suggested above, *Apium* alone dominated the winterbourne sites. These sites were uncut in the study period. Natural permanent stream sites, which were also uncut, were dominated by *Rorippa* and *Callitriche* in deep slow-flowing reaches, or *Rorippa* and *Ranunculus* in shallow faster-flowing reaches. Amongst the lined Gussage sites two were uncut and there *Rorippa* alone was clearly dominant. Although *Ranunculus* occurred, it was more rapidly overgrown in spring than at the wider permanent stream sites. In contrast, at the lined Gussage sites where the weed was cut, the dominance pattern totally broke down, and no two species between them reached 50% of mean aquatic macrophyte cover.

The effect of fencing was difficult to assess as the grazed sites were all on winterbournes. The most probable impact of grazing was the reduction in absolute rather than relative abundance of the species present.

The invertebrate samples were plotted in the same way as the macrophyte samples. Boundaries were drawn to enclose samples in three groups with different flow regimes (Fig. 3). This time the group with artificially maintained discharge included one unlined reach of the Gussage downstream of the boreholes, and the group of sites on natural permanent streams included an unlined permanent flow reach on the Gussage. Statistical analysis showed that samples from the winterbourne sites and the unmodified permanent stream sites are quite distinct, despite the fact that no samples were taken from winterbourne sites during the dry phase. This emphasizes the difference between the fauna of an intermittent and a permanent stream and suggests that alteration of the flow regime could be a very significant factor. Where the flow regime has been changed, as in the Gussage downstream of the borehole, the samples occupy an intermediate position, having moved away from their original winterbourne character towards a permanent stream fauna. Within this group of modified sites there is no apparent gross difference between the invertebrates of unlined reaches or of any type of lined reach.

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INTERPRETING THE ENVIRONMENTAL RECORD IN THE SEDIMENTS OF BLELHAM TARN

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Introduction and methods

The environmental record in the sediments of Blelham Tarn has been investigated from more aspects than has that of most lakes, and is of particular interest in view of the volume of FBA research in progress there. Methods employed in recent research have concentrated on two problems: (1) the ecological history of the catchment, and lake–catchment relationships, by detailed analysis of both the pollen preserved in the sediments (as an index of vegetation) and sediment composition with respect to a range of inorganic and organic geochemical variables (Mackereth 1966; Cranwell 1973b, 1974, 1976). Organic geochemistry has separated the solvent-soluble part of sedimentary organic matter into discrete compound classes, each differing in functional group or structure, which constitute a chemical record of source organisms complementary to the microfossil record; and (2) a detailed investigation of the manner in which sediment is being formed today, including the way in which microfossils (pollen and diatoms) are being recruited and incorporated into the sediments (Pennington 1974; Haworth 1976; Bonny 1976).

When the record was examined by biological and geochemical analysis, together with radionuclide dating, of closely spaced samples, it was found that the changes of the last 30 years represent only the most recent episode in a long history of modification of the lake by man (Pennington et al. 1976). The changes in both water chemistry and lake biota which followed the first direct discharge into the tarn of an effluent from domestic drainage (1951–52) and the impact of increasingly intensive agriculture, have been recorded by the FBA (Lund 1973; Lund and Macan in Pearsall & Pennington 1973). Corresponding changes can be recognized in the sedimentary record, but the latter shows that prior to 1945 the tarn was not in a 'natural' state. To find an approach to this it is necessary to go back for at least 2500 years. The record in the sediments shows that human modification of the primary vegetation and soils of the catchment, during forest clearance and agriculture, had such profound effects on the lake–catchment relationship that a fourfold increase in total output of particulate matter from the catchment soils was trapped in the lake. The consequent increase in the rate of filling of this shallow lake accelerated the reduction in volume of the hypolimnion, increasing the extent to which this became seasonally deoxygenated; present minimum oxygen saturation in Lake District lakes is closely correlated with depth (*Annual Report* 1973). Correlated changes in the fauna have been recorded (Harmsworth 1968).

