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# Monitoring fluvial pollen transport, its relationship to catchment vegetation and implications for palaeoenvironmental studies

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## Abstract

Despite being the most important source of pollen and spore input into most lakes and near-shore marine sediments, we know very little about fluvial (waterborne) pollen and spore transport. This paper presents the results of a dedicated monitoring programme conducted over 2 years and at a catchment scale in South West England. The land use of the nine sub-catchments monitored was determined using Landsat Thematic Data. At two stations, pollen and spore sampling through storm hydrographs was undertaken whilst at the other 7 sub-catchments only peak flow samples were collected. Samples were also collected from re-suspended bed material, riverbanks and at low flows. Airborne pollen flux was monitored using modified Tauber traps. The results support previous research illustrating how the vast majority of fluvial pollen and spores are transported during floods (in this case 91%) and that the main control on waterborne pollen and spore assemblages is the catchment vegetation. However, strong seasonal effects are shown as well as the importance of distinctive sources, such as the riparian input, bed re-suspension and overland flow into drains and tributaries. Fine sediment in river pools appears to act as a selective store of damaged cereal-type pollen grains in arable catchments and this can reduce the inherent underestimate of arable land from pollen diagrams with a high fluvial input and increase the visibility of early agriculture. In order to simulate the likely result of a flood-dominated influx to a small lake scenario, modelling was undertaken whereby different sub-catchments were substituted in order to represent changes in catchment vegetation under a constant hydrological regime. The results show the dampened response of land use groups to catchment land use change, and the frequent occurrence of anomalous single-level peaks due to seasonal flushes from specific near-stream vegetation types. Both these features are commonly seen in lake pollen diagrams. Fluvial pollen and spore loading is dependant upon discharge and so concentrations in laminated or varved sediments could be regarded as a proxy for flood magnitude. The implications for this study on the interpretation of lake and near-shore marine pollen and spore diagrams are discussed and it is argued that a more quantitative approach to waterborne pollen could improve the estimation of land use from lakes in the temperate zone.

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## 1. Introduction

It is widely accepted that the majority of pollen and spores entering most medium-sized and larger lakes and near-shore marine sediments are fluvially transported from river catchments (Federova, 1952; Peck, 1973;

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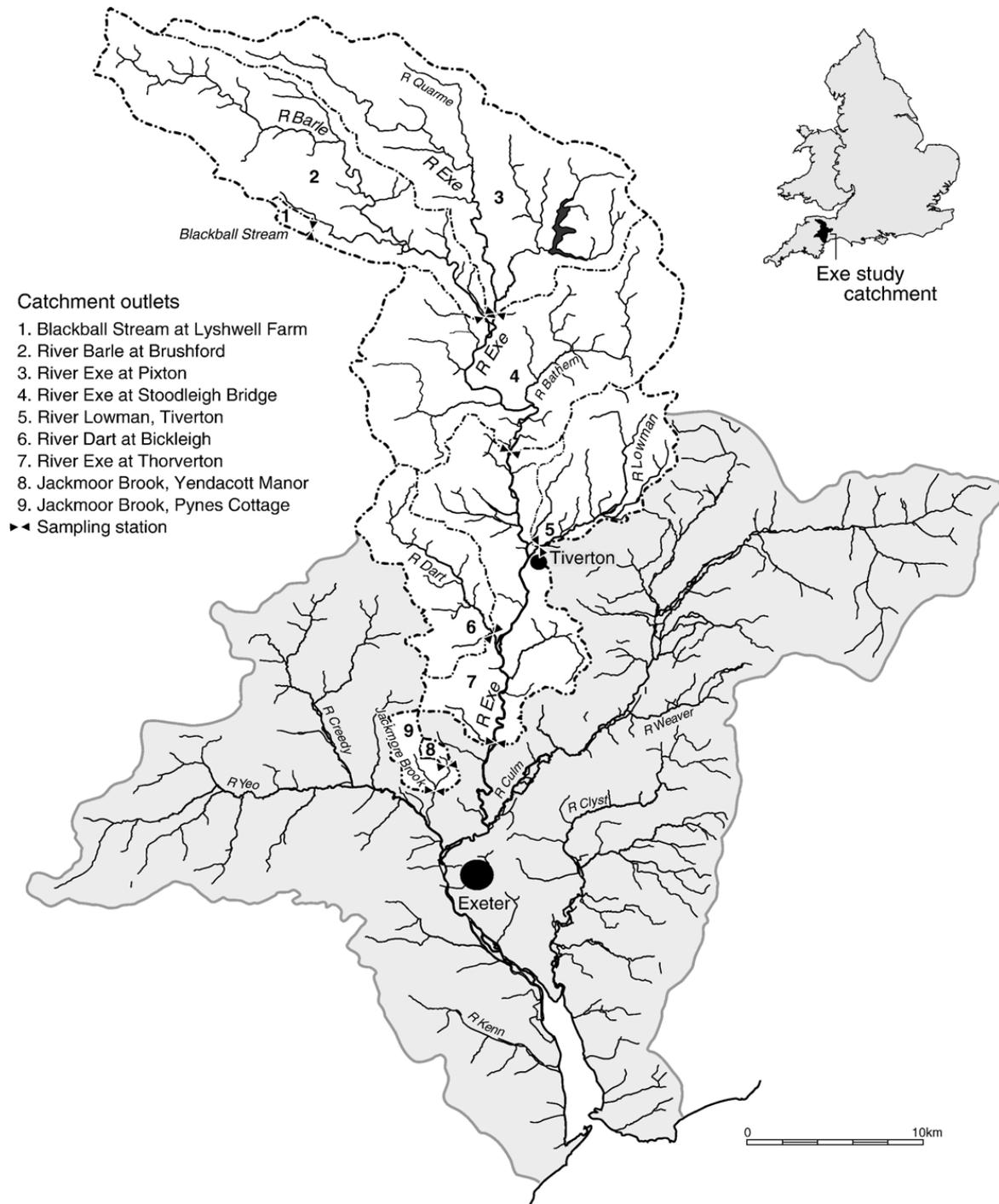


Fig. 1.

McAndrews and Power, 1973; Crowder and Cuddy, 1973; Pennington, 1979; Bonny, 1980; Brown, 1985; David and Roberts, 1990; Traverse, 1992, 1994) and that the ratio of fluvial to airborne (both wet and dry) input depends on the relationship between the size of the catchment, the lake surface area, the topography and the catchment vegetation. In classic studies, Peck (1973, 1974) found 97% of the pollen and spore input to

Oakdale reservoir was fluvial and Bonny (1978) found 87% of the input to Blelham Tarn was of fluvial origin. Fluvial pollen and spore input also forms a significant input into valley mires and alluvial wetlands. Yet we know far less about the fluvial transport of pollen and spores than we do about airborne transport and this raises the possibility that some of the features revealed in these pollen and spore diagrams may be artefacts of

Table 1  
Topographic statistics for the study catchments taken from the Flood Estimation Handbook CD-ROM

Catchment		Area (km <sup>2</sup> )	Max drainage path (km)	Mean slope (m/km)	Mean aspect (deg)	Catchment outlet altitude (m O.D.)	Mean altitude (m O.D.)	Max altitude (m O.D.)
1	Lyshwell Farm	1.8	2.88	66.9	93	287	345	378
2	Brushford	128.8	40.99	136.4	152	128	245	488
3	Pixton	149.8	36.79	153.8	185	128	307	519
4	Stoodleigh	420.7	55.44	142.5	168	74	284	519
5	Tiverton	54.5	15.87	95.1	192	62	168	286
6	Bickleigh	45.4	14.33	146.2	132	52	176	271
7	Thorverton	608.9	76.92	137.8	164	26	244	519
8	Yendacott	1.5	2.38	48.9	161	35	59	85
9	Pyne Cottage	9.3	5.48	58	158	25	66	235

the dynamics of fluvial transport rather than simply reflecting changes in the surrounding vegetation. This paper presents the result of basin-scale monitoring of fluvial pollen and spore transport and uses this data to make inferences concerning the interpretation of lake and near-shore marine pollen and spore diagrams.

