	0.369	0.041	0.156	0.079
Arable/pasture subsoil	5.56	4.13	49.20	7.70	0.78	0.01	0.439	0.475	0.062	0.160	0.237
Woodland topsoil	2.24	3.75	41.23	10.18	0.68	0.018	0.358	0.323	0.193	0.443	0.199
Pasture topsoil	6.68	4.45	36.76	11.59	0.87	0.016	0.970	0.744	0.100	0.342	0.153
Channel bank	3.58	5.06	54.57	8.19	0.77	0.019	0.462	0.235	0.120	0.245	0.147
Lake sediment	7.92	6.52	96.14	12.64	0.76	0.020	1.094	0.869	0.097	0.415	0.292

* Below the 95% limits of detection.

Source samples were oven-dried at 40°C for 24 h and screened through a 63 μm sieve before analysis. Lake sediments were extruded at 2 cm intervals from the Mackereth corer and at 10 cm intervals from the gouge corer for this preliminary investigation. Wet and dry (oven-dried at 40°C for 24 h) bulk densities were determined on samples from the Mackereth corer and the ratio of dry to wet bulk density (DWR) calculated (cf. Foster *et al*., 1990).

Loss on ignition (LOI%) was determined on source and lake sediment samples at 450°C (for 12 h) in order to express mineral magnetic signatures on a minerogenic basis (cf. Foster *et al*., 1998). Particle-size distributions and specific surface areas (ssa) were analysed using a Malvern Master Sizer on hydrogen peroxide treated and chemically dispersed subsamples. Subsamples (*c*. 1 g) were also microwave digested before analysis for Cu and Zn by ICP (inductively coupled plasma) (cf. Foster & Lees, 1999a).

A range of gamma emitting radionuclides have been measured in either a Eurisys or EG&G Ortec hyper-pure germanium well detector of *c*. 4 ml volume following the methods described by Murray *et al*. (1987) and Gilmore & Hemingway (1995). Count times were typically 170×10^3 s. Magnetic susceptibility and remanence characteristics were determined on 10-ml subsamples of the oven-dried source materials and lake sediments and, where relevant, were corrected for loss on ignition (cf. Foster *et al*., 1998).

^{137}Cs AND ^{210}Pb DATING

A variety of procedures has been developed to convert the unsupported ^{210}Pb profile into an age–depth relationship (cf. Robbins & Herche, 1993). Here, since the catchment has a well documented history of disturbance which was likely to result in changes in sedimentation rate, the *cic* and *cra* models (cf. Robbins & Herche, 1993) were deemed inappropriate and the *crs* ^{210}Pb point transformation model of Appleby & Oldfield (1978) was used to establish a preliminary ^{210}Pb chronology (back to 1923) for the main core (cf. Foster & Lees, 1999b). The ^{137}Cs activity profile appears to show evidence for the first fallout of weapons ^{137}Cs in the Northern Hemisphere (1954), the 1963 weapons fallout maximum and the 1986 Chernobyl fallout peak (Fig. 2(a)). Both the ^{137}Cs and ^{210}Pb estimates of 1954 coincide at a depth of *c.* 66 cm in the sedimentary sequence. However, there is a significant difference between the 1963 and 1986 ^{137}Cs peaks and the dates predicted by the ^{210}Pb *crs* model. In both cases, the ^{137}Cs peaks are displaced upcore relative to the ^{210}Pb estimates by as much as 13 and 8 years for 1963 and 1986 respectively. In most circumstances, discrepancies between ^{210}Pb- and ^{137}Cs-derived estimates of age relate to molecular diffusion and bioturbation which usually results in the downcore displacement of the ^{137}Cs peak relative to ^{210}Pb (cf. Robbins & Herche, 1993).

The ^{210}Pb chronology suggests that sedimentation rates increased slightly in the 1930s and 1940s but were considerably higher and more variable in the late 1960s and early 1970s (Fig. 2(b)). The earlier increase in sedimentation is consistent with the known expansion of cultivation during the SWW and appears to correspond to changes in many of the physical, chemical and mineral magnetic signatures at this depth in the sediment column (see below). The later increases in sedimentation were unexpected since, with the exception of expanded cultivation during the SWW, there was a substantial period of agricultural contraction up to the 1930s and only a minor increase in planted woodland in the twentieth century. While there has been some limited hedgerow removal, and an increase in stock numbers, there is no current evidence of stock access to the riparian zones of the river or the lake shoreline since these are predominantly tree lined. The only major contributing factor which might explain such an increase is the widespread installation of land drainage from the 1960s. Such activities are known to increase the contribution of fine sediments to the contemporary drainage systems at Rosemaund (Chapman *et al.*, 2001; Russell *et al.*, 2001) which are associated with an enrichment of ^{137}Cs in comparison with topsoil sources.