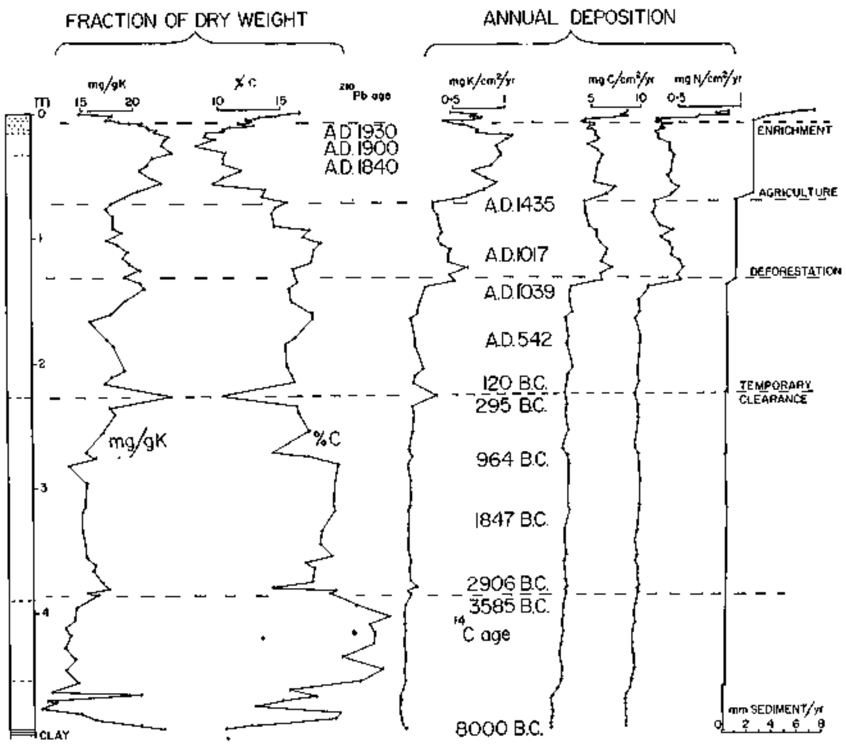

FIG. 1. Sediment composition; proportions and annual input over the last 10 000 years of carbon, nitrogen, and potassium, compared with horizons of major vegetational change in the catchment. Samples for organic geochemistry were taken from this dated core. Space limitations prevented inclusion of the standard errors of the C–14 dates; these are available on request.

Changes c. 5000 radiocarbon years ago – climatic change?

Figure 1, showing data from a 6m core from Blelham Tarn, demonstrates that though sediment accumulation rates have increased steadily through the last 10 000 years, there was about 5000 years ago an increase in annual deposition of sediment which was accompanied by both proportional and absolute increases in the annual deposition of potassium, which is interpreted as showing an increased output of soil felspars from catchment soils (Mackereth 1966). Pollen analysis has shown no local vegetation change at this time. It has been postulated, on evidence from the Lake District and Northern Scotland, that a climatic change at this date resulted in increased run-off from the catchments of western Britain (Pennington 1975).

Changes between c. 250 B.C. and A.D. 1

At a horizon dated by ^{14}C to *c.* 200 B.C., pollen changes indicative of an initial but short-lived effect of man on primary forest (temporary clearances) are found associated with a visible clay band in the sediments and with further increases in potassium (Fig. 1). This suggests a close relationship between disturbances of a primary vegetation cover and the output of particulate matter from mineral soils. The well-established climatic change to a cooler and wetter climate during the period 800–500 B.C. would be expected to have produced a situation in which later destruction of primary forest would be especially likely to produce accelerated soil erosion. Above this horizon percentages of potassium in the sediments are consistently higher than in the older sediments.