However, studies of fluvial pollen and spore transport although rare have revealed that flood concentrations can be from 100,000 grains l<sup>-1</sup> (Peck, 1974) to as high as 130,000–230,000 grains l<sup>-1</sup> (Brown, 1985). Pollen and spores transport has also been investigated in flumes (Brush and Brush, 1972) and Holmes (1990, 1994) reported no differential sorting at velocities over 0.30 m<sup>-1</sup> s<sup>-1</sup> and Meade et al. (1990) also report that flood pollen is well mixed. Assuming this is the case, then we can define the fluvial pollen and spore load as being the combination of several distinct components including the airborne component (directly into the channels from local to regional sources), the riparian component (including leaf drip), the overland flow component, the bank erosion component and river storage in bed-sediments that can be resuspended in floods.

Using the analogy with forest gaps and lakes (Jacobson and Bradshaw, 1981) for rivers under 30 m wide, the significant terms can be reduced to the riparian, overland flow (especially into tributaries), bank erosion and river storage components. However, there is little data on the relative input of these components and the sampling strategy employed in this study was designed to allow some quantification of these different input sources.

## 2. Study site information

The site chosen for this study was the Exe Basin in SW England (Fig. 1). The River Exe drains an area of 1530 km<sup>2</sup>; its source rises at Exe Head on Dure Down, Exmoor (SS 752 415) and flows 87.2 km west and south

until it reaches the Exe Estuary at Exmouth. The Exe catchment was chosen for this study because it exhibits considerable and systematic diversity with regards to vegetation cover, hydrological regimes and climatic conditions (Walling and Moorehead, 1987). Thirteen sub-catchments were monitored (data from 9 is used here) in order to sample this variety. Within the Exe catchment there is an established hydrometric monitoring network operated by the University of Exeter and the Environment Agency, providing suitable monitoring data along with the availability of meteorological data supplied by the British Atmospheric Data Centre. Finally, the Exe catchment has been extensively studied and there is consequently a large amount of literature relating to catchment sediment dynamics (for example, Walling and Webb, 1981; Walling and Woodward, 1993; Walling et al., 1993; Walling and He, 1994; Nicholas and Walling, 1995; Collins et al., 1997a,b; Blake et al., 2002; Collins and Walling, 2002). The geology of the catchment is dominated by Devonian sandstones, slates and conglomerates in the north, and Carboniferous sandstones, conglomerates and mudstones in the middle and south and one area of Cretaceous Upper greensand in the east. The catchment lay outside the maximum Pleistocene glacial limits and has a well-developed strath terrace staircase and basin and gorge type floodplain. The relative relief of the catchment is 519 m and slopes are steepest in the headwaters. The average slope angle is 17° (Webb, 1980) but with considerable variation in the sub-catchments (Table 1). The catchment has a mean annual precipitation of 1097 mm but this also varies in the sub-catchments from 900 to 3262 mm yr<sup>-1</sup> (Table 1). The mean daily flow at Thorverton is 9 m<sup>3</sup> s<sup>-1</sup> with 0.01 probability of exceedence flow being 90 m<sup>3</sup> s<sup>-1</sup> and the 0.99 probability being 1.4 m<sup>3</sup> s<sup>-1</sup>. Vegetation cover and land use was extracted from the Land Cover Map of Great Britain (1990) produced from Landsat Thematic Data (Fuller et al., 1994). Little land use change has

Table 2  
Simplified land cover and associated pollen taxa

Simplified land cover class	Associated pollen taxa
Disturbed ground	<i>Papaver rhoeas</i> -type, Chenopodiaceae, <i>Urtica</i> -type, <i>Hypericum perforatum</i> -type, Brassicaceae, Apiaceae, Lamiaceae undiff., <i>Mentha</i> -type, <i>Scrophularia</i> -type, <i>Rhinanthus</i> , <i>Valeriana officinalis</i> , <i>Arctium</i> -type, <i>Artemisia</i> -type.
Pasture	<i>Ranunculus</i> , Caryophyllaceae, <i>Polygonum</i> , <i>Rumex acetosella</i> , <i>Rumex acetosa</i> , <i>Umbilicus rupestris</i> -type, <i>Potentilla</i> -type, <i>Astragalus danicus</i> -type, <i>Lotus</i> , <i>Medicago sativa</i> , <i>Trifolium</i> -type, <i>Gentianella campestris</i> -type, <i>Plantago lanceolata</i> , <i>Digitalis purpurea</i> -type, <i>Scabiosa columbaria</i> , <i>Cirsium</i> -type, <i>Centaurea nigra</i> , Lactuceae, <i>Solidago virgaurea</i> -type, <i>Aster</i> -type, Poaceae undiff.
Marsh	<i>Sphagnum</i> , <i>Caltha palustris</i> -type, <i>Persicaria bistorta</i> -type, <i>Montia fontana</i> , <i>Filipendula</i> , <i>Gentiana</i> -type, <i>Valeriana dioica</i> , <i>Succisa pretensis</i> , Cyperaceae undiff.
Heath/Moorland Bracken	<i>Lycopodium</i> , <i>Juniperus communis</i> , <i>Betula</i> , <i>Vaccinium</i> -type, <i>Calluna vulgaris</i> , <i>Ulex</i> -type. <i>Pteridium aquilinum</i> .
Deciduous woodland	Pteropsida monoete undiff., <i>Polypodium</i> , <i>Dryopteris</i> -type, <i>Ulmus</i> , <i>Juglans regia</i> , <i>Fagus sylvatica</i> , <i>Quercus</i> , <i>Alnus glutinosa</i> , <i>Corylus avellana</i> -type, <i>Tilia cordata</i> , <i>Populus</i> , <i>Salix</i> , <i>Rhododendron ponticum</i> , <i>Ribes</i> , <i>Rubus</i> , <i>Rosa</i> , <i>Sorbus</i> -type, <i>Ilex aquifolium</i> , <i>Acer campestre</i> , <i>Hedera helix</i> , <i>Fraxinus excelsior</i> , <i>Sambucus</i> .
Coniferous woodland	<i>Abies</i> , <i>Picea</i> , <i>Pinus sylvestris</i> .
Arable	<i>Avena</i> -type, <i>Hordeum</i> -type, <i>Secale cereale</i> , <i>Zea mays</i> .

occurred during the intervening years due to physical limitations and conservation controls on agriculture in the area and this allowed the land use in each of the sub-catchments to be quantified from the predominantly pasture and heathland (sub-catchments 1–3), predominantly pasture and deciduous woodland (sub-catchments 4 and 6), predominantly pasture and arable (catchments 5 and 7) and predominantly arable cultivation (catchments 8 and 9).

### 3. Field, laboratory and modelling methods

Peak flow samples were taken from the outlet of each of the sub-catchments during floods over a period of 24 months. In addition background low flow samples were collected and at two stations samples were taken through storm events (hydrograph samples). Samples were taken either using a submersible pump and portable generator or by hand from the middle of the river at an approximate height of 0.6× the maximum river depth. This was done in order to ensure that the water was fully mixed and avoided the problem of surface water assemblages being biased towards more buoyant and unsaturated pollen grains (Hopkins, 1950; Traverse and Ginsburg, 1966; Traverse, 1988). This assumption was also tested by sampling a depth profile at an intermediate flow (see Results). The volume of water samples was varied depending upon the suspended sediment concentration from as much as 10 l at sites with low concentrations (e.g. catchment 1, Lyshwell Farm) to only 2 l (Catchment 9, Pyne Cottage).

