INSTITUTE OF TERRESTRIAL ECOLOGY
(NATURAL ENVIRONMENT RESEARCH COUNCIL)

DEN/NERC CONTRACT CR20/D4/03
ITE PROJECT 640

# THE YIELD, DEVELOPMENT AND CHEMICAL COMPOSITION OF SOME FAST-GROWING INDIGENOUS AND NATURALISED BRITISH PLANT SPECIES IN RELATION TO MANAGEMENT AS ENERGY CROPS

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June 1981

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## SUMMARY

1 This report discusses the 'energy crop' potential of many species of tall herbaceous plants in Great Britain. Detailed accounts of seasonal dry matter production and chemical composition are presented.

2 Many natural stands of widely distributed species could be harvested immediately as opportunity energy crops to give between 6.5 and 12.5 tonnes $ha^{-1}$. Much larger yields (up to 37.5 tonnes $ha^{-1}$) have been recorded for other, less widespread, species that might succeed if planted and managed as dedicated energy crops.

3 In most locations, opportunity and dedicated energy crops of natural vegetation seem able to give dry matter yields comparable to those of conventional agricultural crops and trees; on poor land, they often yield more than many conventional crops growing on 'good' land with regular applications of fertilizers. Thus, natural vegetation seems to contain some species which have potential as renewable sources of energy.

4 Stands of bracken (*Pteridium aquilinum*), which cover more than [illegible] $km^2$ of Great Britain, could be managed for energy in one of 2 ways:

4.1 Fronds, and possibly rhizomes, could be harvested when standing crops are maximal, in a programme aimed to improve rough grazing by eradicating bracken. The biofuels produced, with dry matter yields of 8.0 to 9.0 tonnes $ha^{-1}$, would have a positive value in contrast to the current cost of eradication of about £120 $ha^{-1}$. Fronds harvested when standing crops are maximal would be decomposed rapidly in anaerobic digestors because they contain large concentrations of carbohydrates.

4.2 Bracken fronds could be harvested when senescent. In this instance, the stands of bracken might be maintained indefinitely as opportunity energy crops. This option would not significantly affect the amenity and wildlife value of bracken land. In fact, in some areas, it would be an extension of the traditional practice of cutting senescent bracken fronds for bedding. Autumn harvests of senescent fronds would be larger (4.6 to 8.0 tonnes $ha^{-1}$) than those achieved by eradicating bracken and promoting rough grazing. Because amounts of nutrients in senescent foliage are small, the need for applications of artificial fertilizers would be minimal.

5 Butterbur (*Petasites hybridus*) would be harvested to give maximal standing crop yields of 8.2 tonnes $ha^{-1}$. It cannot be harvested when senescent as its shoots quickly collapse at the end of the growing season. Although butterbur currently covers only 33.5 $km^2$ of Great Britain, it could be maintained as an opportunity energy crop. It contains about 35% dry weight of soluble carbohydrates and would provide a good substrate for anaerboic digestion. Fertilizer applications would be required to replace nutrients removed when biomass is harvested and yields may increase with increasing amounts of fertilizer.

6 Cord-grass (*Spartina anglica*), which occurs in saltmarshes, could be harvested when green, yielding between 3.1 and 16.8 tonnes $ha^{-1}$, or when senescent, yielding between 4.0 and 11.4 tonnes $ha^{-1}$. Like bracken, green biomass would be converted by anaerobic digestion whereas senescent material would probably be converted thermally. Both harvesting strategies are feasible; the choice would depend upon the type of fuel required and/or the necessity to control the spread of this invasive species. Neither harvesting procedure is likely to impair re-growth as nutrient losses are replaced by tidal inundations. Cord-grass, which occupies 120 $km^2$ of British salt marshes, seems to be an opportunity energy crop of high potential.

7 Japanese knotweed (*Polygonum cuspidatum*) and the closely-related *P. sachalinense* have the potential to yield 9.8 to possibly 37.5 tonnes $ha^{-1}$ of dried green-tops or, at least, 5 tonnes $ha^{-1}$ when senescent. Neither harvesting strategy is likely to impair re-growth even if some rhizomes were harvested. To compensate for losses incurred when harvesting peak standing crops, applications of fertilizer would be within the range currently applied to agricultural crops, whereas applications of N, P and K would be decreased by 90, 93 and 75% respectively if shoots were harvested when senescent. The evidence suggests that *P. cuspidatum* and *P. sachalinense* could be dedicated energy crops of high potential. They could be planted readily on a variety of locations whether good agricultural land, railway embankments, or roadsides (where small stands occur naturally).

8 Policeman's helmet (*Impatiens glandulifera*) is an annual species and could be managed as a dedicated energy crop, and, possibly, an energy catch crop, if its rapid rates of growth were maintained after late planting. Shoots and the small root systems, together give annual yields of 11.4 tonnes $ha^{-1}$. This species would be harvested at peak standing crop, when the soft fleshy tissues with large amounts of proteins and soluble carbohydrates, and little lignin, would decompose rapidly if digested anaerobically.

9 Meadow sweet (*Filipendula ulmaria*) is of marginal interest; its maximal standing crops of shoots are unlikely to exceed 6.5 tonnes $ha^{-1}$, whereas other species capable of growing in its wet habitats are likely to be more productive. Consequently, it seems that meadow sweet would be harvested only if its habitats were being drained and "improved" for other uses. Shoots of meadow sweet harvested at peak standing crop should decompose when subjected to anaerobic digestion even though its foliage contains fewer nutrients than other species. It has relatively large concentrations of holocellulose and lignin (75% of the dry weight).

10 Rosebay willow-herb (*Chamaenerion angustifolium*) could be an important short-term opportunity energy crop if harvested from areas were land use is changing or where more productive energy crops are to be introduced. It currently occupies 138 $km^2$ of the under-utilized land of Great Britain and a yield of 10.6 tonnes $ha^{-1}$ has been recorded. Its green shoots contain 14% by dry weight of soluble carbohydrates and they should decompose rapidly in an anaerobic digestor, with only small amounts of N, P and K being removed from site.

11 Great hairy willow-herb (*Epilobium hirsutum*) and associated plants are very productive, yielding standing crops of 12.9 tonnes ha$^{-1}$ on poor soils and 7.0 tonnes ha$^{-1}$ of dry senescent shoots in autumn. These large yields contain few mineral nutrients - ash amounts to 4.4% of shoot dry weight - and amounts of fertilizer needed to sustain yields are therefore likely to be very small.

12 Stinging nettle (*Urtica dioica*) has potential as a short-term opportunity energy crop; it yields 9.7 tonnes ha$^{-1}$ when harvested green. The species is a weed of agricultural land, covering 331 km$^2$ of Great Britain and herbicides or repeated mowing are used to restrict its spread. If its shoots were harvested when the standing crop was at a maximum, the spread of this weed would be controlled, while at the same time beneficially providing biomass for conversion to fuel.

13 Tentative estimates of the yields of other tall herbs range from 2.6 to 26.7 tonnes ha$^{-1}$. Reed (*Phragmites australis*), yields 7.7 to 26.7 tonnes ha$^{-1}$ and yellow flag (*Iris pseudacorus*) gives 6.3 to 14.8 tonnes ha$^{-1}$.

14 In dedicated energy crops established from 'natural populations of Japanese knotweed, giant hogweed and *Gunnera manicata*, survival was 79%, 23 to 57% and 63% respectively. During the subsequent 2 years, growth rates of Japanese knotweed and giant hogweed increased. The results suggest that it would be feasible to establish monocultures of these 3 species.

RECOMMENDATIONS

1 Large yields have been obtained when harvesting several types of natural vegetation and a variety of introduced plant species. It is now essential to investigate if these yields can be sustained in the longer term when harvested repeatedly.

2 While estimates of productivity of the species sampled on only one occasion can only be tentative at this stage, the large amounts of biomass obtained from reed (*Phragmites australis*) and yellow flag (*Iris pseudacorus*) suggest that these species should not be excluded from further consideration.

3 Because most yields were obtained from plants growing in unfavourable environments and on poor soils, it is probable that relatively large yield increases would be obtained by applying fertilizers. The effects of fertilizers should therefore be examined in detail.

4 Although different populations of a species growing in different habitats have given similar yields, it is still necessary to make detailed investigations of genotype/habitat interactions which might lead to higher yields.

5 The inference made about the suitability of different types of plant material, harvested at different times of the growing season, as feedstock for chemical conversion processes must be verified in pilot chemical conversion units.

6 Because they can be transplanted easily and produce yields competitive with those of conventional crops, species such as Japanese knotweed, giant hogweed and *Gunnera manicata* have potential as dedicated energy crops. Research on monocultures of dedicated energy crops should now be started, studying the effects of dates and rates of planting, of optimal propagule size, and the application of fertilizers. The establishment and yields of multiple species crops should also be investigated.

7 Most of the species studied seem to have potential as opportunity energy crops, ie they could be harvested from their existing habitats, with their 'natural' distribution being extended along railway embankments etc. It is now important to characterise and quantify the habitats available for energy crops, seeking to confirm the provisional estimates obtained with the use of the ITE land classification.

8 Although most of the species studied could be harvested after slightly modifying the machinery currently available, field trials are needed to detect and solve practical problems such as the relation between the extent of maceration and biomass digestibility in anaerobic digestors, and the deterioration of biomass in storage.

## 1 INTRODUCTION

Two recent desk studies (Callaghan *et al.* 1978; Lawson *et al.*) 1980 suggest that the natural vegetation and introduced plant species of Great Britain show considerable potential as renewable sources of energy. This potential results from 2 important features:

- i Natural/semi-natural vegetation is very extensive, covering $8.6 \times 10^6$ ha of land (almost 40% of the rural area) of the UK
- ii Some indigenous and naturalised species show higher yields in uncultivated habitats than many agricultural crops and trees which have been cultivated and supplied with fertilizers.

Using these features, it is possible to construct 2 strategies for managing natural vegetation as a feedstock for fuel production.

### 1.1 Opportunity energy crops

Natural vegetation could be harvested from areas where it presently occurs without significantly affecting traditional uses of the land. An example of such an opportunity energy crop would be heather. Heather moors are currently used mainly for amenity purposes (shooting and walking), and they are burned every 10 to 20 years to enhance the re-generation of young shoots on which grouse feed. If heather was harvested on a similar rotation, a vast area of Great Britain (14 910 $km^2$) could provide $1.5 \times 10^6$ tonnes of dry matter each year for conversion to a fuel without significantly disturbing traditional land use (Lawson *et al.* 1980).

In some situations, land could be managed more efficiently by harvesting plants for fuel rather than "improving" it for agriculture or forestry. Some areas of cord-grass and bracken, for example, are currently sprayed with herbicide either to control the spread of the weeds or, in the case of bracken, to enable the bracken to be replaced by upland pastures. The British Government paid £100 000 in grants towards the eradication of bracken from 1 600 ha of non-crofting land in Scotland in 1978/79 (Lawson *et al.* 1980) and this was only 50% of the cost of a generally unsuccessful process. In terms of dry matter production, however, bracken is a far more productive species than the grasses of upland pastures which farmers are trying to establish.

It is possible that both bracken and cord-grass could be eradicated by an intensive harvesting regime during which the harvested plant material, or biomass, would be available as a source of energy. Once a market has been established for energy feedstocks, farmers etc, would have a financial return during the eradication of their weeds, rather than a financial cost.

On the other hand, it may also be possible to maintain areas of bracken and cord-grass indefintely as opportunity energy crops, if the financial rewards of growing energy crops were sufficiently high, remembering that areas presently covered by cord-grass would have little financial return if cord-grass were eradicated, while upland farming is often highly subsidised by government because of low cost-effectiveness.

Similar arguments can be applied to wet lowlands where the natural vegetation is often more productive than the crops which are introduced after the costly processes of draining etc.

Other areas where natural vegetation could be managed as opportunity energy crops include road-side verges and railway embankments where willow-herbs and knotweed are particularly productive (Callaghan *et al.* 1978). These areas are often mowed to control the growth of the plants, but the subsequent biomass is rarely utilised. This vegetation could be used to produce fuels with harvesting costs only slightly greater than those currently incurred in control measures.

## 1.2 Dedicated energy crops

Although it is probable that energy crops would achieve cost-effectiveness soonest on "waste" land where competition with other land uses is minimal, it is important to consider the energy scenario in which it may become cost-effective to dedicate areas of land - perhaps even good quality agricultural land - to the production of fuel crops (Callaghan *et al.* 1978). In considering this scenario, it is first necessary to maximise the yield of plants on the available land.

This maximisation of yield is a comparatively simple objective in the development of dedicated energy crops, when compared with the parameters on which tree and agricultural crops have been developed, because trees and agricultural crops have been selected and bred for quality, eg timber strength. Sometimes, this selection for quality, eg the development of short-stalked cereal plants, may have resulted in a decrease in over-all productivity.

Some of the plant species native and introduced to this country are highly productive in generally poor environments and often produce more dry matter annually than cultivated species growing in more favourable environments (Callaghan *et al.* 1978). Indeed, the fact that many of these species are noxious weeds shows that they are extremely successful in propagation, establishment and competition with other species. Such species represent a genetic pool from which individuals may be selected to form monocultures either to maximise production on good agricultural land or on poorer uncultivated land. Even though these indigenous and naturalised species already show high productivity, it has been suggested that an increase in production of up to 50% could be possible as a result of selection and application of fertilizers (Cooper pers comm). This management would make these species even more competitive with cultivated species which are probably approaching their upper limits of yield.

Another factor is important in the choice of energy crops: the balance between energy input in crop management and energy output in harvested biomass.