Deforestation at c. A.D. 1000: fauna and geochemistry

Figure 1 shows the marked changes in sediment composition between 150 and 100 cm. Within this zone all samples have a ^{14}C age of about 900 years, indicating a disorderly input of soil organic matter of that age. The mean rate of sediment accumulation was doubled, leading to significant increases in calculated annual deposition rates of both inorganic (K) and organic (C, N) components. Pollen analyses at this horizon show a steep fall in the proportion of arboreal pollen, particularly of oak, with a corresponding rise in grass pollen, indicating a major clearance of forest for pasture (Pennington et al. 1976, Figs 6 & 7). The chemical composition of the sediment, and the high concentration of pollen within it, suggest that it was derived from the surface humus of acid woodland soils; this appears to have been transferred rapidly to the tarn when the first clearance of the woodlands began. Harmsworth (1968) found in a core from this site that the major faunal change in post-glacial sediments took place about 100 cm below the mud surface; this was a change from a midge fauna dominated by *Tanytarsus–Sergentia* to a *Chironomus* fauna. He interpreted this change as the consequence of morphometric eutrophication – an increasing degree of deoxygenation consequent on reduction in volume of the hypolimnion. This interpretation has now been supported by our demonstration of accelerated rates of sediment accumulation in the underlying 40 cm of deposit.

A sample from 100 cm depth (when analysed by the methods of organic geochemistry) showed a predominance of organic indicator compounds associated with terrestrial material, although the saturated carboxylic acid fraction shows a slightly stronger representation of the component derived from aquatic detritus than do contemporary sediments from oligotrophic lakes. This is consistent with Harmsworth's faunal evidence for increasingly eutrophic conditions in Blelham Tarn at this time. The distribution of saturated hydrocarbons is characteristic of terrestrial detritus derived from deciduous mixed woodland (Cranwell 1973b) but includes a proportion of microbially-derived components higher than is found in more recent sediments. This feature was found at another site within sediments of anomalous ^{14}C age, which suggests either that the microbially-derived components are preserved only in situations where they are rapidly buried, or that their presence may be associated with stimulation of microbial activity by accelerated inwash of particulate matter from soils (Collins 1970, p. 4).

This evidence for an increase of at least twofold in the rate of sediment accumulation after deforestation, at the time of the historically recorded settlement of the Lake District by Norse-speaking immigrants, forms an interesting comparison with the recent experimental deforestation of the Hubbard Brook catchment (Likens et al. 1969) which increased the output of particulate matter in the streams by ×4.

The onset of more intensive agriculture in the catchment

A return to approximate stability in the ecosystem appears to have followed the establishment of grassland for pastoral farming, but at a horizon dated by ^{14}C to *c.* A.D. 1500 (Fig. 1) a second and more conspicuous episode of change began. The mean annual rate of sediment accumulation was again doubled, and potassium increased very significantly both as a percentage of dry weight and in terms of estimated annual deposition over unit area (Fig. 1). The proportional organic content of the sediment declined steeply, but the increased annual rate of sediment accumulation produced an approximately constant estimated rate of annual deposition of carbon and nitrogen. At exactly the same horizon as these pronounced changes in sediment composition, pollen of cultivated cereals, flax and hemp indicates the beginning of a local episode of arable farming, and coincides with a fall in the percentage representation of oak to values now found only at sites in almost completely deforested areas (e.g. Whinfell Tarn, in agricultural land north-east of Kendal). These indications that a greatly increased input of mineral soils coincided with the first local cultivation of these crop plants agree with what is now generally known of the effects of initial ploughing in disturbing soils and giving rise to intensified soil erosion. In addition, the courses of inflow becks include artificially straightened reaches indicative of human interference in the past, which must have accelerated the transfer of mineral soils from catchment to lake.

It would be expected that this episode, which by dilution with mineral soils reduced the organic fraction of the lake sediment to a post-glacial minimum, must have exerted some effect on lake biota. It seems probable that the changes in the cladoceran fauna noted by Harmsworth (1968) were brought about by changing soil input, rather than by changes in lake level as he postulated.