In addition samples were taken of the bed sediment in a pool and riffle using a 1 m high steel cylinder pushed into the bed and the water agitated before sampling

(Lambert and Walling, 1988). This sediment re-suspension technique was adopted in order to sample the pollen which could be re-suspended during a flood event. Eight samples were also taken from an actively eroding riverbank in the Bickleigh reach of the River Dart (sub-catchment 6). All the water samples were filtered (some after centrifugation at 2500 rpm for 10 min) using glass fibre Whatman filters (GF/A) with a pore size of 1.6 µm. The filters were then oven-dried and the suspended sediment weight recorded before they were subjected to a standard chemical processing using hydrofluoric acid digestion followed by acetolysis. Pollen concentrations were determined by the addition of *Lycopodium clavatum* tablets containing a known number of spores (Stockmarr, 1971). Pollen identification routinely used ×400 magnification with ×1000 magnification for small and difficult types with reference to standard keys (Andrew, 1984; Faegri and Iversen, 1989; Moore et al., 1991) and the Exeter University Pollen and Spore reference collection. Pollen and spore nomenclature follows Bennett et al. (1994). Pollen preservation was recorded using a three-fold classification adapted from Delcourt and Delcourt (1980); corroded, degraded and mechanically damaged. Where more than one form of degradation was present only the most developed was recorded.

At each of the sub-catchment sampling stations airborne pollen flux was also monitored using a modified Tauber trap (Tauber, 1974; Hicks and Hyvärinen, 1986) with a central aperture of 5 cm diameter and sloping collar of 15 cm diameter. The traps were located in an open area of at least 30 m in diameter. Two traps were located adjacent to each stream sampling location, the results averaged and the traps were emptied after each rainfall



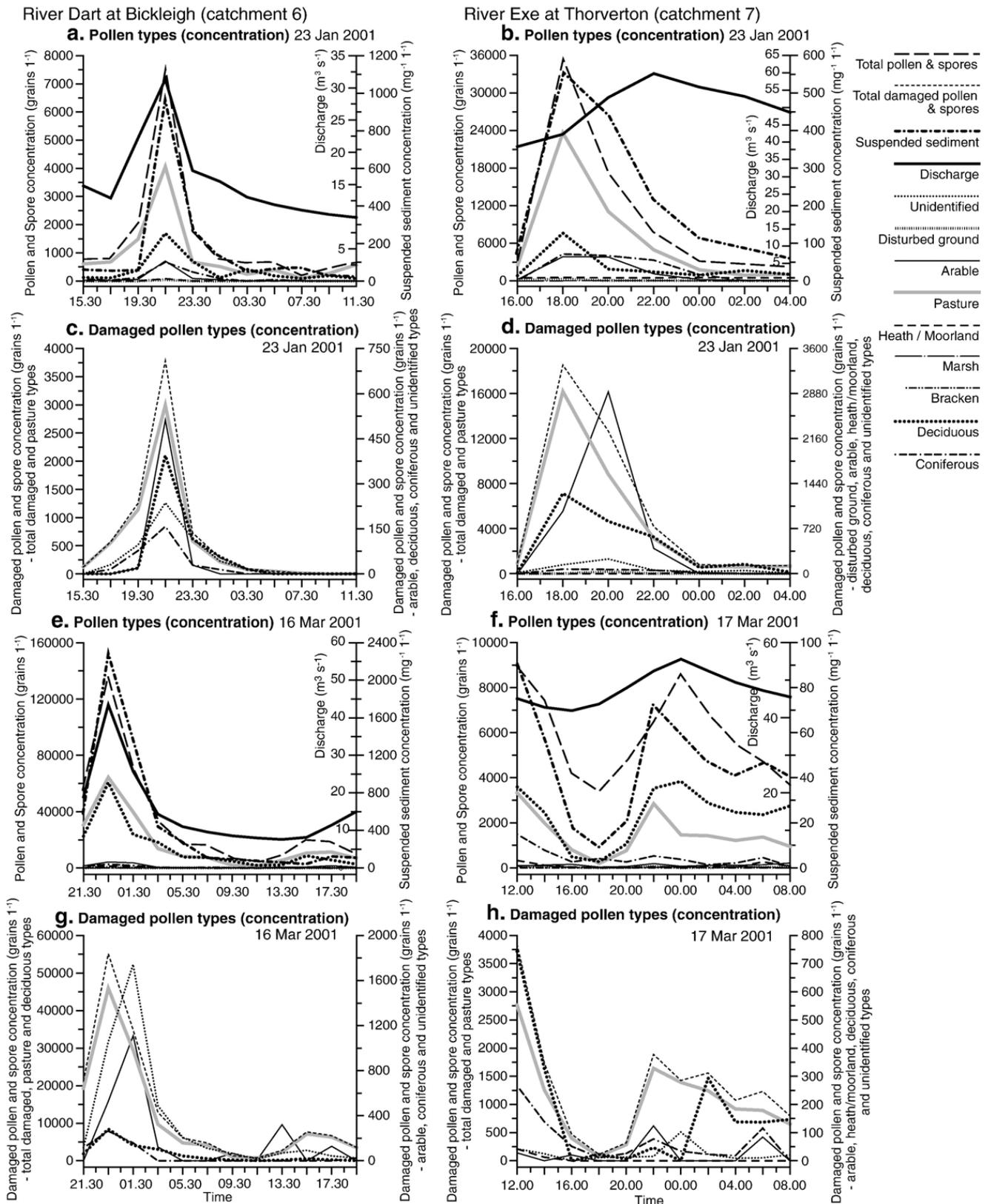


Fig. 3.

event or in dry periods each month. The traps were not meshed and the samples were processed in the same manner as the water and bank samples.

In order to be able to compare the pollen data with the land use data it was necessary to convert the pollen and spore data into 8 vegetation/land use classes (Table 2).