Energy inputs in management arise mainly from planting, applying fertilizers and harvesting. The native and naturalised British plant species which show the greatest potential as energy crops are those which have a perennating system below the soil. Perennial oppportunity energy crops, therefore, have no energy inputs in land cultivation and planting, whereas it may be possible to harvest perennial dedicated energy crops indefinitely after planting on only one occasion. This system contrasts strongly with the annual planting of cereal and root crops, etc, and may involve lower inputs of energy than long-rotation forestry (Callaghan *et al.* 1978).

According to provisional estimates outlined in the 2 desk studies referred to above, opportunity energy crops could give yields of 5 to 15 dry tonnes per hectare per year (t ha$^{-1}$ yr$^{-1}$), while dedicated energy crops developed from native and naturalised British plants such as Japanese knotweed could yield over 20 t ha$^{-1}$ yr$^{-1}$.

## 1.3 Objectives of a field-based assessment of the potential of native and naturalised British plant species as sources of energy

### 1.3.1 Measurement of the productivity of potential energy crops

The potential of native and naturalised plant species as energy crops discussed above is based upon 2 desk studies which collated and reviewed a fragmentary record of productivity values in the literature. Most of these records related to species of upland and other poor environments, and it became apparent that little is known about the productivity of fast growing species in Great Britain, apart from work by Al-Mufti *et al.* (1977). The present study was designed, therefore, to provide data on the yield of tall herbs, and the variation in yield between various geographical locations. However, the potential of plants as energy crops must depend upon factors other than yield alone.

### 1.3.2 Characterisation of the seasonal development of potential energy crops

In order to manage an energy crop, it is essential to understand the way the crop develops throughout a growing season. The pattern of dry weight changes is of particular importance to the optimisation of harvesting time. For example, some species may show a sharp peak of dry weight in mide-season and the time of harvesting will be critical in order to maximise yield. Other species may show prolonged periods of high dry weights allowing the time of harvesting to be flexible.

It is also important to characterise the change in quality of the biomass throughout the growing season, as this will be important in determining the choice of machinery for harvesting and collecting the crop, and the chemical conversion processes required to produce a usable fuel. Water contents, for example, are important in determining the actual weight and texture of material for cutting and transporting, while of paramount importance in determining the suitablility of anaerobic digestion or thermal methods for converting the biomass to fuel.

A knowledge of the chemical content of plant material at the time of harvesting is also important in determining the energy content of the plant material and its suitability for various chemical conversion processes. Of particular importance are the contents of soluble carbohydrates, nitrogen (which is proportional to protein content) and fibre (eg lignin), but the concentrations of theses compounds can only give a rough estimate of the suitability of plant material for conversion to fuel, and are not a substitute for trial coversions.

### 1.3.3 Estimation of the stability of yield

It is obviously important that an energy crop should give high yields year after year. The process of harvesting will affect the subsequent re-growth of the crop mainly by the removal of inorganic and organic nutrients which would normally be re-cycled naturally at the site via translocation, leaching and decomposition. N, P and K are essential for plant growth, and yield is generally very responsive to increased amounts of these elements in the soil. The constant removal of these elements from the site will reduce subsequent yields at a rate dependent upon the size of the available nutrient pools held in the below-ground biomass and soil. It is essential, therefore, that the seasonal contents of these inorganic nutrients are measured in order to estimate the size of the nutrient pools which would be removed from site in harvested biomass. With this information, it is possible to:

i optimise the dry matter yield in relation to nutrient removal, eg accept a 25% loss of yield if 75% of N, P and K are re-cycled naturally by harvesting the crop during the initial stages of senescence rather than earlier;

ii calculate subsequent applications of fertilizer required to replace lost nutrients.

In some cases, nutrient removal from site may necessitate applications of fertilizers far in excess of those currently used in agriculture. Although nutrient replacement may be possible by the return of nutrient-rich residues from the chemical conversion of biomass to usable fuels, it is important to compare nutrient replacement requirements with levels of fertilizers traditionally applied to various agricultural crops. This comparison has been made using data of Church (1975) on "Fertilizer use on farm crops in England and Wales" (Appendix V). The comparison is crude, however, in that natural inputs of inorganic nutrients in rainfall and ground water have not been taken into account.

Organic nutrients are also important in determining re-growth subsequent to harvesting. Photosynthate produced in leaves and stems is translocated to below-ground organs and is stored here during winter to provide an energy source for new shoot production in the following spring. The removal of this energy source from the rhizomes will decrease the subsequent re-growth. However, the developmental stage of shoots at the time of harvesting determines the amount of carbohydrate removed and subsequent re-growth. Shoots harvested when young will have the maximum effect on re-growth, whereas shoots harvested when dead should have little effect on re-growth, because mobile energy sources will have been translocated to perennating tissues. Large perennating organs in relation to the size of deciduous shoots would be expected to enhance re-growth after harvesting. Throughout this report, soluble carbohydrates, starch and crude fat are regarded as energy-storing compounds in a botanical sense, whereas holocellulose and lignin are regarded as structural compounds although they contain energy which may be released.

### 1.3.4 Estimation of the potential for crop re-growth within a growing season

Re-growth may also be considered within one growing season rather than between different growing seasons. Grasses are the best example of plant species with a leaf development pattern which is adapted to continuously replace leaves lost through senescence, grazing or mechanical harvesting. In order to maximise grass yields, it is necessary to harvest the crop several times during one season (Beddows 1973). As some of the 'weeds' investigated in the present study are particularly prolific, some were harvested twice during the growing season to investigate if 2 harvests during one growing season could produce a greater total yield than one harvest.

## 1.4 Methodology and presentation

The field study described in this report was carried out in just one year - 1979. Its first priority was an intensive study of native and naturalised plant species which earlier desk studies had suggested showed particular potential as energy crops. Several sites (which were logistically easy to maintain) were selected, and sampling was carried out each month. Where possible, species of particular importance were studied at 2 widely separated sites in order to obtain some estimate of the variation in yield between sites.

The second priority of the study was to obtain some estimate of the productivity of other tall herbs, and to investigate the variation in yield between diverse geographical locations. This extensive survey was carried out by sampling species at sites throughout Great Britain at single harvest dates in late summer, often with limited replication. These data should, therefore, be treated with caution. Finally, in order to provide background information for a more detailed study of dedicated energy crops, methods of propagating and establishing some species at garden sites were investigated.

A detailed account of the methods involved in this investigation is contained in Appendix I, while detailed descriptions of the study sites are presented in Appendix II. Wherever possible, statistical analyses were used to test the significance of differences between means, and the results of these analyses are contained in Appendix III.

The following chapters present and discuss the results obtained during the 1979 field study for each species in turn.

# 2 *PTERIDIUM AQUILINUM* - BRACKEN

## 2.1 General description

This fern (Plate 1(a)) is a rhizomatous species which possesses long creeping, perennial underground rhizomes and photosynthetic fronds which are produced each season and die each autumn. Fronds are commonly 30-180 cm high but can reach 4 m (Clapham *et al.* 1962). Reproduction in established clones is mainly vegetative, by proliferation of the rhizomes, but sexual reproduction is also successful, particularly after forest fires (Oinonen 1968).

## 2.2 Distribution and extent

Bracken occurs throughout Great Britain and Ireland (Figure 2.1, A) and is widespread throughout the northern hemisphere (Meusel 1965). It occurs in many habitats, from fells at 610 m in Scotland to lowland heaths and woodlands in the south of England, although it prefers light acid soils and is not tolerant of wet peaty soils or limestone areas (Clapham *et al.* 1962).

Where bracken occurs, it often dominates the plant community, forming almost pure stands. It occupies approximately 1.6% of the land area of rural Britain, between 3 224 $km^2$ (Lawson *et al.* 1980) and 3 470 $km^2$ (Callaghan *et al.* 1978).

## 2.3 Rate of development

Fronds appear above ground comparatively late in the season during May and June, but quickly develop, particularly at the Chisworth site, and reach maximum height in July (Figure 2.1, B). A leaf area index (LAI) of 1.2 $m^2$ $m^{-2}$ may be produced in shade conditions (Roberts *et al.* 1980). Spores are formed, ripening in July and August. Nearly all fronds are produced within the same month, achieving densities of between 50 and 60 $m^{-2}$ (Figure 2.1, B). The fronds turn brown in October and November and eventually fall to the ground. Decomposition varies dramatically with site conditions, fallen fronds disappearing from the Chisworth site before the next growing season, whereas they persist until at least late summer at the Lowick Common site.

Rhizomes may persist between 35 and 100 years before they decompose (Watt 1940), and rhizome growth can be up to 18 cm $yr^{-1}$ (Oinonen 1968).

## 2.4 Productivity

Estimates in the literature of above ground production by bracken vary between 2.43 and 31.59 tonnes per hectare per year (t $ha^{-1}$ $yr^{-1}$) (Callaghan *et al.* 1978), although the higher values are probably fresh weights. In the present study, maximum above ground standing crop varied between 4.6 and 8.9 tonnes $ha^{-1}$ $yr^{-1}$ dry matter (Table 2.1). Unfortunately, values from sites sampled at only one time during the growing season may not represent maximum values, but they are consistently higher than 4 t $ha^{-1}$ $yr^{-1}$.

A B

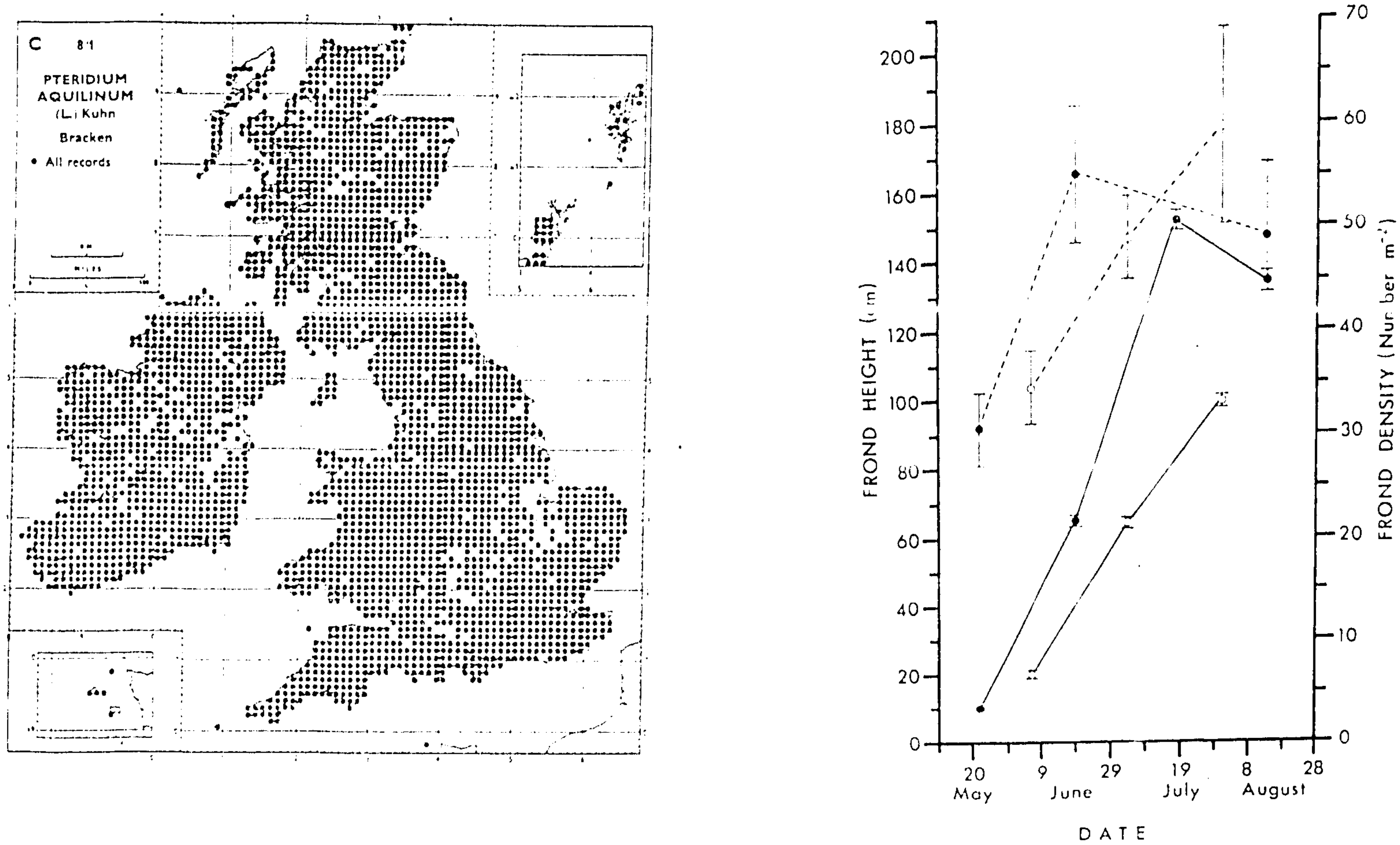


Figure 2.1 A The distribution of bracken in Great Britain and Ireland; from Perring and Walters (1962).

B Seasonal changes in the height (solid lines) and density (broken lines) of bracken fronds from the Chisworth site (solid circles) and Lowick Common site (open circles). Bars represent standard errors.