Changes between 1850 and 1930

Figure 2 shows some changes in sediment composition over the last 600 years. Between 1848 and 1888, the effects of landscaping in the catchment (construction of a fishpond and diversion of one of the main inflows)

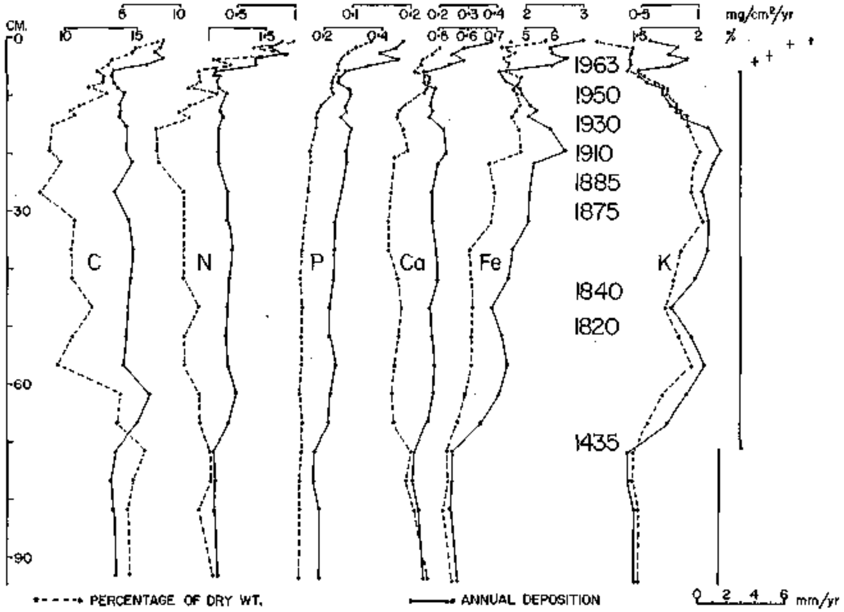

FIG. 2. Geochemistry of sediments of the last 600 years – a comparison of proportional composition and the estimated annual input of 6 variables.

appear to have maintained the high rate of transfer to the lake of mineral soils. Shortly after 1900, potassium in the sediments began to decrease, both as a percentage and in annual deposition rate, towards the pre-1500 values, reflecting the stabilization of the catchment which followed the reversion of arable land to pasture and amenity woodland in the late 19th century. Comparison of the proportional composition and annual input for each element illustrates (a) the effect of accelerated input of mineral soils between 1500 and 1900 in increasing *both* proportional and absolute representation of potassium and iron; (b) the close correlation between annual deposition rates of these two elements which shows that the transport of iron must have been by erosion and not in solution (Mackereth, 1966); (c) the very low contribution of phosphorus and calcium within the mineral soil input; and (d) the comparatively low organic content (carbon and nitrogen) throughout the period of high input of mineral soils, and shows that organic content did not begin to increase again towards its pre-1500 levels until *c.* 1930.

Organic geochemical analysis of the sample dated to *c.* 1875–1900 showed that the composition of the sterol and saturated straight-chain acid fractions indicates a higher autochthonous input to the sediments than in the sample dated to *c.* 1017, but this is expected in view of the postulated origin of the older sediment (in inwashed forest mor). The distribution of saturated hydrocarbons in the 1875–1900 sample is characteristic of deciduous mixed woodland sediments deposited in chronological sequence, but the distribution of saturated alcohols now differs from the earlier sediment (in which a higher plant input was indicated) and resembles that of the surface mud. This distribution pattern, also observed in recent sediments of a more productive lake, may reflect an increased contribution from zooplankton.