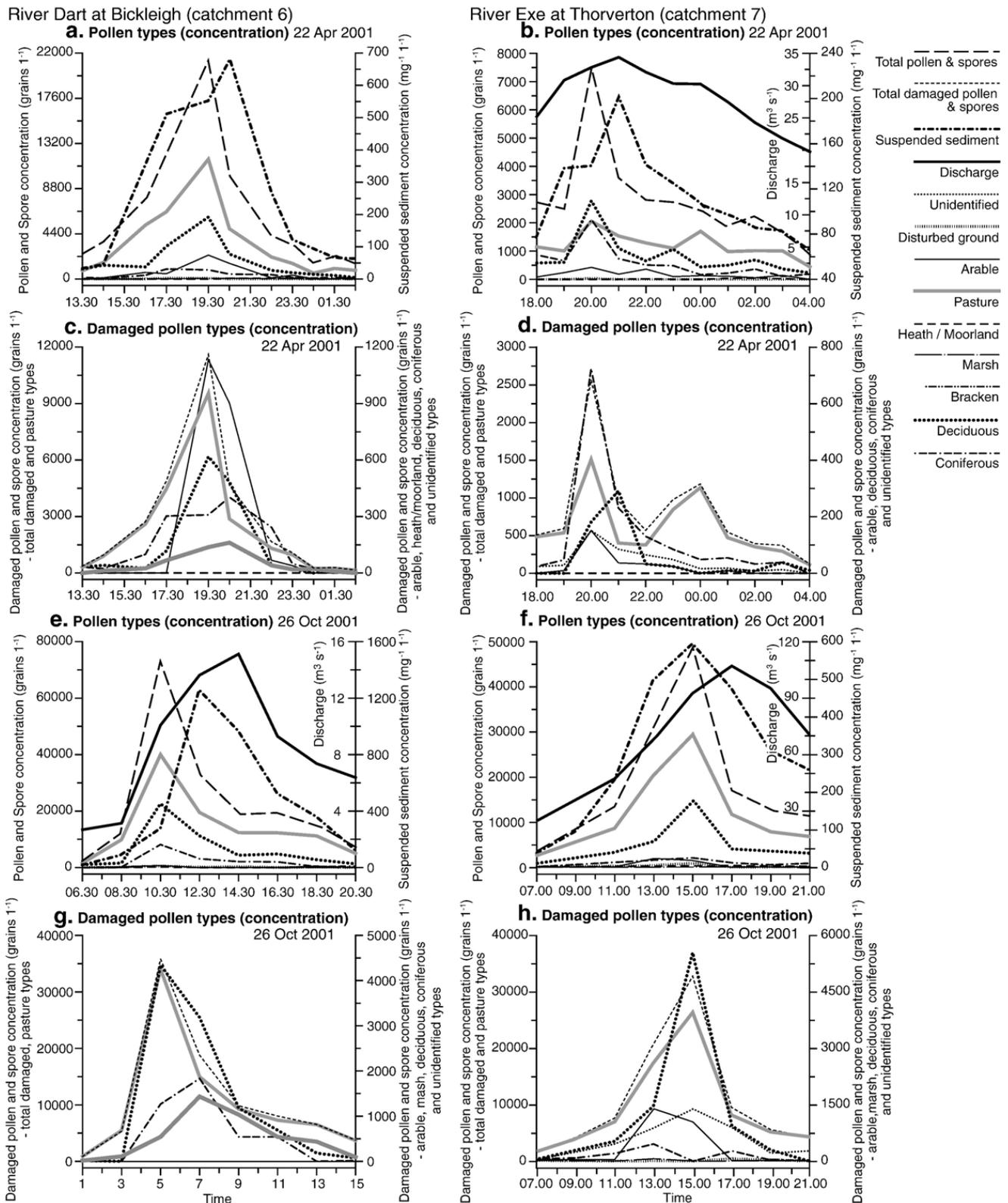


Fig. 4.

This is problematic due to problems of taxonomic precision but was done using the ecology of the dominant species in each of the pollen types *sensu* Bennett et al.

(1994). There are clearly some species of a different ecology within these groups but the overwhelming majority in pollen-producing terms will have been derived

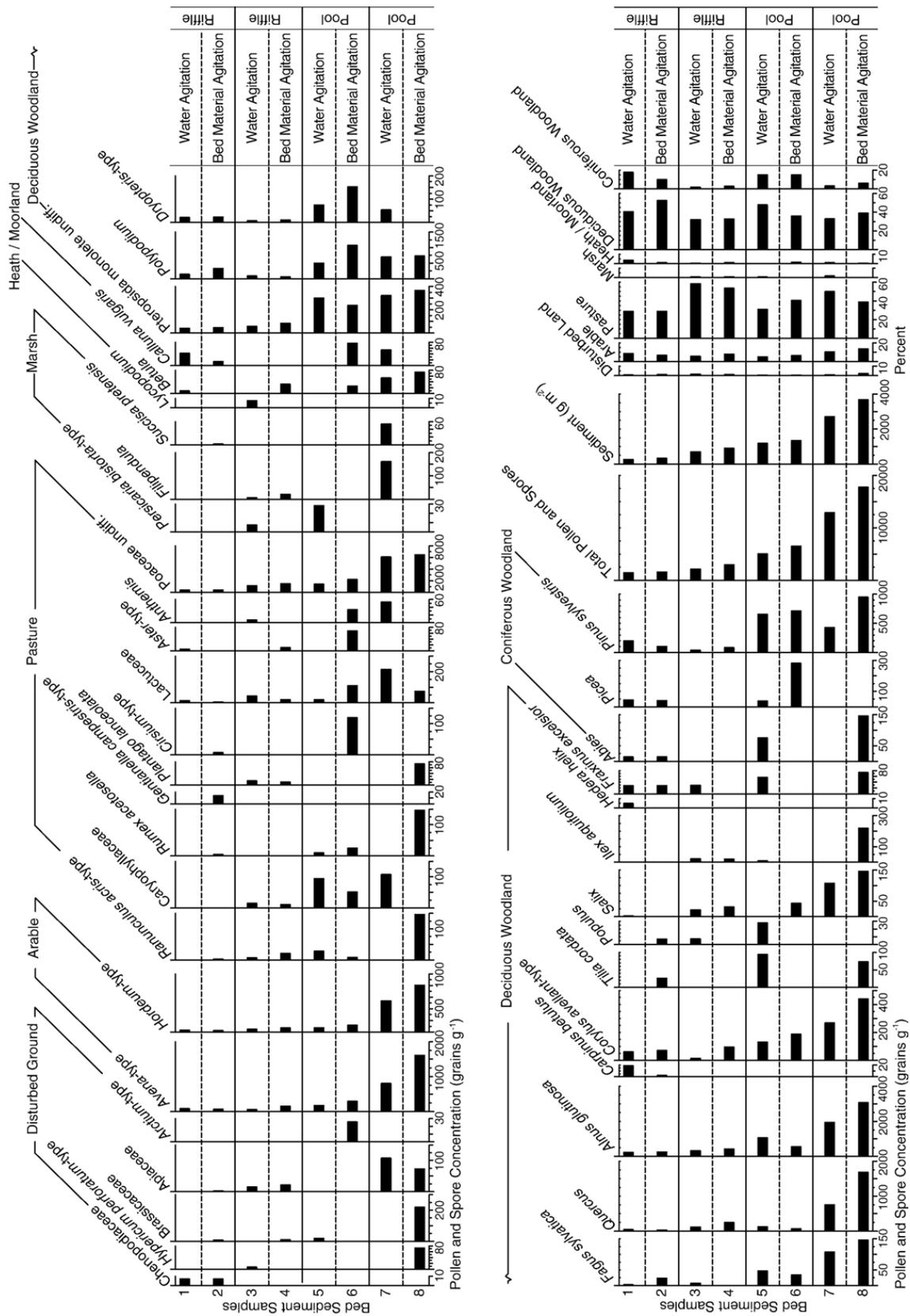


Fig. 5.