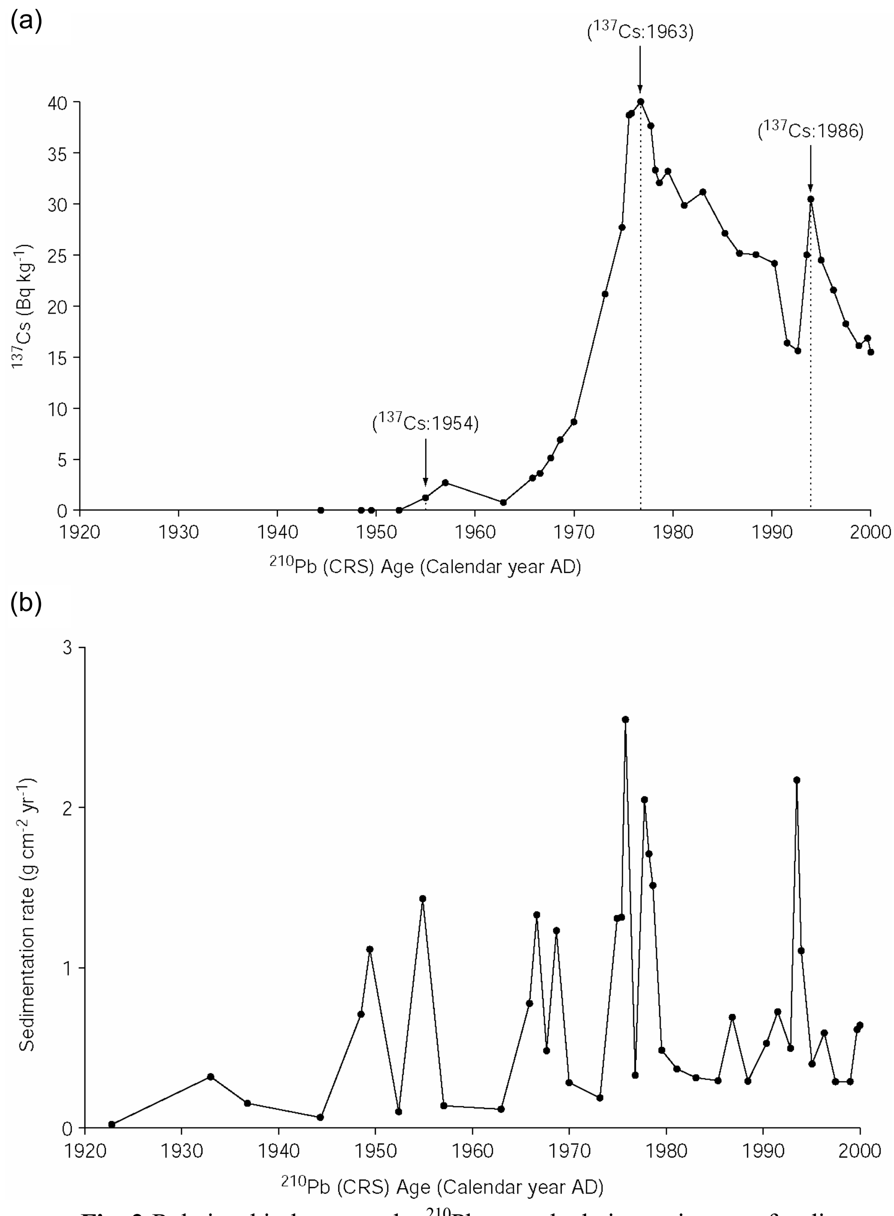

Fig. 2 Relationship between the ^{210}Pb *crs* calculation estimates of sediment age and the ^{137}Cs profile (a) and sedimentation rates estimated from the ^{210}Pb *crs* calculation (b).

The upward displacement of the ^{137}Cs peaks after 1954 relative to the ^{210}Pb predicted ages are thus plausibly interpreted as a consequence of installing new more efficient hydrological pathways connecting the topsoils of arable land and pasture to the river systems and to Kyre Pool. While further analysis of the ^{210}Pb chronology is required, the analysis and discussion given above suggest that the *crs* ^{210}Pb model probably provides the most robust chronology at this site.