TABLE 2.1 Between-site variation in the above-ground standing crop of bracken (t $ha^{-1}$ dry matter) and fresh weight/dry weight ratios. Full site descriptions are given in Appendix II.

| SITE | SITE No. | COMMUNITY | SAMPLE DATE | STANDING CROP | FRESH Wt./DRY Wt. |
|---|---|---|---|---|---|
| Romsey, Hampshire | 30 | wood understorey | 8 September | 4.12 ± 0.47 | 4.30 ± 0.25 |
| Ashurt Wood, Sussex | 31 | wood understorey | 5 September | 4.62 ± 0.58 | - |
| Lowick Common, Cumbria | 16 | upland heath | 5 October | 5.74 ± 0.19 | - |
| Loughrigg, Cumbria | 19 | upland heath | 20 July | 5.81 | 4.52 |
| Gaufron, Powys | 24 | upland heath | 16 August | 6.44 ± 0.28 | - |
| Strathoykel, Lairg | 10 | birch scrub | 13 September | 6.65 ± 0.32 | 4.10 ± 0.18 |
| Eggerslack, Cumbria | 17 | wood understorey | 8 October | 6.97 ± 0.20 | 3.28 ± 0.18 |
| Lowick Common, Cumbria | 1 | upland heath | 31 July | 8.69 ± 1.63 | 4.19 ± 0.11* |
| Chisworth, Derbyshire | 6 | clearing in wood | 13 August | 8.87 ± 0.54 | 6.55 ± 0.16** |

* Fresh weight/dry weight data for 4 July

** Fresh weight/dry weight date for 19 June

Values measured over the growing season of 1979 at 2 different sites, Chisworth and Lowick Common, showed very similar trends and maxima (Figure 2.2). However, frond expansion occurred 2 weeks earlier at Chisworth, and the initial increase in dry weight was more rapid than at the Lowick Common site. At both sites, neither of which had a particularly favourable environment, an above ground standing crop of almost 9 t $ha^{-1}$ was achieved in less than 12 weeks.

Fresh weight/dry weight ratios during the summer show that the bracken fronds had about 75% water content (Table 2.1), but the beginning of season water content was much higher, with fresh weight/dry weight ratios of 9.76 ± 0.31 and 6.55 ± 0.16 at the Lowick Common and Chisworth sites respectively. When the fronds were brown at the Lowick Common site on 23rd October, water content was reduced to less than 50% with a fresh weight/dry weight ratio of 1.8 ± 0.06.

Values for the standing crop of rhizomes and roots are rare in the literature. In the present study, dry biomass of rhizomes at the Lowick Common and Chisworth sites varied between 11.24 and 16.69 t $ha^{-1}$, with no significant seasonal trends. However, turnover of rhizome material must occur as the apical ends grow and distal regions senesce and die. The following rhizome biomass values were obtained.

i. Lowick Common : 12.65 ± 1.47 (9 May), 11.24 ± 1.42 (26 September) and [illegible] t $ha^{-1}$

ii. Chisworth : 16.69 ± 1.51 (22 May), 12.64 ± 1.59 (10 September) and 12.70 ± 2.67 (5 December) t $ha^{-1}$

## 2.5 Re-growth after cutting

Because of the synchronous development of fronds, the potential for re-growth after curring is low. However, some re-growth is possible (Table 2.2), although it may not be feasible or economically viable to harvest this material. Re-growth after an early harvest at the Chisworth site amounts to about 1 t $ha^{-1}$, whereas re-growth after peak standing crop has been obtained is only 0.4 t $ha^{-1}$ (Table 2.2). The maximum yield of bracken fronds (9.24 t $ha^{-1}$ $yr^{-1}$) would be obtained by harvesting on 13 August at peak standing crop (8.87 t $ha^{-1}$) and then again on 10th September (0.37 t $ha^{-1}$) (Table 2.2). Dead bracken fronds quickly decompose at the Chisworth site and the area is colonised by a grass (*Poa trivialis*) during the winter. On 14 December, the above ground standing crop of this grass was 1.22 ± 0.15 t $ha^{-1}$, so the maximum annual yield of the site (within the limitations of the experimental design) is 8.87 + 0.37 + 1.22 = 10.46 t $ha^{-1}$ $yr^{-1}$. A higher yield may have been achieved if re-growth had been measured after 10 September and the grass sampled again during the following spring.

At the Lowick Common site, there was considerable re-growth (3.8 t $ha^{-1}$) after cutting fronds on 6 June when frond expansion was still in progress (Table 2.2).

Re-growth after later harvests was similar to that at the Chisworth site, with a maximum yield of 8.98 t $ha^{-1}$ achieved by cutting fronds on 31 July and again on 26 September (Table 2.2).

The growth of other species was less pronounced than at the Chisworth site, and they were not sampled, although grass did occur in some quadrats in autumn.

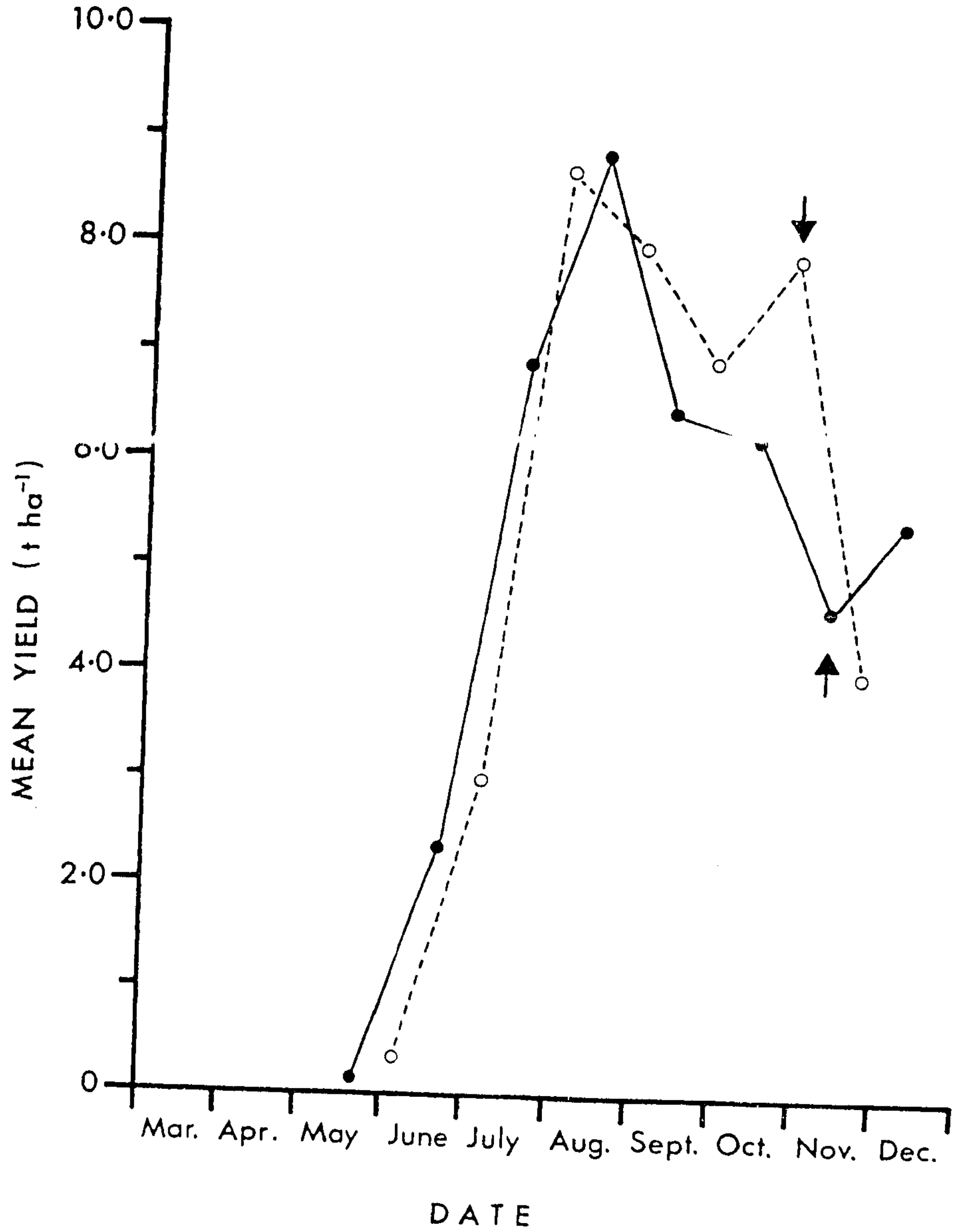


Figure 2.2 The seasonal growth of fronds of bracken from the Chisworth site (solid line and solid circles) and the Lowick Common site (broken line and open circles). The arrows denote the date by which all fronds had turned brown.

TABLE 2.2 The re-growth of bracken fronds measured on 10 September (Chisworth site) and 26 September (Lowick Common site) after cutting at earlier times in the growing season. Yields are t $ha^{-1}$; dates refer to the Lowick Common site or, when bracketed, the Chisworth site.

| | | 6 June (19 June) | 4 July (18 July) | 31 July (13 August) | 28 August |
|---|---|---|---|---|---|
| CHISWORTH SITE | yield at specified date: | 2.35 | 6.90 | 8.87 | - |
| | re-growth after specified date: | 1.01 | 1.29 | 0.37 | - |
| | total yield | 3.37 | 8.19 | 9.24 | - |
| LOWICK COMMON SITE | yield at specified date: | 0.33 | 3.01 | 8.69 | 7.99 |
| | re-growth after specified date: | 3.79 | 1.13 | 0.29 | 0.18 |
| | total yield | 4.12 | 4.14 | 8.98 | 8.17 |

Removing fronds appears to have little effect on the subsequent standing crop of rhizomes at the Chisworth and Lowick Common sites (Table 2.3). However, standing crop measurements of rhizomes are probably an insensitive parameter from which to predict frond re-growth in subsequent years, because little is known about turnover from living to dead material in rhizomes.

## 2.6 Nutrient content of bracken

### 2.6.1 Inorganic nutrients

The concentrations of all the inorganic nutrients studied were low at the beginning of the growing season (Figure 2.3) when frond expansion was starting. Nitrogen, phosphorus and potassium concentrations then showed similar trends, increasing rapidly and reaching a maximum value approximately 2 months before maximum dry weight (Figure 2.2), and then decreasing throughout the remainder of the season to very low values (Figure 2.3, A). Concentrations of P are about one tenth of those of N and K.

In contrast, concentrations of Ca show a marked increase over the growing season (Figure 2.3, B), a trend which is typical of many plant species. Mg concentration also shows increased values throughout the summer months (Figure 2.3, B). The trends described above are similar to those described for bracken by Allen (unpublished data) quoted in Lawson *et al.* (1980), although Allen's data do not show the early season increase in nutrient concentrations and his concentrations of Ca are lower than those in Figure 2.3, B. Compared with angiosperms (Lawson *et al.* 1980) and the pteridophyte *Lycopodium annotinum* (Callaghan 1980), bracken shows high concentrations of N, P and K, and this would suggest that bracken fronds would be suitable for anaerobic digestion, as they contain a high protein fraction. Potassium concentrations in Figure 2.3, A show an anomaly, in that it is usually the most mobile element and often shows the fastest decrease in concentration (Malmer & Nihlgård 1980). The double peaks shown by N, P and K in Figure 2.3, A are also difficult to explain, as they are not associated with a period of renewed growth (Figure 2.2).

Nutrient concentrations in rhizomes (Table 2.4) are generally much lower than those in the fronds (Figure 2.3), and no significant seasonal trends are evident. However, because rhizome standing crop is high and fairly constant throughout the season, a constant pool of nutrients is held in the rhizomes although ash contents are quite low (Table 2.4).

In the fronds, the contents of nutrients show a clear mid-season peak with low values at the beginning and end of the season (Table 2.5). The mid-season peak in the N, P and K contents generally coincides with peak standing crop (Figure 2.4), but the subsequent decrease in nutrient content is far faster than the decrease in standing crop. As the pinnae of the fronds die before the main rachis (or stem) and the rachis does not die until November (Figure 2.2), this reduction in the content of N, P and K (Figure 2.4) probably represents re-translocation into the rhizome, although corresponding increases in the total content or concentrations of N, P and K are not evident (Table 2.4).