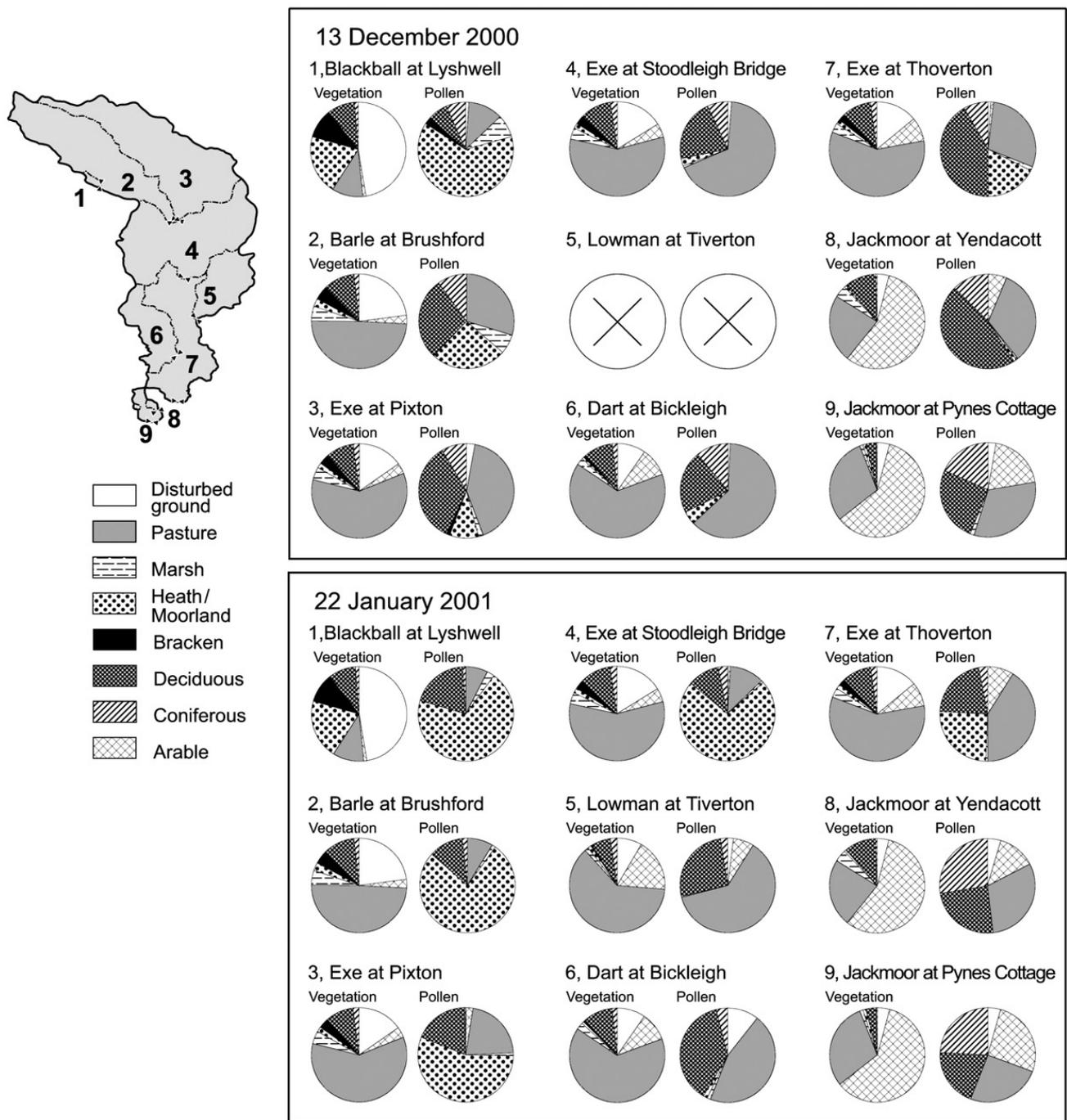


Fig. 6.

from that vegetation type (e.g. *Ranunculus* includes aquatic species but the vast majority of pollen will be from pasture species). The scenario modeling was undertaken by using the monitored fluvial pollen output for a sub-catchment and repeating it for several annual cycles and then substituting another sub-catchment with a different land use and repeating the procedure. In effect, it is an application of the ergodic approach (space for time substitution) using the monitored data in order to estimate

what the effect of a land use change might be on the fluvial input to a lake or near-shore marine sediments.

#### 4. Results

##### 4.1. Pollen and spore hydrographs

Sampling of the vertical water profile (Fig. 2) showed the pollen and spores to be well mixed but with a distinctly

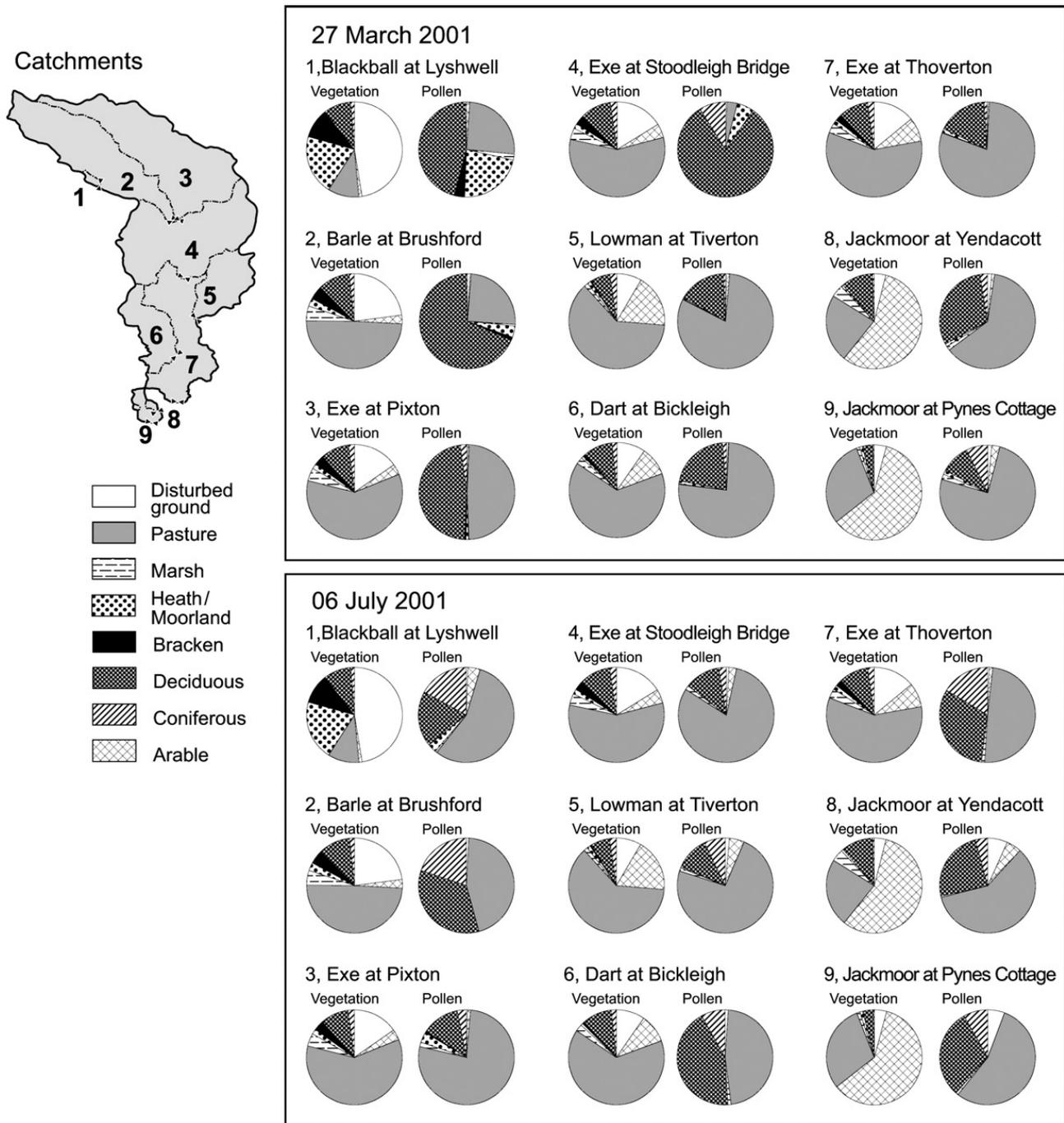


Fig. 7.

higher concentration (50%–20%) at the water surface (Brown et al., in press). This has been reported by Traverse and Ginsburg (1966) and Traverse (1988) who regard it as a function of the saturation time of airborne inputs. Starling and Crowder (1981) also observed significantly higher concentrations of pollen towards the surface of the Salmon River a phenomena also reported by Smimov et al. (1996) who observed a high degree of variation within the vertical profile (600–2300 grains l<sup>-1</sup>) with the highest concentrations of *Pinus* and *Salix* occurring at the surface. Smimov

et al. (1996) suggests that this high surface concentration is due to input from riparian vegetation. However, as Brush and Brush (1972) had already shown once saturated transport is mixed and unsorted.