CHARACTERISTICS OF SOURCES AND LAKE SEDIMENTS

Summary statistics for selected radionuclide and mineral magnetic properties of lake sediments and potential sources are given in Table 2. The raw data from which these summary statistics were computed have been corrected for particle ssa since it is well documented that many radionuclide and mineral magnetic signatures are inversely correlated with particle size, and therefore positively correlated with ssa (cf. Foster *et al.*, 1998; Walling *et al.*, 1999). Correction was performed by simple linear regression between ssa and the measured concentration or activity and residuals from these relationships added to the mean value.

Although this preliminary data set is small (especially for pasture topsoil), average lake sediment properties after 1923 appear to more closely reflect those of pasture and arable topsoils. Pasture topsoils appear to be slightly depleted in ^{40}K relative to other sources but slightly enriched in ^{234}Th, ^{226}Ra and ^{235}U. Mineral magnetic characteristics also appear to discriminate well between the major potential sources, with mean Xarm, $IRM_{(0.8T)}$, S ratio and $IRM_{(-0.1T)}$ values of pasture topsoils most closely matching those of the average lake sediments.

Substantial variations in ssa corrected mineral magnetic and radionuclide signatures (Fig. 3(a)) are evident in the downcore profiles (Fig. 3(b)–(d)). The data points plotted at 4.16 m depth (Fig. 3) characterize the original flood-plain surface (pre-1585). The rise in Cu concentrations (Fig. 3(b)) upcore from the basal sediments to *c.* 1.4 m depth appears to be consistent with trends in atmospheric pollution derived from Cu smelting works in the Swansea Valley (Rosen & Dumayne-Peaty, 2001), south Wales, which peaked in production by *c.* 1860 (cf. Jones *et al.*, 1991). The 1923 ^{210}Pb date is at 78 cm depth and the ^{137}Cs and ^{210}Pb 1954 date is at 66 cm depth. The ^{210}Pb chronology predicts 1970 at *c.* 48 cm depth. Significant changes in almost all properties plotted in Fig. 3 occur at between 1.4 and 80 cm depth and again between 80 cm depth and the mud–water interface. From the land-use history, reductions in ssa and increases in bulk density (Fig. 3(a)) could be associated with afforestation and disturbance of subsoils around the lake margins in the late nineteenth century. However, most of the substantial changes in sediment properties occur above 80 cm depth (after 1923) and could correspond to the short period of expanded cultivation and to later drainage operations in the catchment.

Downcore trends in Xarm and HIRM are plotted in Fig. 3(c). Table 2 suggests that contemporary pasture topsoils have high Xarm values relative to other potential sources and that their average signatures most closely reflect those of the upper 48 cm of the lake sediments. The ^{40}K activities start to decline upcore from *c.* 60 cm depth, which appears to be consistent with the post-war expansion of pasture. The ^{226}Ra and HIRM patterns are less clear. Coefficients of variation for HIRM and ^{226}Ra activities in