Changes after 1930

A stratigraphic change from brown to black mud, found in this core at 15 cm below the mud surface, falls consistently at *c.* 1930 in four cores dated by ^{210}Pb. It coincides with an increase in water content and in proportions of carbon, nitrogen and phosphorus, and follows shortly after a proportional increase in iron (Fig. 2). There is no recorded change in catchment or lake at about 1930 which could explain this discontinuity in the sediments, and further work on it is in progress.

Since 1945 Dr. Lund has monitored changes in the phytoplankton of Blelham Tarn; these changes are recorded in the topmost 10 cm of sediment in the core shown in Fig. 2. In this core, changes in sediment composition are found in sediments dated by ^{137}Cs to just before 1954 and to 1962–3. In 1951–2 effluents from septic tanks first began to reach the tarn, and this correlates with an increase in annual deposition of nitrogen and phosphorus in the sediments (Fig. 2). Detergents, which arrived at about this time, probably contributed to deposition of phosphorus. In 1962–3, it became necessary to install sewage treatment to deal with increasing amounts of domestic sewage, and this correlates with further increases in annual deposition of carbon, nitrogen and phosphorus from the horizon dated, by the peak of ^{137}Cs, to 1963.

When compared with other samples, the post-1950 deposits contain a larger amount of a branched-chain C_{18} alkane found in blue-green algae, while the sterol fraction is richer both in cholesterol, as in surface sediments from other productive lakes, and in another sterol which is dominant in several species of diatom. These results are consistent with Dr Lund's records which show increase in these algae since 1945 (Lund 1973). The distribution of saturated unbranched acids also reflects an increased contribution from aquatic organisms compared with older samples, while the abundance of unsaturated acids may result from deoxygenation of an increasing proportion of the water volume during this period (Lund 1973). Many constituents of the sedimentary branched-chain acids are abundant in bacteria, including two cyclopropanoid acids which were identified for the first time in the geosphere (Cranwell 1973a).

Fertilizers (ground limestone, nitrates and phosphates) have been added to the farmed land in the catchment in steeply increasing amounts since 1945. To what extent have these been trapped in the sediments? Fig. 2 shows that since 1950 calcium has increased, both as a proportion of dry weight and as estimated annual deposition, to values higher than any found during the last 700 years. Fine particles of ground limestone, which have been detected in air-borne dust, appear to be transferred from catchment to lake and to become incorporated in the sediments. There is no evidence for any increased contribution of potassium to the sediments which date from 1945 and later years (cf. Lund 1973). The decline in potassium as a proportion of dry weight in sediment above the 1950 level (Fig. 2) is explained as the result of an increased contribution of biogenic silica (implied by the increasing production of diatoms (Lund 1973) but not estimated quantitatively) and the postulated increase in calcium carbonate from fertilizer. Fluctuations in estimated annual input of potassium after 1950 (Fig. 2) are interpreted as arising mainly from the difficulty of accurate estimation of the thickness of each annual increment; they indicate a mean annual deposition of *c.* 0.75 mg of potassium per cm^2 of mud surface at this position in the tarn. This rate of output of potassium from the now stabilized catchment is about 50% higher than in the pre-agricultural period.

The formation of sediment today

Both depth–time scales based on radionuclide dating (Figs 1 & 2) and estimates of the present annual addition to the mud surface based on seston trapping (Pennington 1974) show that in Blelham Tarn and Esthwaite there has been a very marked increase in thickness of the annual increment of sediment since the onset of cultural eutrophication. This raises the question of to what extent the organic matter resulting from primary production is now being oxidized within the lake. In order to investigate more closely the present formation of lake mud, the distribution within the sediment of certain microfossil markers, and the manner in which these are recruited to the sediments, have been studied in detail.

Diatoms

The most recent event in the limnological history of the tarn has been the appearance of a distinctive form of *Stephanodiscus astraea* var. *minutula* (Kützing) Grunow in spring 1973. It is hoped that this will form a permanent layer in the sediments as it has been part of the 'diatom bloom' for three successive years but in decreasing abundance (5000 cells ml^{-1} maximum in 1973, 730 cells ml^{-1} in 1974 and 54 cells ml^{-1} in 1975; Lund and Irish, personal communication). The significance of this bloom is that it allows us to observe how a change in the living population becomes incorporated into the relic assemblage in the sediments (Haworth 1976), and what magnitude of change is necessary before there is a permanent record.