Sampling through floods at Bickleigh and Thorverton confirm the dramatic increase in pollen and spore concentration through the flood hydrograph with peak concentrations at Bickleigh reaching 7000 grains l<sup>-1</sup> even on January 23rd 2001 (Fig. 3) and coincident with the peak in discharge and suspended sediment. At Thorverton

peak concentration are even higher for the same event reaching 35,000 grains  $l^{-1}$  coincident with the peak in suspended sediment but preceding the peak discharge (Fig. 3). Damaged grains show a similar trend but with the second highest concentration being of arable types which at Thorverton is lagged behind the other types. These concentrations are too high to simply be derived from the channel bed and banks and so indicate pollen being washed in from other sources such as overland flow into tributaries and drains as well as some riparian wash-off. Unsurprisingly spring hydrographs show even higher concentrations reaching 150,000 grains  $l^{-1}$  at Bickleigh but only 7000 grains  $l^{-1}$  at Thorverton (Fig. 4) probably due to the location of the storm over the Dart Catchment. Arable types are again disproportionately high. In April, peak concentrations reach 22,000 grains  $l^{-1}$  with damaged arable types alone reaching 11,000 grains  $l^{-1}$  (Fig. 5). Autumn hydrographs (Fig. 6) show a fall in peak concentrations to 7000 grains  $l^{-1}$  and 50,000 grains  $l^{-1}$  and arable types, both undamaged and damaged become proportionately less important whilst deciduous types become more important.

The relatively high proportion of damaged grains, and particularly those of the arable group is echoed in the river bed samples (Fig. 7). These show that even in the Dart sub-catchment which is predominantly pasture and woodland *Avena* type is the second highest after

Poaceae reaching over 1500 grains  $g^{-1}$ . Nearly all of these grains were broken, crumpled or degraded providing a potential signature of this pollen component. This is an important potential store of pollen and is probably the source for much of the degraded pollen observed in the flood samples.

## 5. Flood and low flow comparisons

The monitoring of pollen and spore concentrations during both low flow and floods at Thorverton and constant measurement of discharge has allowed an estimate to be made of the total pollen and spore loading at low flows (<95% flow duration) and floods (5% flow duration) leaving the majority of the basin (Table 3). As Table 3 shows that, for 9 out of the 12 months (November 2000–October 2001), the flood load exceeded the low flow load. Additionally in the months January–June the flood loading was 15–23× that of the low flow. The result is that over the year the flood flows carried 91% of the total pollen and spores that left the upper and middle Exe catchment.

## 6. Sub-catchment flood samples and vegetation

Samples taken at a flood peak on the 13th of December 2000 show significant inter-catchment variations (Fig. 8A) which in general reflect the sub-catchment variation. The upper pasture and heath dominated sub-catchments show large relative proportions for pasture and heath. The correspondence for the middle pasture dominated catchments (4 and 6) is particularly strong and the high arable land use of the lower catchments is reflected in the pollen and spore proportions. However, there are differences and most notably exaggerations in the pollen and spore proportions (in relation to the percentage of land use in each catchment) particularly of heathland and deciduous in catchments 2 and 3, heathland in catchment 1 as well as underestimates such as the arable types in all sub-catchments even though the values are extremely high in comparison to most pollen diagrams at 10%–20% total land pollen. Very similar results were derived from a flood on 22nd January 2001 (Fig. 8B) with even greater exaggeration of heathland and arable reaching 25% in sub-catchment 9. A particular feature of this storm is the peak in *Calluna* from the Blackball sub-catchment (1) which reached a concentration of 7241 grains  $l^{-1}$  at Lyshwell Farm which was 66% of the total concentration. Even at the lowest monitoring station at Thorverton this *Calluna* flush still made up 25% of the total basin output. By March 2001, the situation had changed with a universal over-representation of deciduous types due largely to the

Table 3  
The low flow (95% duration) and high flow (5% duration) pollen loads calculated for Thorverton from November 2000 to October 2001 in grains  $\times 10^{12}$

Month	Total flood flow pollen and spore loading ( $\times 10^{12}$ grains)	Total low flow pollen and spore loading ( $\times 10^{12}$ grains)	Total monthly pollen and spore load ( $\times 10^{12}$ grains)
November 2000	13.195	17.168	30.363
December 2000	6.021	5.602	11.624
January 2001	135.112	9.824	144.937
February 2001	233.882	19.733	253.616
March 2001	139.257	6.931	146.188
April 2001	46.888	2.081	48.969
May 2001	21.767	1.132	22.900
June 2001	6.986	1.274	8.261
July 2001	0.777	6.931	7.708
August 2001	19.887	2.002	21.889
September 2001	6.330	0.463	6.794
October 2001	258.483	14.379	272.862
Total 2000–2001	888.591	87.525	976.117

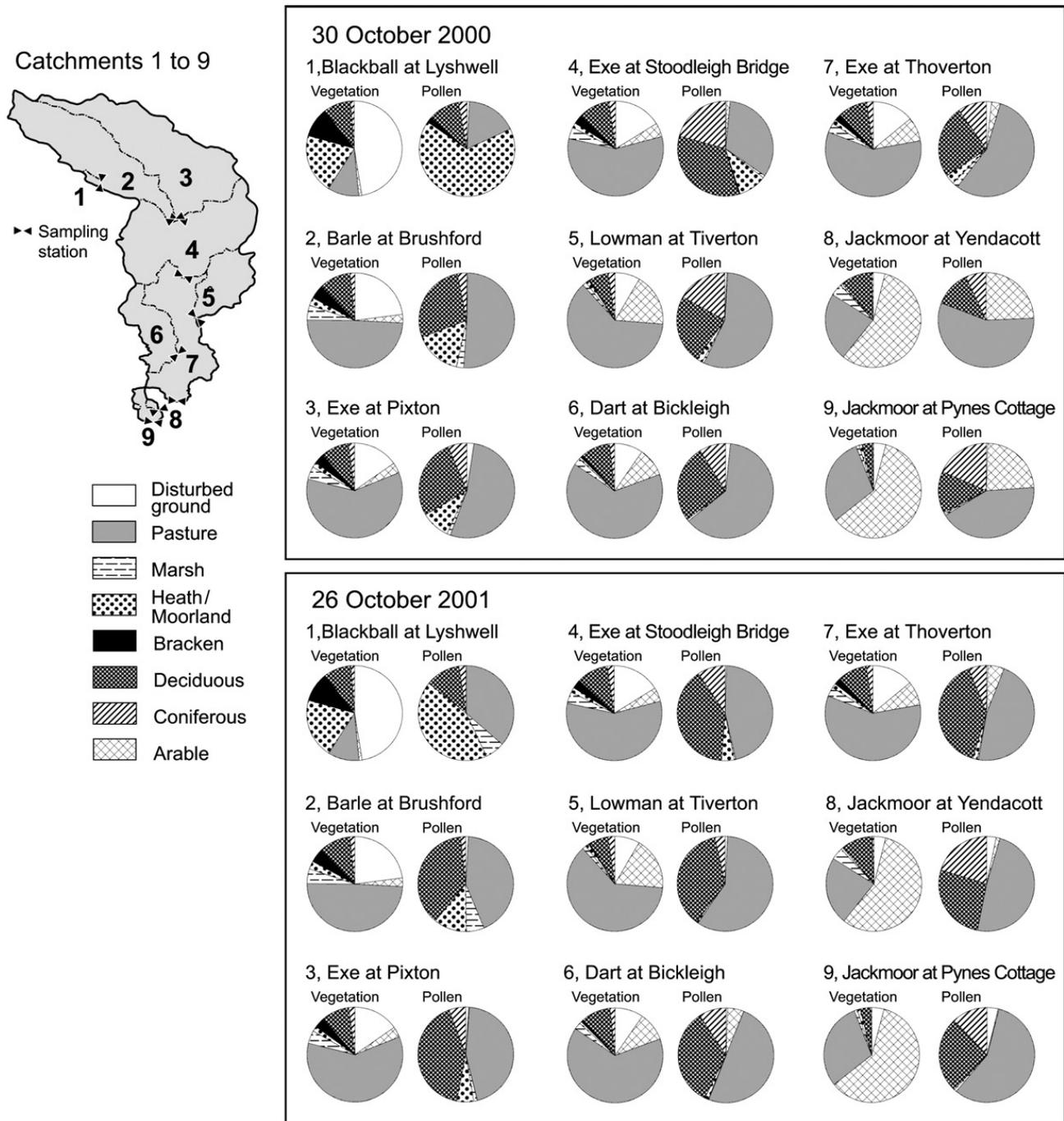


Fig. 8.