TABLE 2.3 The effect of harvesting bracken fronds on rhizome standing crop (t $ha^{-1}$) at the end of the growing season. Dates refer to the Lowick Common site or, when bracketed, to the Chiswroth site.

| SITE | DATE OF FROND REMOVAL | | | | | DATE OF RHIZOME REMOVAL |
|---|---|---|---|---|---|---|
| | 6 June (19 June) | 4 July (18 July) | 31 July (13 August) | 28 August | 26 September (10 September) | |
| Chisworth Site | 12.93 | 11.38 | 14.46 | - | 12.64 | 10 September |
| Lowick Common Site | 5.86 | 7.09 | 7.94 | 14.36 | 11.24 | 26 September |

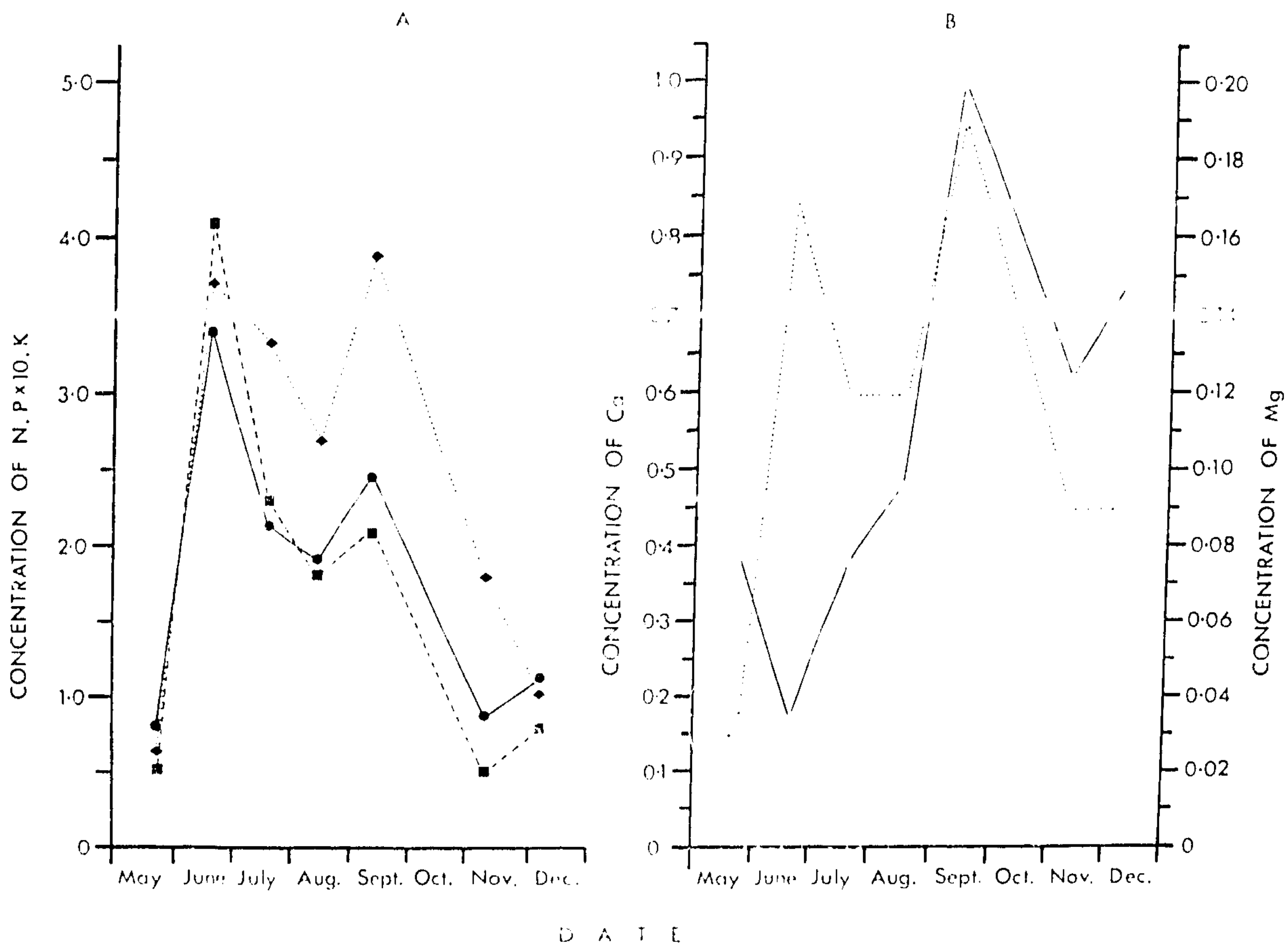


Figure 2.3 The seasonal trends of concentrations of inorganic nutrients (% dry weight) in fronds of bracken from the Chisworth site.

A Concentrations of N (solid line and solid circles), P (broken line and solid squares) and K (dotted line and solid diamonds).

B Concentrations of Ca (solid line and open circles) and Mg (dotted line and open diamonds).

NB Concentrations of P are 1/10th of those of N and K.

TABLE 2.4 Concentrations and contents (concentration x dry weight) of inorganic nutrients in bracken rhizomes from the Chisworth site

| ELEMENT | CONCENTRATION (% dry wt) | | | CONTENT (kg ha$^{-1}$) | | |
|---|---|---|---|---|---|---|
| | 22 May | 10 September | 5 December | 22 May | 10 September | 5 December |
| N | 1.60 | 1.35 | 1.80 | 267.0 | 170.6 | 228.6 |
| P | 0.15 | 0.13 | 0.17 | 25.0 | 16.4 | 21.6 |
| K | 2.00 | 1.87 | 2.00 | 333.8 | 236.4 | 254.0 |
| Ca | 0.18 | 0.18 | 0.15 | 30.0 | 22.8 | 19.1 |
| Mg | 0.21 | 0.24 | 0.16 | 35.1 | 30.3 | 20.3 |
| Ash | 8.97 | 7.20 | 6.4 | 1497 | 910 | 813 |

The pattern of nutrient loss means that, if bracken fronds were harvested when dead and dry on 8 November, about 48% of the maximum dry weight yield would be sacrificed, but only 33%, 20% and 15% of K, N and P respectively would be removed from site (Figure 2.4). These percentages represent 34 kg $ha^{-1}$, 2.32 kg $ha^{-1}$ and 83.5 kg $ha^{-1}$ of N, P and K respectively, compared with the 169 kg $ha^{-1}$ and 240 kg $ha^{-1}$ which would be removed if the maximum dry matter yield were obtained by harvesting on 13 August (Table 2.5). Accumulations of ash (Table 2.5), after a chemical conversion process, would be low because of low concentrations of ash in the frond (between 3 and 9.3% dry weight).

The N, P and K contents of bracken fronds at peak biomass (Table 2.5) are very similar to their levels in the rhizomes on 10 September (Table 2.4). Thus, the pool of nutrients held in the rhizome is small, and harvesting maximum yield would be expected to result in a severe set-back to re-growth in subsequent years. Harvesting brown bracken fronds would enable some re-cycling of N, P and K, via translocation and leaching, and would affect re-growth less severely.

Calcium presents a different picture to N, P and K in that it is not re-cycled within the plant, and the same amount would be removed from site whether fronds were harvested when green or brown (Table 2.5). Bracken prefers acid soils in which Ca concentrations are already low, but the removal of Ca may present a problem to re-growth after continued harvesting, and applications of calcium may even be necessary.

If fronds of bracken were harvested at maximum standing crop, ie 13 August (Figure 2.2), more nitrogen would be removed from the site (Table 2.5) than is traditionally added to maincrop potatoes and sugarbeet (ie 169 and 132 kg $ha^{-1}$ respectively, Church 1975). The quantity of K which would be removed in the fronds (240 kg $ha^{-1}$, Table 2.5) is considerably greater than the quantities traditionally applied to root crops (between 136 and 183 kg $ha^{-1}$, Church 1975). On the other hand, only 16 kg $ha^{-1}$ of P would be removed, and this is small compared with the amounts given to potatoes and sugarbeet (72 and 81 kg $ha^{-1}$ respectively, Church 1975).

If brown bracken fronds were harvested on 8 November, the amounts of N, P and K removed would be approximately only 24%, 3% and 54% respectively of the amounts traditionally applied to root crops (Table 2.5, Church 1975). Thus, considerable applications of fertilizer, in excess of the levels currently applied to commercially viable crops, would be needed to replace nutrients lost by harvesting bracken fronds at peak standing crop, whereas only a very small fertilizer application, less than that currently given to most root, arable and grass crops, would be necessary if fronds were harvested in autumn.

### 2.6.2 Organic fractions

Concentrations of the organic plant fractions in the shoots of bracken show different seasonal trends to the concentrations of the inorganic nutrients. Soluble carbohydrates, starch and crude fat show high concentrations during mid-season when standing crops are highest, and decrease when senescence begins in September (Figure 2.5, A). Concentrations of soluble carbohydrates fluctuate more than the concentrations of starch and crude fats, reaching a maximum of 13.3% at peak standing crop. The subsequent decrease in concentration may

TABLE 2.5 The nutrient content (concentration x dry weight) of bracken fronds from the Chisworth site throughout the growing season of 1979. Values are kg $ha^{-1}$.

| ELEMENT | 22 May | 19 June | 18 July | 13 August | 10 September | 8 November | 5 December |
|---|---|---|---|---|---|---|---|
| N | 0.97 | 80.2 | 148.4 | 168.5 | 159.8 | 33.9 | 61.9 |
| P | 0.064 | 9.68 | 15.87 | 15.97 | 13.59 | 2.32 | 4.38 |
| K | 0.079 | 88.03 | 231.2 | 239.5 | 252.3 | 83.52 | 55.90 |
| Ca | 0.47 | 4.01 | 26.22 | 42.58 | 65.99 | 28.77 | 40.55 |
| Mg | 0.041 | 4.01 | 8.28 | 10.64 | 12.29 | 4.18 | 4.93 |
| Ash | 3.6 | 208.4 | 552.0 | 636.0 | 599.8 | 280.7 | 257.6 |

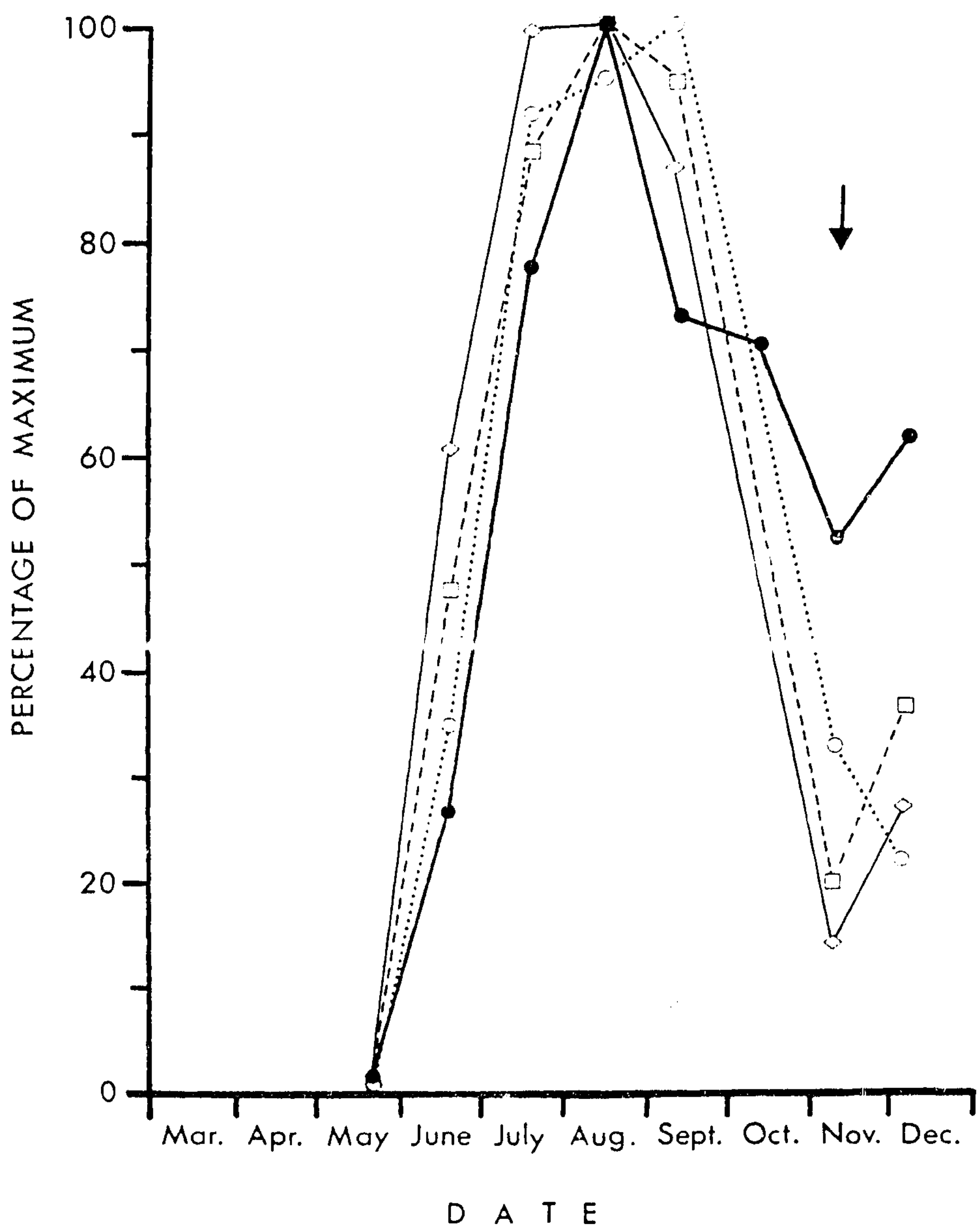


Figure 2.4 The relationship between the seasonal trend of standing crop (thick solid line and solid circles) and the total contents of N (broken line and open squares), P (thin solid line and open diamonds) and K (dotted line and open circles) in bracken fronds from the Chisworth site. All values are expressed as percentages of the maxima to standardise the vertical axis. The arrow denotes the date by which all fronds had become brown.

well be the result of the translocation of this mobile energy source from the shoots to the rhizomes at the end of season. It may be inferred, therefore, that the harvesting of bracken shoots at peak standing crop would remove an important energy source necessary for re-growth during the following year, but experiments are necessary to determine the precise effect on re-growth of harvesting shoots at that time.

The concentrations of the other energy-storing compounds, starch and crude fat, vary little over the season, and end of season concentrations are high (Figure 2.5, A) suggesting little, if any, translocation below ground. Starch and crude fat concentrations follow very similar trends but starch concentrations are around one-tenth of those of crude fat.

High mid-season concentrations of soluble carbohydrates and crude fat (totalling almost 16% of shoot dry weight) suggest that green shoots of bracken would be a good substrate for conversion to methane or alcohol via anaerobic digestion or alcoholic fermentation.

Holocellulose and, in particular, lignin are more difficult to break down under anaerobic digestion and fermentation processes. High concentrations of these fractions would indicate that a thermal conversion method might be preferable to convert plant material to fuel. In shoots of bracken, the concentrations of holocellulose are high at the beginning and end of season (67%) and a clear mid-season depression can be seen when soluble carbohydrates show their highest concentrations (Figure 2.5). Lignin concentrations show a similar trend to the concentrations of holocellulose but have lower values, between 9 and 21% (Figure 2.5, B).