Analysis of successive 0.5 cm slices of the topmost sediment of a core from near the centre of the tarn (in 13.5 m water depth) shows (Fig. 3a) how the three years' material had accumulated there by July 1975. The numbers of *Stephanodiscus* valves at each level suggest that the remains of the 1973 bloom are found between 4 and 5 cm. The diagram also shows that some material has clearly moved downwards by as much as 2 cm (Haworth 1976, Fig. 5) and suggests that there may have been later redeposition as well, as the 1·5 – 2·5 cm layer has proportionately more valves in relation to the maximum abundance of the population in 1974.

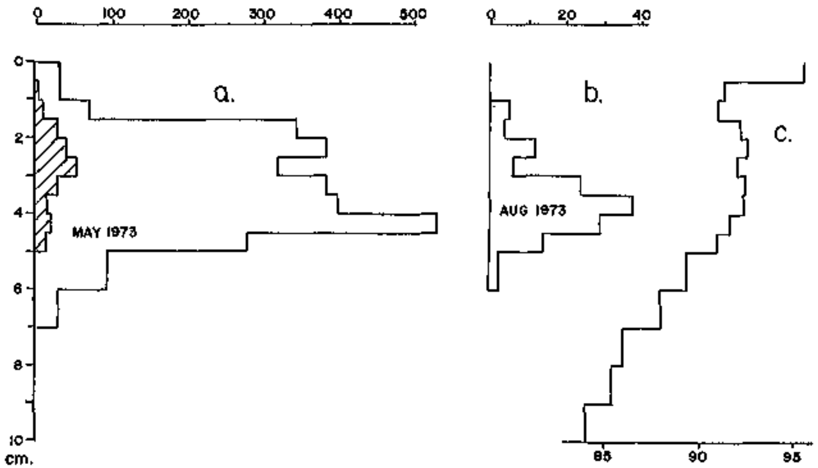

FIG. 3. (a) Numbers of *Stephanodiscus* valves/10^{-4} cm^3 sediment in the topmost 10 cm of a minicore. The shaded part represents the numbers of a form that corresponds to the description of *S. subtilis* van Goor but which is suspected to be properly a part of this population.
(b) Numbers of pieces of marine diatoms/5×10^{-4} cm^3 appearing in the same samples.
(c) Percentage water content of the sediment.

Prior to the appearance of a natural marker, Dr Lund had arranged for the addition of diatomite to make a layer for similar observations on sediment formation. He calculated that 330 kg of marine diatomite (mainly *Coscinodiscus* sp.) would make a 2 mm uncompacted layer inside the prototype experimental tube in Blelham; this was duly added on 23rd August 1973. Although this layer has remained undisturbed, the tube was never absolutely complete and it subsequently sank in November 1974. It was, therefore, likely that some material would be transported out into the tarn and, as the present core site is *c.* 25 m from the tube, the maximum of marine diatom fragments found just above the *Stephanodiscus* maximum (Fig. 3b) suggests that this material relates to the period when the diatomite marker was added. A subsequent slight increase also supports the theory of redeposition during 1974. Hopefully all this material will remain as a discrete marker layer in Blelham sediments so that we can observe how surface sediment assemblages become part of the distant past.

Pollen grains

These represent particles of mean size *c.* 30–40 μm which reach the sediments partly by fall-out from the air and partly by stream transport from the surface of the catchment. The former are predominantly freshly-liberated 'in-season' grains whereas the latter are predominantly grains liberated at some time in the past and secondarily transferred, i.e. 'out-of-season' pollen.