flowering of *Alnus*. By the end of March, this effect had largely been replaced by the increase in pasture types due to the beginning of flowering of *Poaceae* spp. (Fig. 9A). This rise in pasture types occurs in the upper sub-catchments by July (Fig. 9B) when overall the pollen and spore representation is very similar to the relative proportions of land use classes with the exception of an under-representation of types characteristic of disturbed ground. This remains true in October 2000 and October 2001 (Fig. 10) although there are individual variations

such as a very high flux of heath types from catchment 1 and high representation from the other headwater sub-catchments (2 and 3). Overall these results show that the major control on the sub-catchment pollen and spore waterborne output is the spatial pattern of land use, however, that there are also very strong seasonal effects.

These peak values have been cumulated and can be compared with the airborne annual assemblage from Bickleigh (Fig. 11). As can be seen there is an under-representation in some herb types (e.g. Brassicaceae and

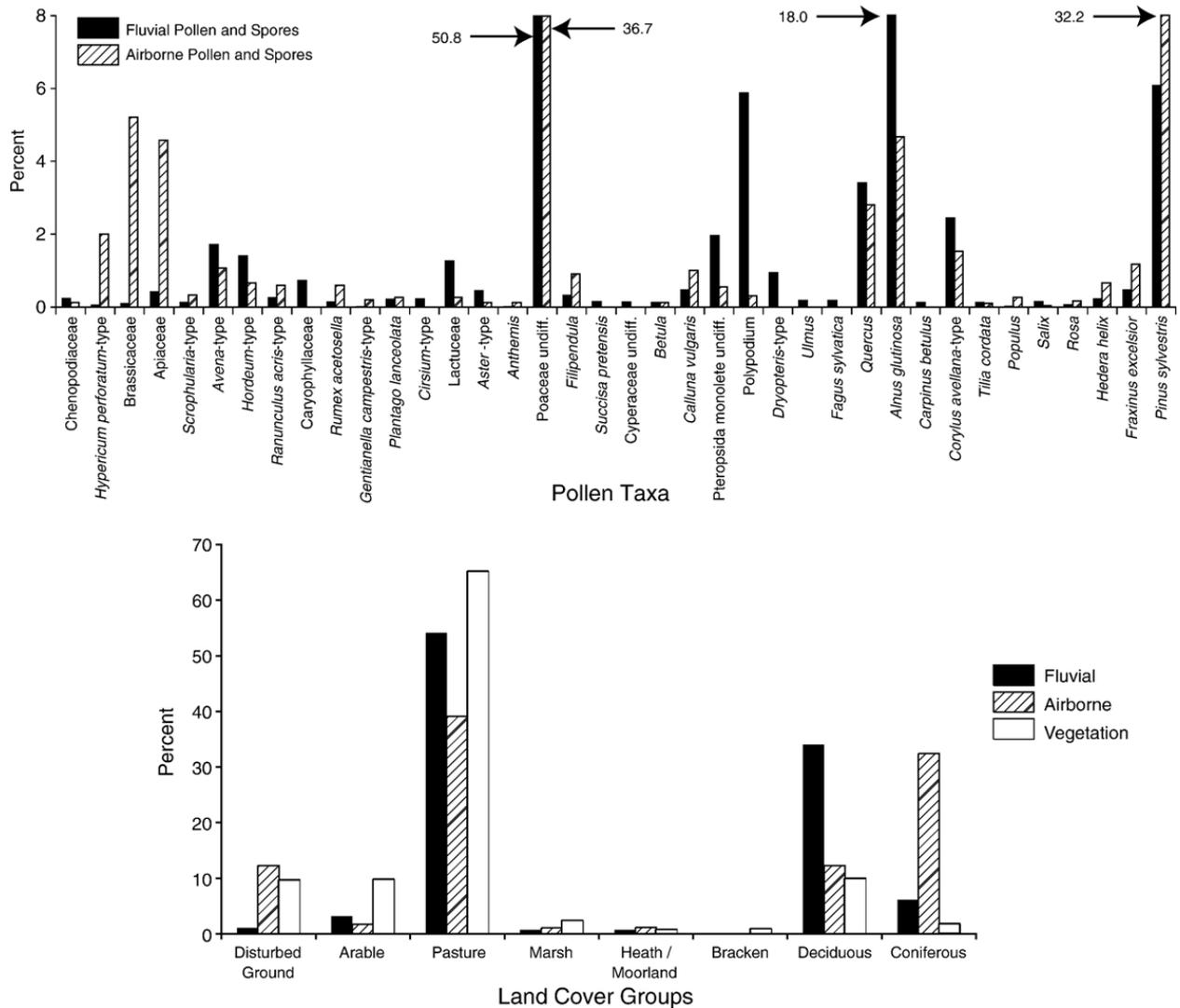


Fig. 9.

Apiaceae) and most notably *Pinus*, but an over-representation in arable types (e.g. *Avena* type), Poaceae, fern spores and most notably *Alnus*. Given the coincident location of the airborne traps and the stream sampling locations, it is suggested that this represents the different pollen and spore sources with greater importance of riparian vegetation, pasture adjacent to river courses and the contribution from the bed sediment store. However, it is also true that overall the waterborne pollen and spore values are a closer approximation of the catchment land use for arable, pasture, and coniferous classes but a poorer representation for disturbed ground, marsh, heath, and deciduous.

**7. Discussion and scenario modelling**

For lakes and marine sites where waterborne pollen is the major influx it follows that the assemblage must be

constructed from a series of storm input spectra, which may or may not be blurred depending upon the water-bed sediment conditions. In order to try and predict the possible effects of land use changes on a fluvially derived assemblage, a modelling experiment was conducted. The monitoring produced data from between 15 and 20 flood events depending upon the sub-catchment. These data were used to cumulate steady state diagrams representing a cycle of 17 months for each of the sub-catchments. This was done by simply repeating the monitored flood series from the sub-catchment of interest and ignoring the low flow contribution. A change in land use was simulated by the substitution of one sub-catchment for another as indicated by the change in zones. Since the same underlying hydrological structure exists within the sub-catchment data, this experiment only simulates a change in land use. Two scenarios were simulated (Fig. 10) and what is immediately noticeable is the high level to level