In the rhizomes of bracken, concentrations of the organic plant fractions show no clear seasonal trends except that starch shows a high end of season value (Table 2.6). Concentrations of soluble carbohydrates, crude fat and holocellulose are lower in the rhizomes than in the shoots, but concentrations of starch are up to 300 times higher in the rhizomes than in the shoots. This high starch concentration suggests that the rhizomes serve as an important energy storing organ. A large end of season increase in starch concentration in the rhizomes (Table 2.6), together with a great decrease in the concentration of soluble carbohydrates in the shoots (Figure 2.5, A), suggests efficient translocation of energy stored in the shoots in a mobile form to the perennating tissues, where it is stored in an immobile form.

The high concentrations of starch, together with quite high concentrations of cell wall materials in the rhizomes of bracken, suggest that conversion to a usable fuel by anaerobic digestion would be inefficient, even if it were feasible to harvest rhizomes of bracken.

The energy content of a plant is determined by the concentrations of its various organic fractions. Although these concentrations vary throughout the growing season, the energy content of the shoots, on a per gramme dry weight basis, change insignificantly, varying between 20.5 and 21.5 KJ $g^{-1}$ (Figure 2.6), with a mean of 21.1 ± 0.1 KJ $g^{-1}$. This figure is slightly higher than the energy content of the rhizomes which is 19.6 ± 0.2 KJ $g^{-1}$ dry weight.

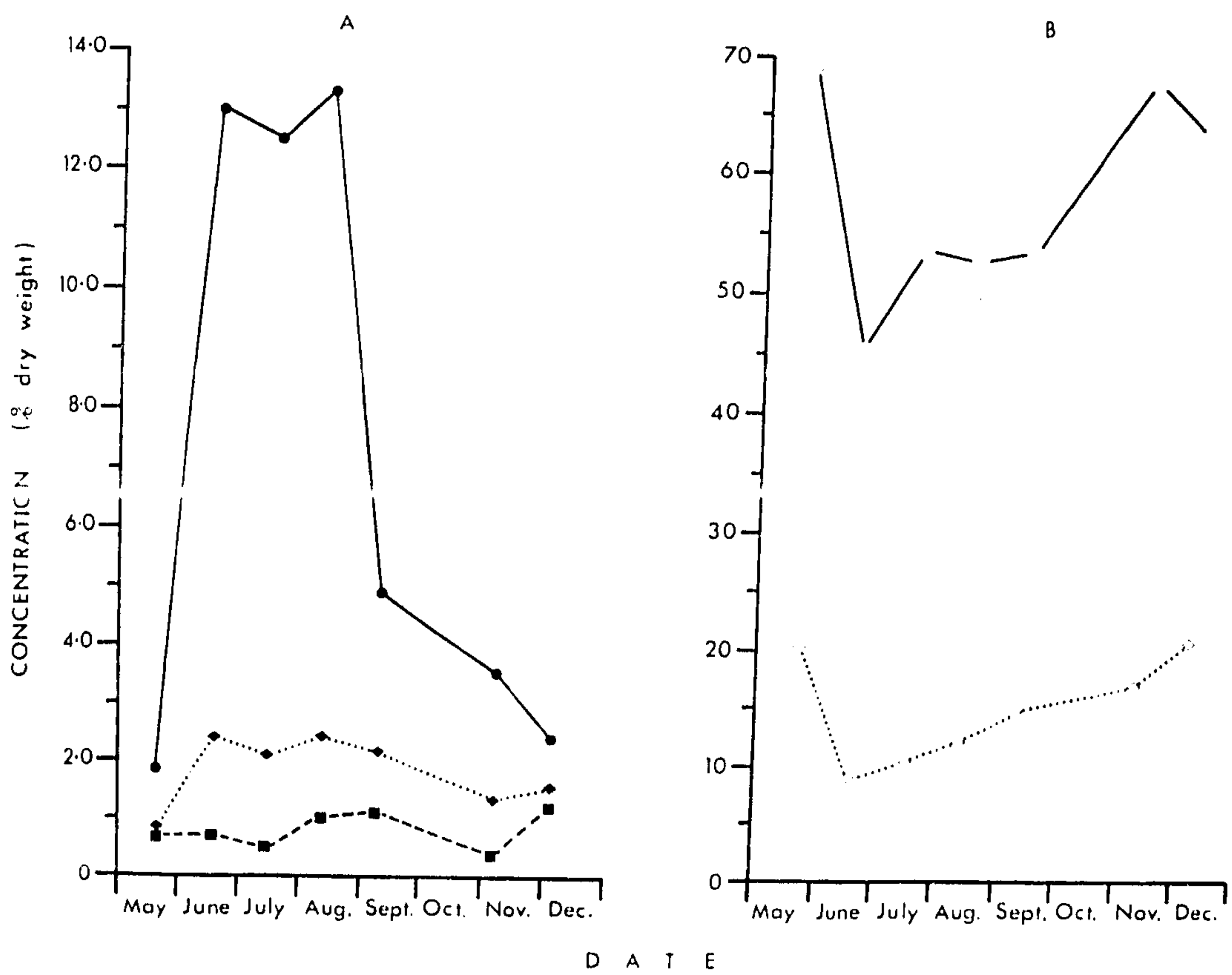


Figure 2.5 The seasonal trends of concentrations or organic plant fractions in fronds of bracken from the Chisworth site.

A Soluble carbohydrates (solid circles and line), crude fat (solid diamonds and dotted line) and starch x10 (solid squares and broken line).

B Holocellulose (open circles and solid line) and lignin (open diamonds and dotted line).

NB Concentrations of starch are 1/10th of the values on the Y axis.

TABLE 2.6 Concentrations (% dry weight) of organic plant fractions in the rhizomes of bracken collected from the Chisworth site

| COMPOUND | CONCENTRATION | | |
|---|---|---|---|
| | 22 May | 10 September | 5 December |
| Soluble carbohydrate | 16.3 | 18.3 | 20.0 |
| Starch | 17.7 | 15.8 | 32.0 |
| Crude fat | 0.90 | 1.20 | 0.98 |
| Lignin | 25.5 | 32.1 | 14.8 |
| Holocellulose | 33.0 | 28.0 | 37.0 |

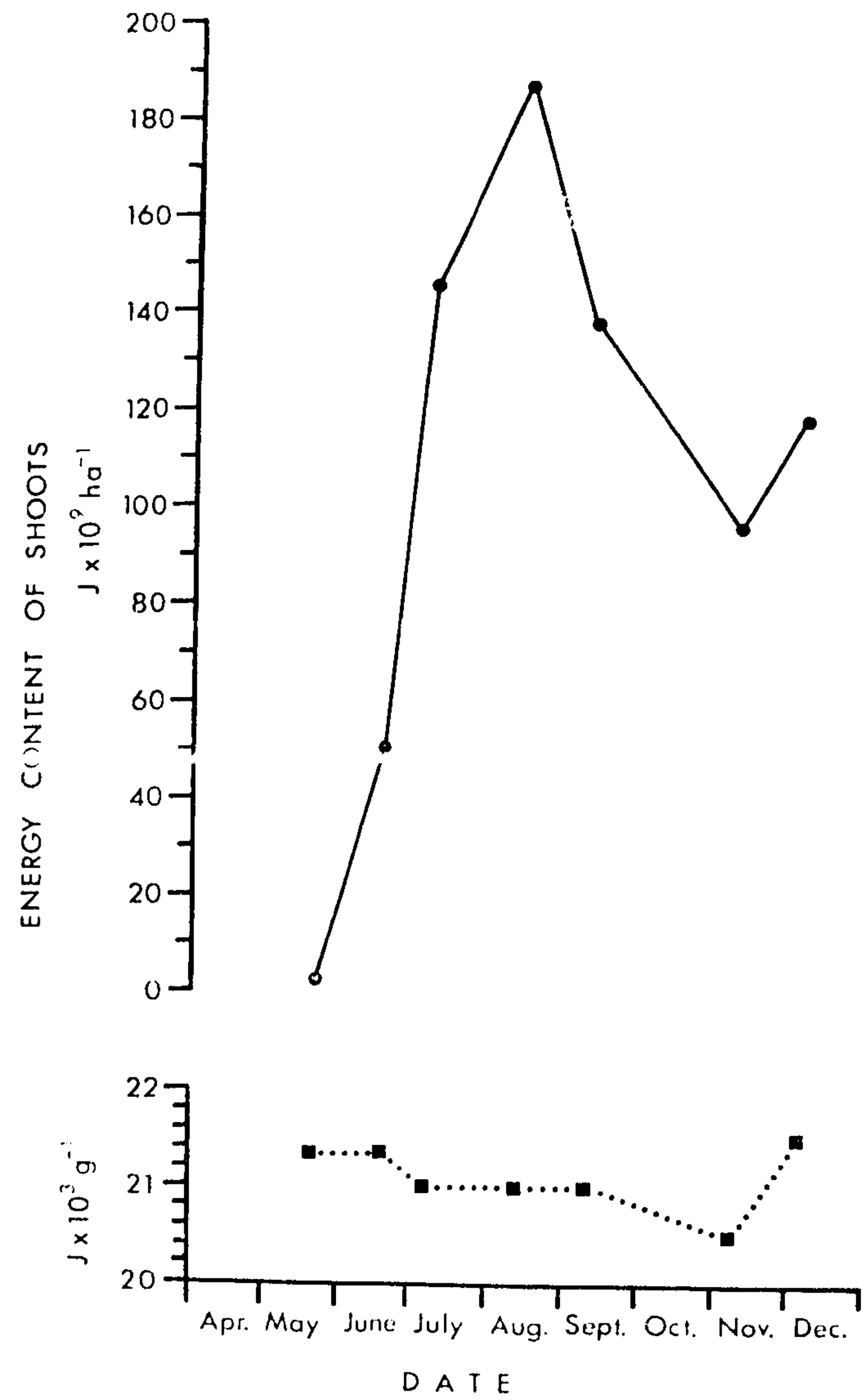


Figure 2.6 The seasonal trends of the energy contents of fronds of bracken expressed on a land area basis and on a unit dry weight basis.

Seasonal trends of the energy content of the shoots of bracken on a land area basis are determined mainly by the standing crop. During August, the energy content of bracken stands is at a maximum of 186 x $10^9$ J $ha^{-1}$ (Figure 2.6) but, if rhizomes were harvested also, approximately 440 x $10^9$ J $ha^{-1}$ would be available for conversion to fuels. Although it may not appear to be feasible, or desirable, to harvest the rhizomes of bracken, a detailed consideration should be given to this large store of energy, particularly if the bracken control is of major importance in the management of an area of land.

## 2.7 A summary of the potential of bracken as an energy crop

2.7.1 Bracken would be managed mainly as an opportunity energy crop as it grows throughout Great Britain up to an altitude of 610 m and covers between 3 224 and 3 470 $km^2$ of England, Scotland and Wales.

2.7.2 Dry matter yields of green shoots should be at least 4.6 t $ha^{-1}yr^{-1}$ with a more typical value between 8 and 9 t $ha^{-1}$ $yr^{-1}$ (168 x $10^9$ and 189 x $10^9$ J $ha^{-1}$).

2.7.3 Shoots of bracken harvested at peak biomass should be easily digested anaerobically to produce methane, as water content is about 75% fresh weight, concentrations of N, P, K and soluble carbohydrates are high (1.9, 0.18, 2.7 and 13.3% dry weight respectively), while concentrations of lignin, holocellulose and ash are quite low (12.3, 52.7 and 7.2% dry weight respectively).

2.7.4 If shoots of bracken were harvested at peak biomass, re-growth may be affected because translocation of energy-storing compounds into the rhizomes would be prevented. The effect on re-growth should be determined in long-term experiments.

2.7.5 Applications of N and K to areas of harvested bracken would be greater than those traditionally applied to agricultural crops, if the N and K removed in harvested biomass (169 and 240 kg $ha^{-1}$ respectively) were replaced. Additions of Ca may become necessary after repeated harvesting.

2.7.6 If fronds of bracken were harvested when senescent, dry matter yields of between 4.6 and 8.0 t $ha^{-1}$ $yr^{-1}$, 94 x $10^9$ and 164 x $10^9$ J $ha^{-1}$ $yr^{-1}$ respectively, should be obtained, and a thermal chemical conversion process may be necessary as water contents are as low as 65% of the fresh weight.

2.7.7 If fronds of bracken were harvested when senescent, approximately 70% N and 88% K in the fronds would be re-cycled naturally on the site and replacement applications of fertilizer would be low.

2.7.8 Only small quantities of soluble carbohydrate, starch and crude fat would be prevented from reaching the rhizomes if bracken fronds were harvested when brown. Re-growth in subsequent years should, therefore, be unaffected by harvesting. Indeed, some areas of bracken have sustained repeated harvesting at this stage for many centuries.

2.7.9 It is technologically feasible to harvest much of the above-ground standing crop of bracken from natural sites.

2.7.10 If it were possible to harvest the rhizomes of bracken, an additional yield of between 11 and 17 t $ha^{-1}$ $yr^{-1}$(ie 215 x $10^9$ and 333 x $10^9$ J $ha^{-1}$ $yr^{-1}$ respectively) could be expected during the year of harvesting, but it is not known if regeneration would take place in following years.