The present-day recruitment of pollen to the tarn has been investigated by means of seston traps suspended in the water both inside and outside the experimental tubes. Catches inside the tubes included mainly fresh in-season pollen transported aerially to the water surface inside the tube rim. At the time of the overturn, however, some out-of-season pollen was caught by traps inside the tubes; this is believed to have been resuspended by turbulence from the small area of mud surface inside the tubes. Pollen catches in traps in the open water of the tarn were always higher than those from traps inside the tubes (Fig. 4i), because of input of additional pollen by streams, from which the tube traps were isolated. The numbers

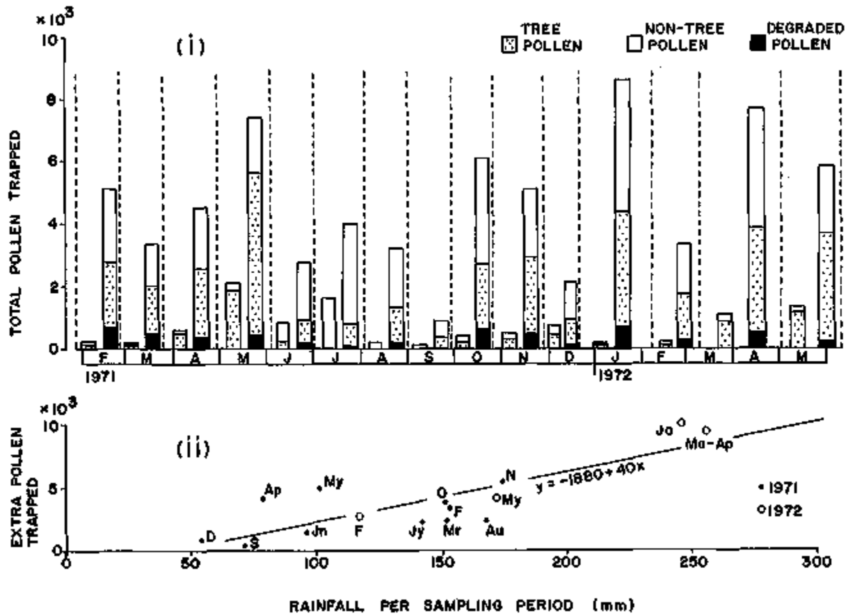

FIG. 4. Pollen trapped in Blelham Tarn, 1971-1972: (i) Histograms representing average daily pollen catch for each sampling period (denoted by pecked lines); left-hand bars show catch inside the experimental tubes, right-hand bars show catch outside the tubes. (ii) Average numbers of extra pollen trapped per cm^2 per sampling period outside the tubes plotted against rainfall.

of this additional (extra) pollen caught in open-water traps during each sampling period were correlated significantly with rainfall on the catchment, and so with stream discharge (Fig. 4ii). This, together with a similar correlation between rainfall and the potassium content of seston trapped in open water (Pennington 1974) supports the hypothesis that the input of fine particulate matter from the catchment, both pollen grains and particles of soil felspars, is closely correlated with rainfall.

In 1971–72, only 10–15% of the pollen entering the tarn appeared to have been brought in by air, the rest being supplied by streams. The streamborne pollen component is qualitatively important, since it supplies to the lake certain pollen types which are not well dispersed in air, and so provides in the sediments a pollen assemblage more representative of the vegetation of the catchment than that found inside the tubes.

The cores from the sediments of Blelham Tarn were obtained, using 1 m and 6 m Mackereth corers, by Mr B. Walker, Mr P. R. Cubby, Mr J. D. Freeman and Mr P. V. Allen. Mr Cubby and Mr Freeman carried out the programmes of monthly sampling from seston traps, and Mr Allen assisted both with the close sampling of sediment on which Fig. 3 is based, and with preparation of samples for diatom analysis. Mrs K. J. Clark prepared samples for pollen analysis and carried out the determinations and calculations necessary to convert percentage chemical data into annual deposition rates. We thank them all for their contributions.

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