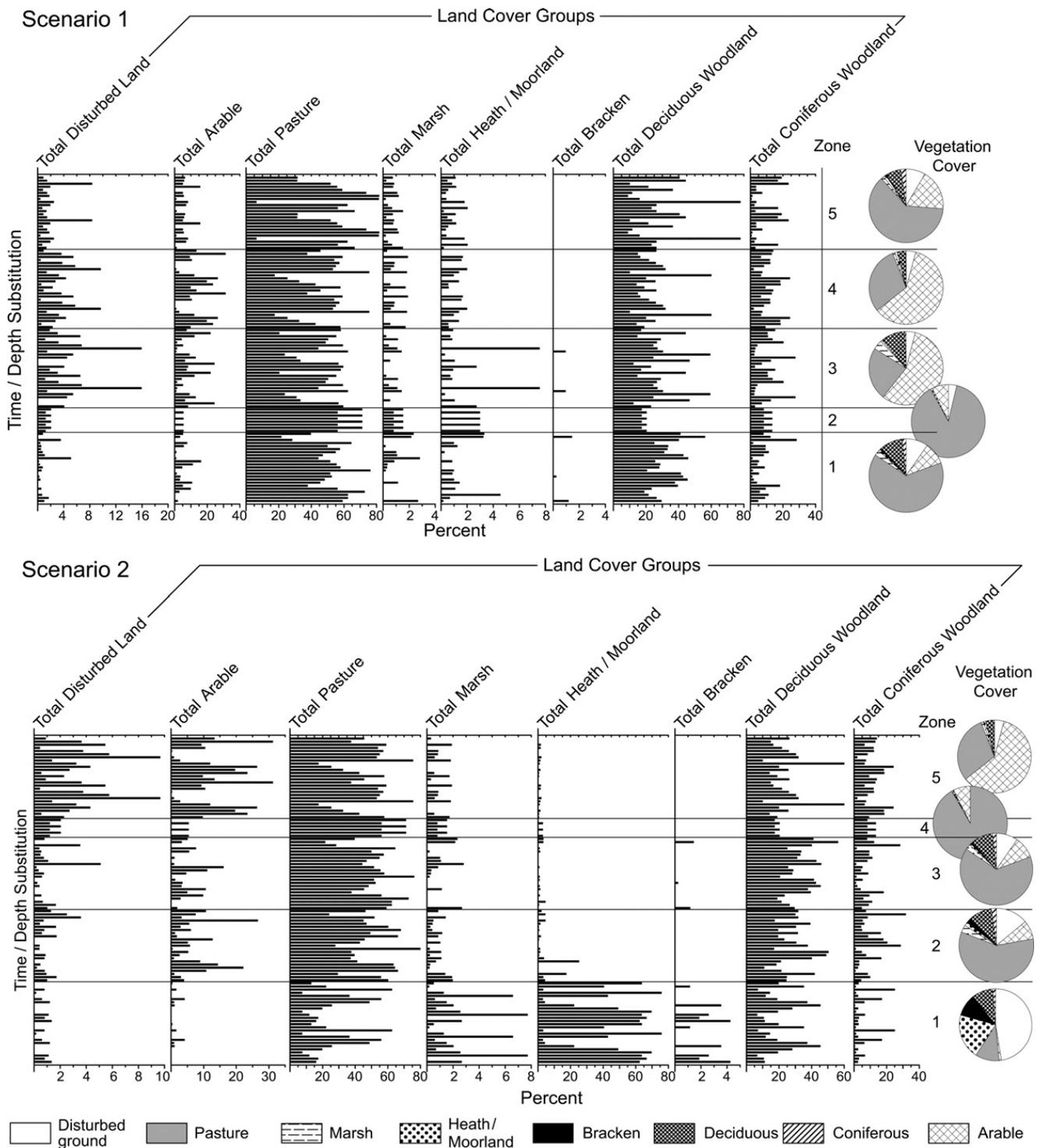


Fig. 10.

variation in all values. This is due to there being no mixing included in the model. This is directly comparable to some high-resolution pollen and spore diagrams from varved or laminated lake sediments which typically show these high-frequency fluctuations in values (e.g. Coard et al., 1983; Kerig and Lechterbeck, 2004). However, despite this high inter-level variation, the overall response of the

assemblage is dampened in comparison with the dramatic changes in land cover. This accords with the general dampened response of many lake diagrams to human impact (Brown et al., 2005), particularly if land use classes have been used. What is also evident is particular artefacts, such as the single high peaks in heath, deciduous, marsh and arable types. These are all caused

by seasonally related high influxes of particular pollen types such as *Calluna/Erica*, *Alnus* and *Avena* type.

Many floodplain or alluvial wetland pollen and spore diagrams also show anomalous peaks especially in close proximity to changes in lithology which is caused by hydrological change. Examples are peaks associated with discrete flood layers (e.g. Brown, 1988). Another example can be seen from Slapton Ley in Devon, England, where an alluvial pollen diagram shows a pronounced peak in *Alnus* prior to a dramatic influx of overbank sedimentation which coincided with an increase in damaged grains and arable indicators (Foster et al., 2000). In this case, the authors could link this alluviation directly to the combined effect of intense arable cultivation and climatic change and do not implicate any increase in the extent of alder woodland. Whilst stratigraphic changes in through-flow lake and alluvial sequences may mark changes in vegetation due to climate change or human impact they also are likely to represent a change in the pollen and spore source area and the ratio of airborne to waterborne pollen. In this respect, the strong relationship of waterborne pollen to catchment vegetation is beneficial as it can accentuate the effects of local environmental change. The frequency of corroded grains within lake sediments has also been associated with catchment disturbance and soil erosion (Wilshurt and McGlone, 2005a,b) and the results of this study support this association.

The results of this catchment monitoring also have implications for the interpretation of near-shore marine cores which still present difficulties of interpretation (Clark, 1986; Wilshurst et al., 1999; McGlone, 2001). Studies on modern pollen deposition in coastal waters indicate the rapid incorporation of pollen to marine sediments (Chmura and Eisma, 1995). This is probably due to deposition through aggregation or incorporation into faecal pellets of zooplankton, as single-grain settling from suspension would take more than a year and lead to distant transport by marine currents (Mudie and McCarthy, 1994). As a result, pollen and spore concentrations increase with proximity to large fluvial inputs and within confined seas with high fluvial input discharges. An example is the eastern Mediterranean and Black Sea where there is a strong link between surface pollen concentrations and salinity with a minima of 5 grains  $g^{-1}$  in the Eastern Mediterranean and a maxima of 160,000 grains  $g^{-1}$  in the Black Sea (Sanchez Goni et al., 2002; Mudie et al., 2002). The high pollen and spore concentrations in deep-sea sediment cores but with high fluvial inputs, such as off the western Iberian coast, can provide waterborne pollen diagrams which can be used to infer vegetation

change over large areas which track millennial-scale climate change (Baas et al., 1997; Roucoux et al., 2001).

## 8. Conclusions

This large-scale monitoring of fluvial pollen and spore waterborne transport has confirmed a number of previous conclusions derived from the limited monitoring of single sites. Firstly, that the pollen and spore water depth profile is generally uniform indicating full mixing, except for a surface enhancement effect. Secondly that the vast majority of fluvial input in temperate basins occurs during flood events and thirdly that the overall variation of fluvial input is controlled by catchment variation. However, this study has gone on to show that there are very strong seasonal effects causing both over and under-representation of catchment vegetation in the fluvial output. These reflect the pathways of pollen transport into rivers particularly direct input probably via leaf-drip of riparian vegetation, overland flow in autumn and winter, and bed sediment re-suspension. A particularly important finding is the high storage in river pool sediments of arable pollen grains and particularly damaged arable pollen grains. The exact cause of this is unknown but it may be due to the greater settling velocity of these large grains on the declining limb of winter–spring hydrographs in areas of high arable cultivation. Scenario modelling of event-cumulated curves for land-use change has shown several characteristics that can be seen in lake pollen and spore diagrams. These include the greater inter-level variability of varved sediment diagrams than non-varved diagrams, the overall dampened response of pollen and spore classes, and the occurrence of anomalous peaks in types caused by season dependant flushes from vegetation with good connectivity to river courses. However, this data also shows that it is the closer similarity of the waterborne pollen than the airborne pollen to catchment vegetation that is the cause of strong correspondence between small lakes with significant stream inputs with their catchment vegetation cover. Future work could develop these relationships in a quantitative fashion following a similar modelling approach to that for the airborne component (Prentice, 1985, 1986, 1988; Prentice and Parsons, 1983; Sugita et al., 1999; Fyfe, 2006; Caseldine and Fyfe, 2006) with the hope of improving the accuracy of pollen based vegetation reconstructions from lakes and marine sediments with substantial fluvial inputs.

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