## 2.8 Conclusion

Bracken could, therefore, be managed as an opportunity energy crop in one of 2 ways:

i Fronds could be harvested at peak standing crop, possibly together with their rhizomes, in a programme aimed at eventual eradication to promote rough grazing. The biofuel produced would have a positive value in contrast to the current cost of about £120 $ha^{-1}$ for eradication.

ii Fronds of bracken could be harvested when senescent and maintained indefinitely as an opportunity energy crop. This option would not significantly affect the amenity and conservation uses of the land where bracken occurs, as it would only involve the removal of senescent fronds in autumn. This option would result in greater rates of plant production on areas of land than those achieved by eradicating bracken and introducing rough grazing.

# 3 *PETASITES HYBRIDUS* - BUTTERBUR

## 3.1 General description

This species possesses stout, creeping rhizomes, the crowns of which produce an inflorescence very early in the season followed by large, flat, deciduous leaves. Each leaf is supported by a petiole, which may exceed 1.5 m in height and the leaves form a horizontal canopy beneath which there is dense shade (Plate 1 (b)). Reproduction in established clones is mainly vegetative by proliferation of the rhizomes, and in many localities this is the only means of reproduction because female plants are absent (Clapham *et al.* 1962).

## 3.2 Distribution and extent

Butterbur occurs throughout most of Great Britain, but appears to be absent from the north of Scotland and Welsh Mountains (Figure 3.1). It thrives along stream and river banks and can form extensive "monocultures" in wet meadows, damp woods and copses (see Plate 1.2 in Lawson *et al.* 1980). Soil pH does not appear to affect the distribution of butterbur, as it is found on acid soils in older copses and under ash woodland in limestone areas.

Although common, butterbur is not extensive, occupying only about 33.5 $km^2$ of Great Britain (Bunce pers comm).

## 3.3 Rate of development

Leaf production starts in late autumn and some young tightly-folded leaves over-winter. In spring, inflorescences are produced and leaf expansion occurs as the inflorescences die. The initial density of leaves and petioles is 83 $m^{-2}$ at the Chisworth site but, as the season progresses, the density falls quickly to 30 $m^{-2}$ by the end of August (Figure 3.2, A). Surviving leaves and petioles increase in height from 13 cm to 1 m in about 11 weeks (Figure 3.2, A).

As petioles grow in height, the leaf laminae expand linearly with time, until a mean leaf area of 16 $dm^2$ is achieved by the end of season (Figure 3.2, B). Thus, individual leaves are very large in size (Plate 1(b)) and this, combined with high densities of leaves per unit ground area, results in the development of a dense canopy. This dense canopy not only supresses the growth of other species beneath, but also causes self-thinning (White & Harper 1970) of the butterbur leaves described above.

High densities of leaves at the beginning of season result in the early development of high leaf area indices (reaching a maximum of 5 $m^2$ of leaf per $m^2$ of ground) and the prolongation of a well-developed photosynthetic canopy (Figure 3.2, B) Thus, whereas the mean area per leaf on 28 June shows only 46% of its maximum development, mean leaf area index on the same date shows 86% of its maximum development (Figure 3.2, B).

In autumn, the leaves begin to die, lose turgor and the petioles and leaves collapse, falling to the ground where they decompose quickly over the winter months. Indeed, little leaf and petiole material is identifiable in the following spring cf Al-Mufti *et al.* 1977).

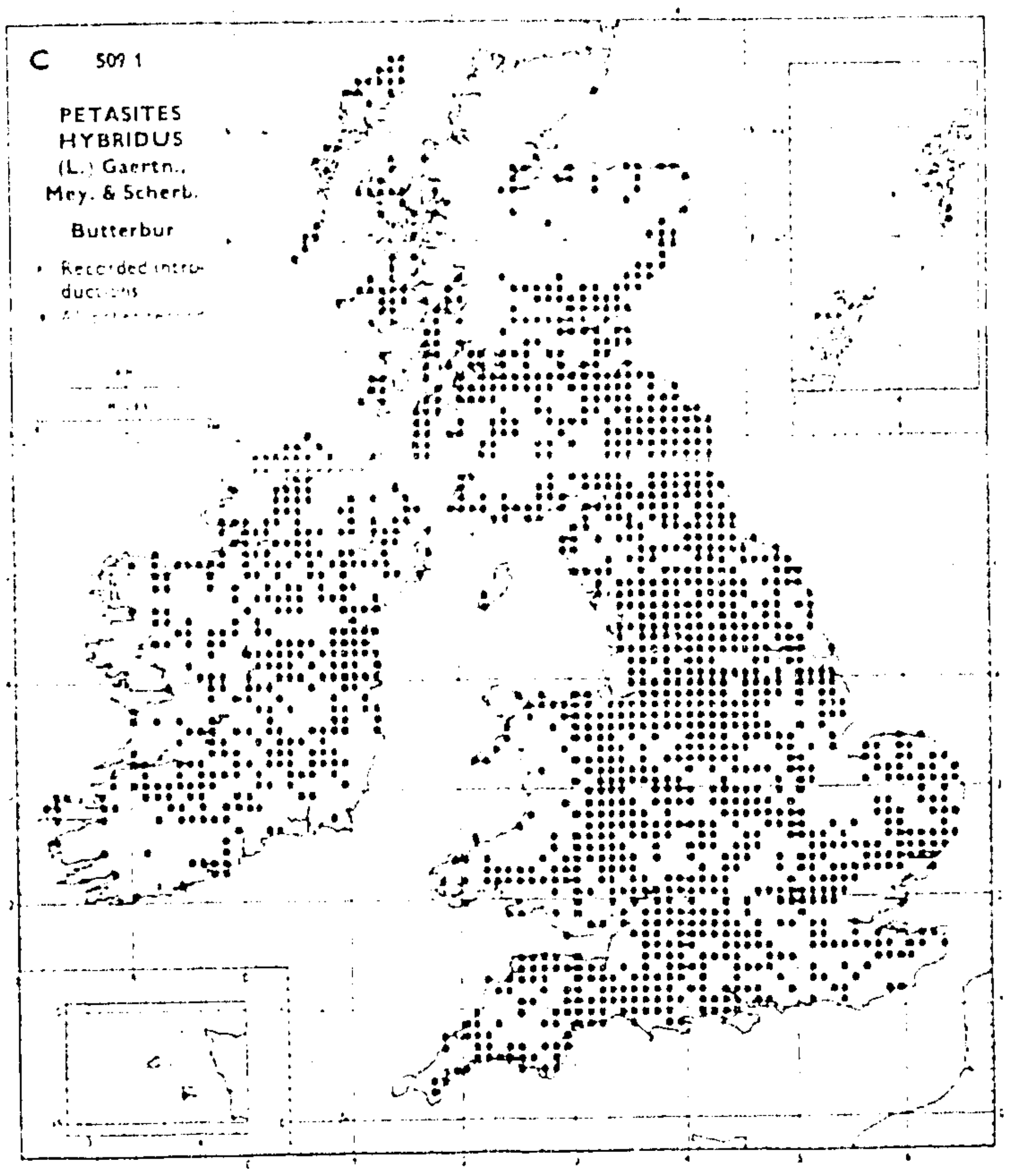


Figure 3.1 The distribution of butterbur in Great Britain and Ireland; from Perring & Walters (1962).

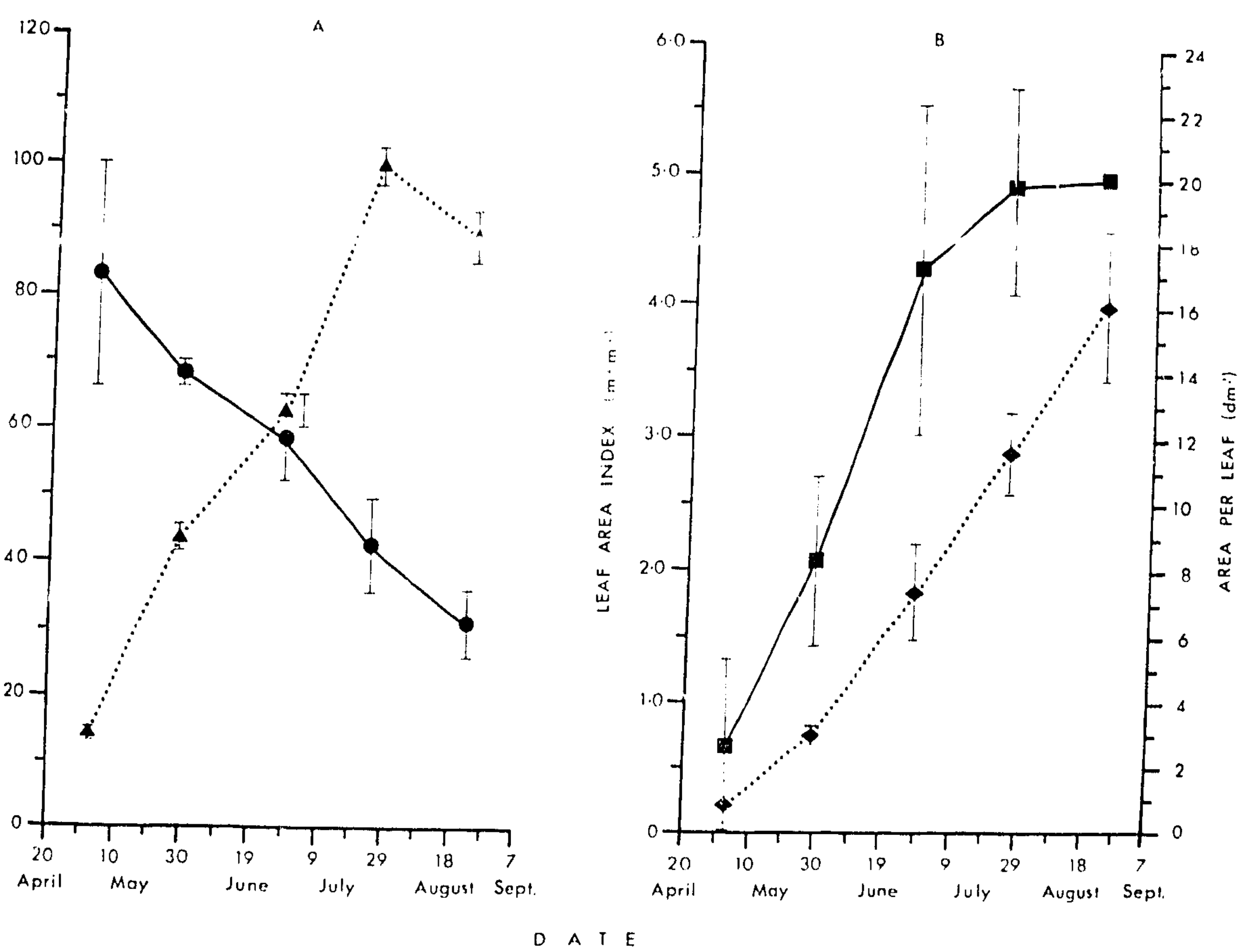


Figure 3.2 The seasonal development of leaves and petioles of butterbur at the Chisworth site.

A Number of leaves and petioles per $m^2$ of ground (circles and solid line) and height of petioles (triangles and dotted line).

B Leaf area (diamonds and dotted line) and leaf area index (squares and solid line). Bars denote standard errors.

## 3.4 Productivity

Estimates of the productivity of butterbur are rare in the literature. Al-Mufti *et al.* (1977) recorded a maximum living shoot biomass of 4 t $ha^{-1}$ during July 1975, and a maximum living shoot biomass of all species at the site of about 6 t $ha^{-1}$. A higher provisional estimate of 8.2 t $ha^{-1}$ was made by Callaghan *et al.* (1978) for butterbur alone. A low value of 2.1 ± 0.26 t $ha^{-1}$ was obtained for a site at Winterbourne Research Gardens (site number 23, Appendix II) during the present study, but this was beneath a tree canopy.

At the intensive site of the present study (Chisworth, site number 6, Appendix II), a peak standing crop of 7.1 t $ha^{-1}$ was obtained for butterbur and 1.0 t $ha^{-1}$ for the other species at the site (Figure 3.3). Peak standing crop was obtained during July, whereas the peak standing crop of bracken at a neighbouring site was achieved during August. However, the growth of butterbur started 2 months earlier than that of bracken so that the growth rate of butterbur is comparatively slow. Water contents of leaves and petioles of butterbur were very high, varying between 89% and 85% of the fresh weight. Fresh weight/dry weight ratios on 29 May, 28 June and 17 October were 9.03 ± 0.56, 7.68 ± 0.23 and 6.84 ± 0.84 respectively, with no significant seasonal trend (Appendix III). At the end of season (14 November), all of the above-ground tissues of butterbur had died and most had collapsed (Figure 3.3).

The dry weights of rhizomes were determined on only 3 occasions, and the following results were obtained: 30 March, 8.96 ± 1.71 t $ha^{-1}$; 19 September, 8.89 ± 0.57 t $ha^{-1}$; 14 December, 8.17 ± 0.16 t $ha^{-1}$. Thus, no clear seasonal trend is evident. However, turnover of living material occurs within the season, and "area sampling" cannot discern these changes which must be investigated using demographic methods (Callaghan 1976, 1980).

Other species growing at the site (mainly *Poa trivialis* and *Heracleum sphondylium*, Appendix II) contributed to the above-ground production of the site by as much as 2.2 t $ha^{-1}$, and increased the peak standing crop of the site to over 8 t $ha^{-1}$ (Figure 3.3).