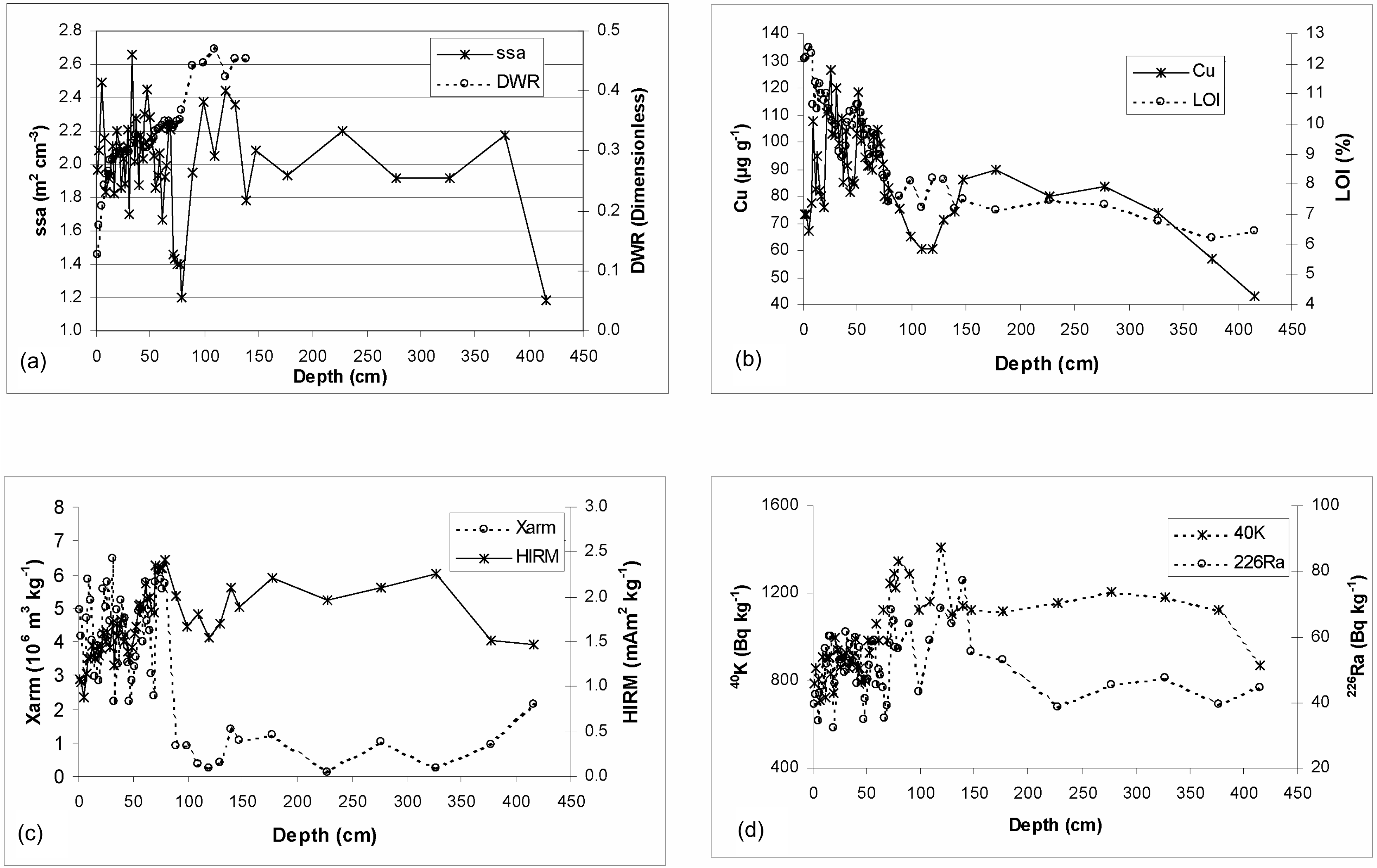

Fig. 3 Downcore trends in: the ratio of dry to wet bulk density (DWR) and particle specific surface area (ssa) (a); Cu concentrations and loss on ignition (LOI); Xarm and HIRM (c); ^{40}K and ^{226}Ra activities; in the 4.16 m long lake sediment core retrieved from Kyre Pool (coring location MC Fig. 1(d)).

the sources are almost three times those of ^{40}K in the same materials which makes interpretation more problematic. Nevertheless, HIRM does show a consistent decline upcore of *c*. 80 cm depth which might indicate increasing proportions derived from arable topsoil.

The initial installation of drains is likely to make subsoil, as well as topsoil, available for transport. The evidence from the characteristics of sediment sources shown in Fig. 3 supports this contention, but the sustained high ^{137}Cs activities in the most recently deposited sediments (Fig. 2(a)) would suggest that topsoil has remained the dominant source over the last *c*. 40 years.

CONCLUSIONS

Several lines of evidence combine to suggest that there were three major phases of disturbance in the catchment. The first, between 140 and *c*. 80 cm depth (late nineteenth/early twentieth century), probably reflects planting of broad-leaved forests around the pool. The second phase, upcore of 80 cm depth, could reflect the expansion of arable agriculture during the SWW. The third phase, upcore of *c*. 48 cm depth, appears to correlate with the installation and/or replacement of land drains within the catchment which began in the 1960s. These installations may have given rise to the significant increases in sedimentation, the displacement of the 1963 and 1986 ^{137}Cs peaks upcore relative to the ^{210}Pb estimated ages, and a change in many of the mineral magnetic and radionuclide signatures contained in the sediment column.

The aim of this project was to establish whether land drainage could increase the potential for sediment delivery to rivers. The ^{210}Pb chronology appears to be consistent with known phases of catchment disturbance over the nineteenth and twentieth centuries and the calculated sedimentation rates since the 1970s have increased by a factor of *c*. 4 over earlier twentieth century rates. The increase in sedimentation suggests that sediment yields will also have increased by a similar order of magnitude, assuming uniform sedimentation across the lake bed, and that the most likely cause of such an increase is the installation of new land drainage schemes. These results may have wide-ranging implications for interpreting the recent sediment yield histories of lowland UK catchments since it is estimated that *c*. 50% of UK agricultural land is under-drained (Robinson & Armstrong, 1988).

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