## 3.5 Re-growth after cutting

Like bracken, leaf production in butterbur is synchronous and the potential for re-growth is limited. However, over 1 t $ha^{-1}$ was produced between a first cut on either 28 June or 25 July and 19 September (Table 3.1), which would increase the maximum harvestable standing crop of butterbur (under the present experimental conditions) from 7.2 t $ha^{-1}$ $yr^{-1}$ to 8.2 t $ha^{-1}$ $yr^{-1}$ (Table 3.1). Considerable re-growth of the associated species also occurs over the season, amounting to as much as 2.8 t $ha^{-1}$ following an early cut (Table 3.1). The maximum above-ground yield from the site (10.4 t $ha^{-1}$ $yr^{-1}$) is, therefore, obtained by cutting all the species on 28 June and again on 19 September (Table 3.1). This yield is almost identical to that obtained on the neighbouring bracken site (10.5 t $ha^{-1}$ $yr^{-1}$), although the increased importance of other species after cutting butterbur suggests that the vegetation of the site may change quickly with repeated harvesting.

Removing the leaves and petioles of butterbur during the summer has no significant effect on the standing crop of rhizomes at the end of season (Table 3.2). Rhizome longevity appears to be short while growth is fast, so that removing photosynthetic tissue during the summer, eg 28 June, may well retard rhizome growth although between-sample variation is great.

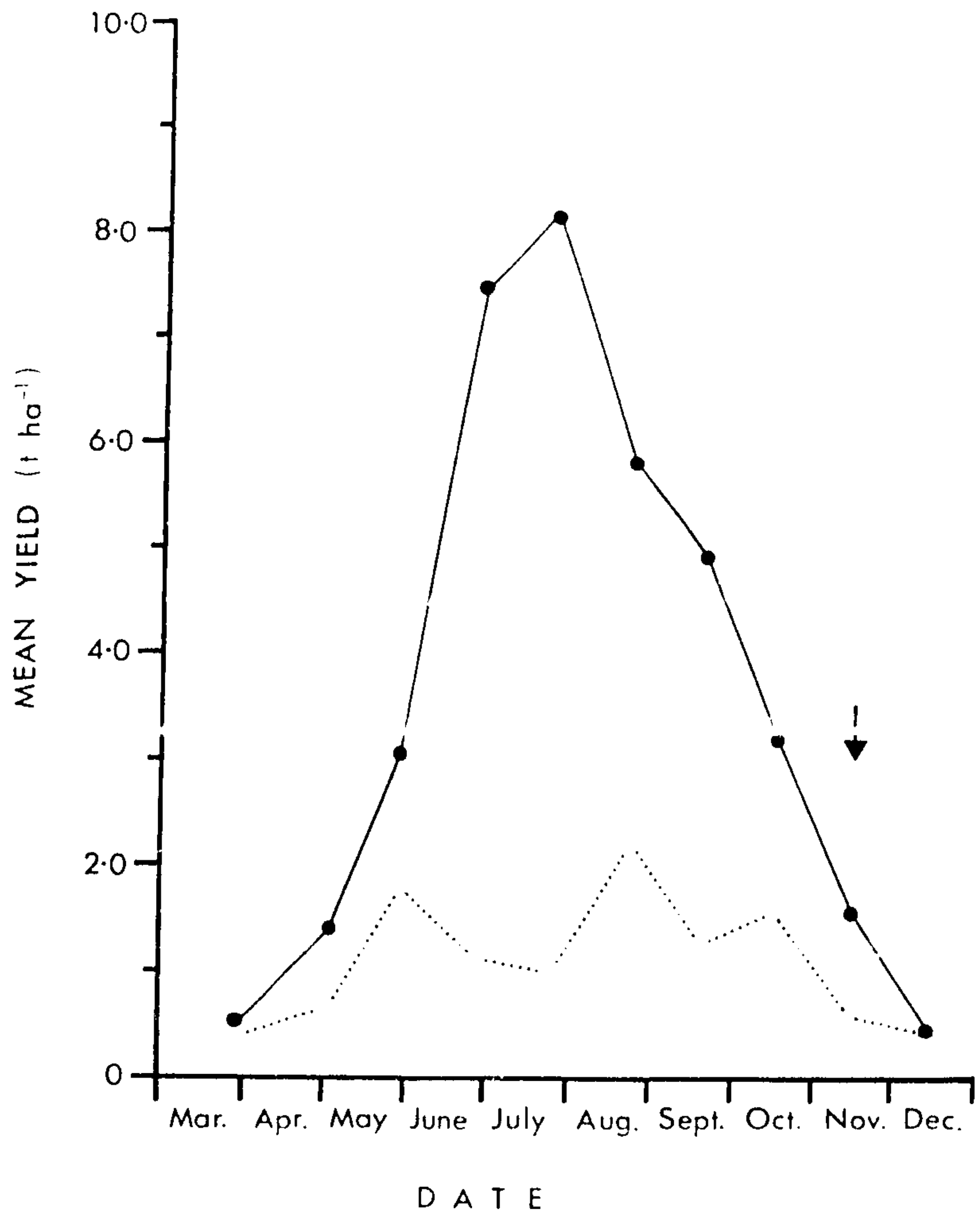


Figure 3.3 The seasonal growth of leaves and petioles of butterbur (solid line and solid circles) and other species (open circles and dotted line) at the Chisworth site. Standing crops of butterbur and the other species are plotted cumulatively; the arrow denotes the date by which all the above-ground tissues of butterbur were dead.

TABLE 3.1 The re-growth of above-ground shoots of butterbur and associated species from the Chisworth site measured on 19 September 1979 after cutting at 3 earlier times in the growing season. Yields are t $ha^{-1}$.

| | 28 June | 25 July | 23 August |
|---|---|---|---|
| BUTTERBUR | | | |
| yield at specified date: | 6.33 | 7.15 | 3.55 |
| re-growth after specified date: | 1.20 | 1.06 | 0.32 |
| total: | 7.53 | 8.21 | 3.87 |
| ASSOCIATED SPECIES | | | |
| yield at specified date: | 1.15 | 1.00 | 2.21 |
| re-growth after specified date: | 1.69 | 0.52 | 0.12 |
| total: | 2.84 | 1.52 | 2.33 |
| TOTAL ABOVE-GROUND YIELD OF SITE | 10.37 | 9.73 | 6.20 |

TABLE 3.2 The effect of harvesting butterbur leaves and petioles on rhizome standing crop (t $ha^{-1}$)

| | SAMPLES COLLECTED ON 19 SEPTEMBER WITH LEAVES AND PETIOLES REMOVED ON: | | | UNDISTURBED SAMPLES COLLECTED ON: |
|---|---|---|---|---|
| | 28 June | 25 July | 23 August | 19 September |
| RHIZOME STANDING CROP (t $ha^{-1}$) | 6.49 | 8.18 | 6.66 | 8.89 |

Obviously, the effect should be more pronounced during the following growing seasons, particularly with the repeated harvesting of above-ground material.

## 3.6 Nutrient content of butterbur

### 3.6.1 Inorganic nutrients

Concentrations of N, P and K, which showed very similar seasonal trends in bracken (Figure 2.3), are far less closely related in the above-ground tissues of butterbur. Nitrogen concentrations show an increase at the beginning of season followed by a characteristic decrease over summer and autumn (Figure 3.4, A) and are very similar to those of bracken fronds, suggesting high protein content.

Concentrations of P are exceptionally high at the beginning of season (Figure 3.4, A) when leaves are starting to expand, and far exceed the concentrations of P determined for other tall British herbs (Allen unpublished, quoted in Lawson *et al.* 1980). Throughout the summer, concentrations of P decrease and at the end of season they are less than one-third of their original level.

Concentrations of K are also exceptionally high, approximately twice the highest values determined by Allen (unpublished), and the seasonal trend is unusual in that a peak concentration occurs in September (Figure 3.4, A). Usually, this element reaches a maximum concentration early in the season and then decreases faster than concentrations of N and P decrease (Lawson *et al.* 1980).

No significant seasonal trends are shown by concentrations of Ca and Mg, but end of season concentrations of Ca are characteristically high (Figure 3.4, B) and are within the range found in other species. Concentrations of Mg (Figure 3.4,B) are twice those found in bracken (Figure 2.3, B) but are within the range shown by other herbs (Lawson *et al.* 1980).

In butterbur rhizomes, concentrations of N and K show a significant decrease over the growing season, whereas concentrations of P, Mg, Ca and ash show no significant seasonal trend (Table 3.3). On 30 March and 19 September, the concentrations of N, P, K, Mg and ash in the rhizomes are lower than the corresponding concentrations in the above-ground tissues (Table 3.3, Figure 3.4). Concentrations of Ca, however, are greater in the rhizomes than in the above-ground tissues.

A comparatively large underground standing crop of butterbur rhizomes results in large pools of inorganic nutrients below ground. At the beginning of season, as much as 170 kg $ha^{-1}$ of N and 352 kg $ha^{-1}$ of K may be held in the rhizomes (Table 3.3), quantities similar to those held in the much larger rhizome standing crop at the bracken site (Table 2.4). Indeed, high concentrations of P in butterbur rhizomes result in a greater pool of P in butterbur rhizomes, even though the standing crops of bracken rhizomes are at least 50% greater than those of butterbur.

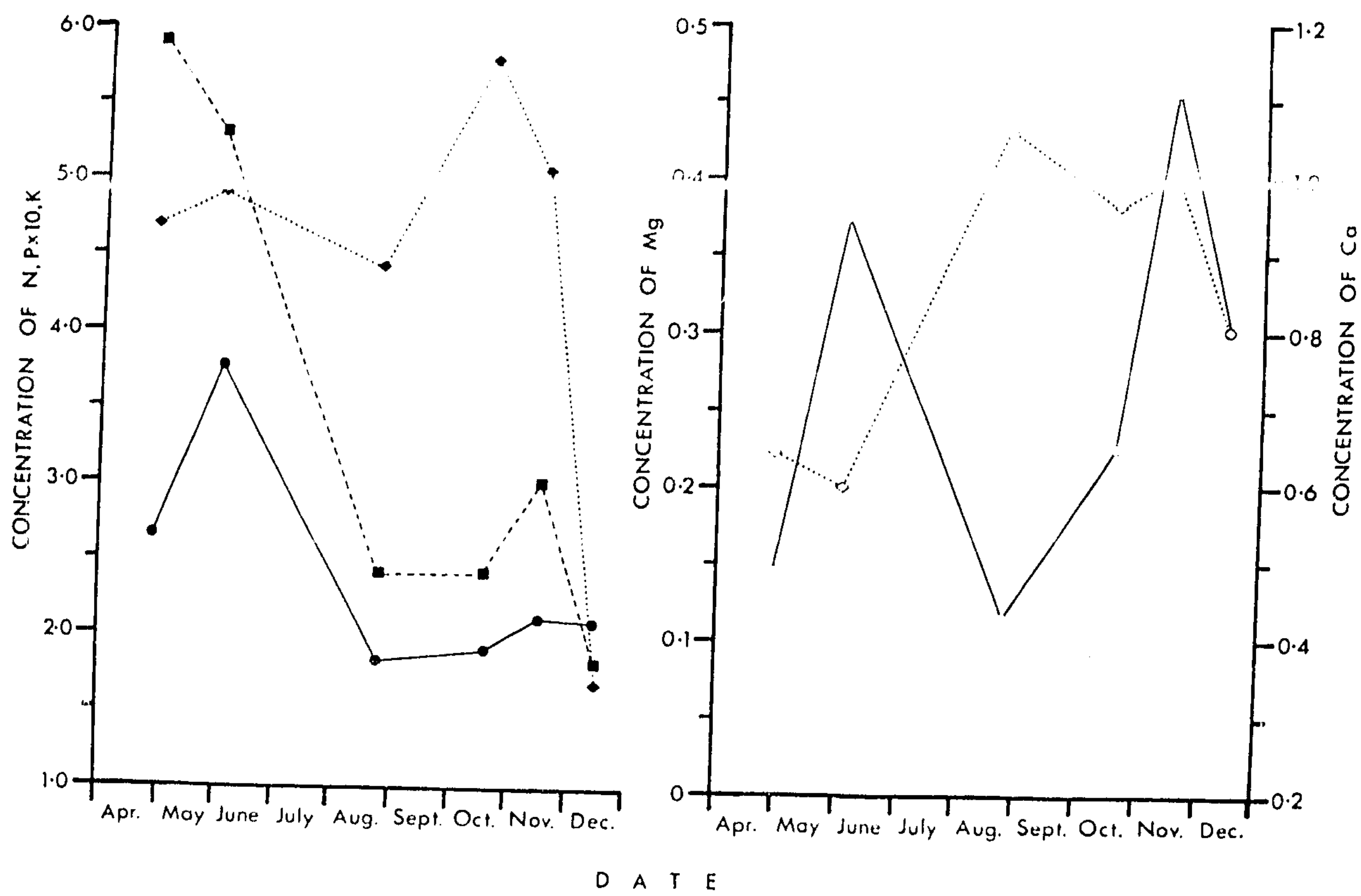


Figure 3.4 The seasonal trends of concentrations of inorganic nutrients (% dry weight) in leaves and petioles of butterbur from the Chisworth site.

A Concentrations of N (solid line and solid circles), P (broken line and solid squares) and K (dotted line and solid diamonds).

B Concentrations of Ca (solid line and open circles) and Mg (dotted line and open diamonds).

NB Concentrations of P are 1/10th of those of N and K.

TABLE 3.3 Concentrations and contents (concentrations x dry weight) of inorganic nutrients in butterbur rhizomes from the Chisworth site.

| ELEMENT | CONCENTRATION (% dry weight) | | | CONTENT ($kg\ ha^{-1}$) | | |
|---|---|---|---|---|---|---|
| | 30 March | 19 September | 14 December | 30 March | 19 September | 14 December |
| N | 1.90 | 1.01 | 1.40 | 170.2 | 89.8 | 114.4 |
| P | 0.34 | 0.23 | 0.20 | 30.5 | 20.5 | 16.3 |
| K | 3.93 | 2.83 | 2.93 | 352.1 | 251.6 | 239.4 |
| Ca | 0.70 | 0.90 | 0.95 | 62.7 | 80.0 | 77.6 |
| Mg | 0.079 | 0.075 | 0.075 | 7.08 | 6.67 | 6.13 |
| Ash | 10.3 | 9.1 | 8.7 | 920.2 | 806.3 | 710.8 |

There appears to be a compensating balance between the pools of Ca and Mg in the rhizomes of bracken and butterbur, in that the pool of Ca in butterbur is approximately 4 times that in bracken, but the pool of Mg is only one-quarter of that in bracken (Tables 3.3, 2.4).

A clear mid-season peak of nutrient contents occurs in the above-ground tissues of butterbur and this corresponds to peak standing crop (Table 3.4, Figure 3.5). Indeed, the seasonal trend of N, P and K in leaves and petioles of butterbur closely follow the seasonal trend of standing crop (Figure 3.5), which suggests that nutrients are not re-translocated into the rhizomes (as in the case of bracken), but are returned to the soil each year in the highly efficient decomposition process at this site. A harvesting strategy at this site would be directed towards harvesting the maximum amount of green matter for processing in an anaerobic digestor, with the subsequent return to site of the nutrient-rich residues. Accumulations of ash (Table 3.4) would, however, be great because of the apparent lack of nutrient translocation to below ground organs.

The re-growth of above-ground tissues of butterbur would probably be quickly affected by harvesting if fertilizers were not added, because the pools of nutrients in the rhizomes are not much greater than those removed from the site in leaves and petioles (Tables 3.3, 3.4). However, the application of fertilizer should result in an increased yield, as the roots appear to be efficient in taking up nutrients from the soil after the annual decomposition cycle which seems to replace re-translocation of nutrients from above- to below-ground tissues. The levels of N and P which would be needed from artificial fertilizers to replace nutrients lost in harvesting would be in the range traditionally applied to cereals and 2-7 year grass leys (Church 1975). However, approximately twice the traditional application of K would be necessary, because of the very high content of this element in leaves and petioles of butterbur at peak standing crop (Table 3.4).

### 3.6.2 Organic fractions

Concentrations of soluble carbohydrates reach high values of nearly 50% of the dry weight of shoots of butterbur, but the values fluctuate greatly over the growing season (Figure 3.6, A). The seasonal trend suggets that young emergent shoots contain a large source of energy in soluble carbohydrates which is used up during extension growth. After extension growth, soluble carbohydrate concentrations increase as photosynthesis takes place (compare with leaf development in Figure 3.2). At the end of season, however, concentrations of soluble carbohydrates are still very high (the data for October are probably anomalous), and it is possible that this energy source is not translocated into rhizomes at the end of season but decomposes over the winter. This strategy would agree with the evidence that N, P and K are re-cycled externally rather than internally, and perhaps explains why decomposition is so rapid.

Concentrations of crude fat and starch show no clear seasonal trends and, as in the case of bracken, appear to follow the same fluctuations within the season (Figure 3.6, A). High concentrations of the 3 energy-storing compounds suggest that the shoots of butterbur will be a good substrate for chemical conversion methods using fresh biomass as a feedstock. The apparent lack of translocation of soluble carbohydrates into rhizomes at the end of season would suggest that, unlike bracken, shoots could be harvested at peak standing crop without greatly affecting subsequent re-growth.

TABLE 3.4 The inorganic nutrient contents (concentration x dry weight) of leaves and petioles of butterbur from the Chisworth site throughout the growing season of 1979. Values are given in kg $ha^{-1}$.

| ELEMENT | 30 MARCH | 3 MAY | 25 JULY | 19 SEPTEMBER | 17 OCTOBER | 14 DECEMBER |
|---|---|---|---|---|---|---|
| N | 4.27 | 27.1 | 130.9 | 69.4 | 33.4 | 19.3 |
| P | 0.94 | 3.82 | 17.16 | 8.76 | 4.77 | 1.67 |
| K | 7.52 | 35.3 | 314.6 | 209.9 | 80.0 | 15.6 |
| Ca | 0.78 | 6.84 | 30.8 | 23.7 | 17.7 | 7.44 |
| Mg | 0.35 | 1.44 | 30.8 | 13.9 | 6.36 | 2.79 |
| Ash | 20.8 | 72.0 | 1001.0 | 657.0 | 275.1 | 123.7 |

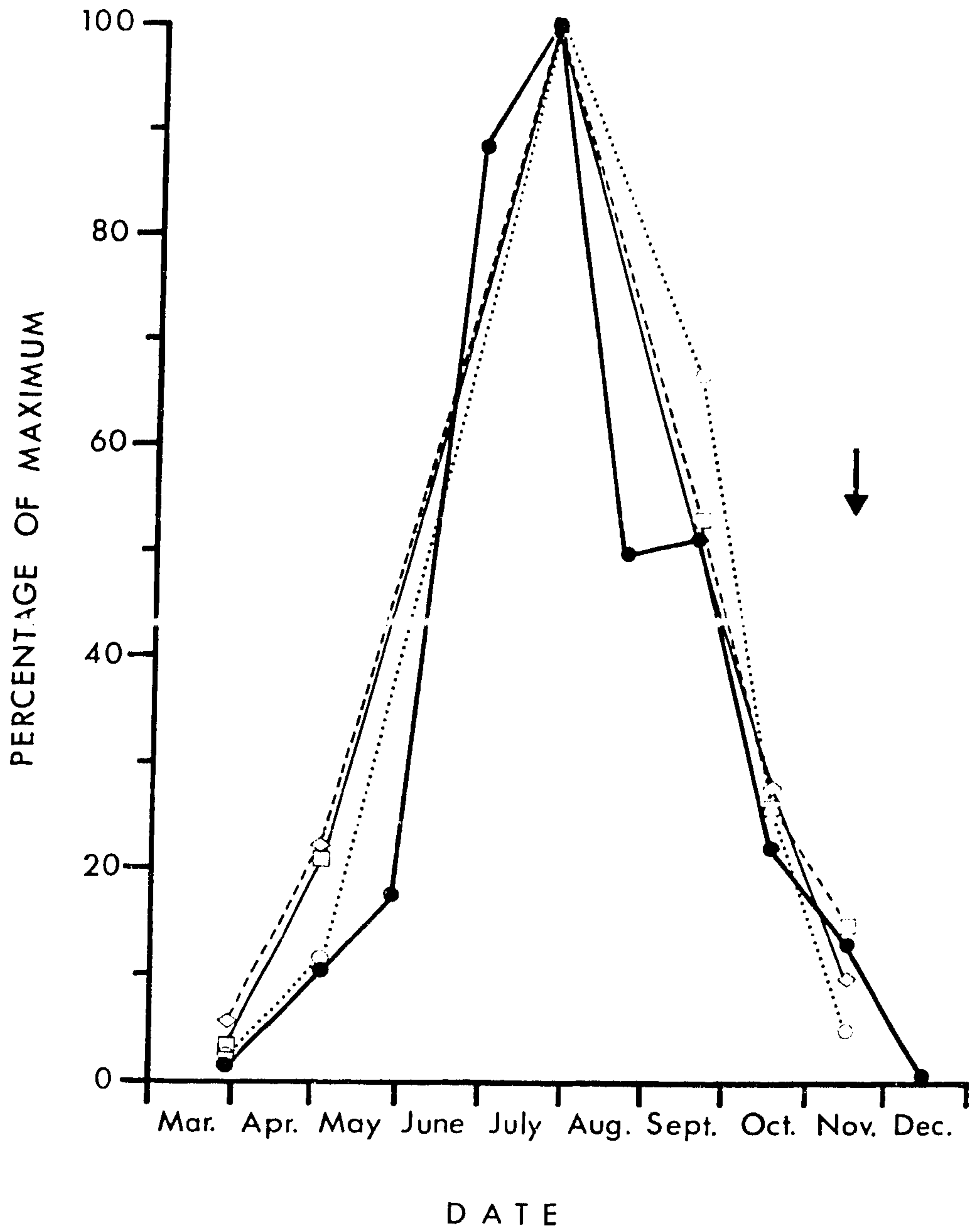


Figure 3.5 The relationship between the seasonal trend of standing crop (thick solid line and solid circles) and the total contents of N (broken line and open squares), P (thin solid line and open diamonds) and K (dotted line and open circles) in leaves and petioles of butterbur from the Chisworth site. All values are expressed as percentages of the maxima to standardise the vertical axis. The arrow denotes the date by which the above-ground tissues had died.

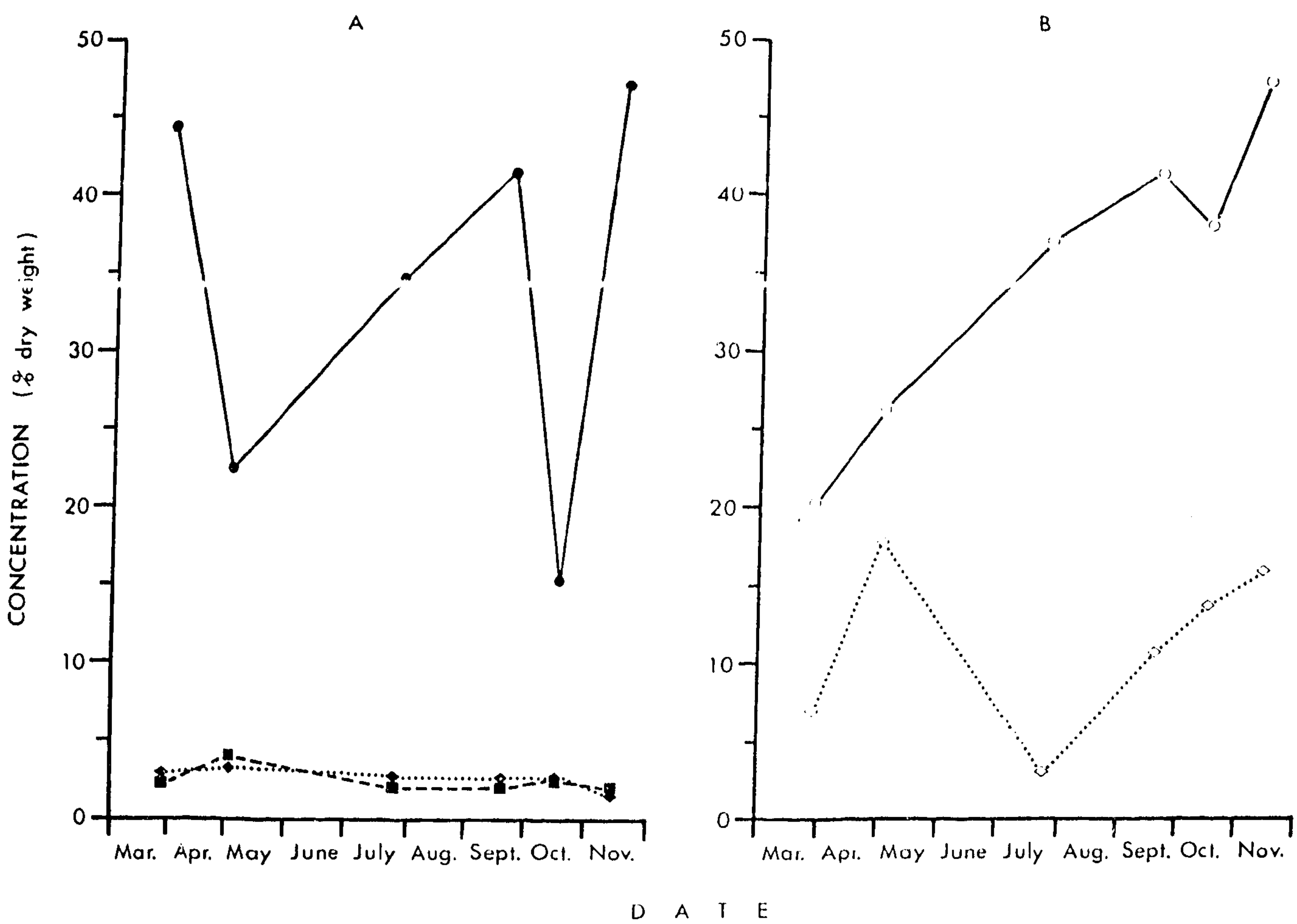


Figure 3.6 The seasonal trends of concentrations of organic plant fractions in shoots of butterbur from the Chisworth site.

A Soluble carbohydrates (solid circles and line), crude fat (solid diamonds and dotted line) and starch x 10 (solid squares and broken line).

B Holocellulose (open circles and solid line) and lignin (open diamonds and dotted line).

NB Concentrations of starch are 1/10th of the values on the Y axis.

Butterbur shows much lower concentrations of holocellulose in its shoots (Figure 3.6, B) than bracken, but lignin concentrations are very similar in both species. As in bracken, there appears to be an increase in the concentrations of both fractions at the end of season, but, if shoots were harvested at peak standing crop (in July), fibrous tissues would be at their minimum concentrations.

In the rhizomes of butterbur, concentrations of soluble carbohydrates are very high reaching 68% in December (Table 3.5). On the other hand, concentrations of starch and fats are similar to those in the shoots (Table 3.5), and the low concentrations of starch (about 50 times lower than those in bracken) suggest that the rhizomes of butterbur are not simply an over-wintering storage organ. The presence of a mobile (soluble carbohydrate) rather than immobile (starch) energy source in the rhizomes of butterbur at the end of season may, to some extent, reflect the production of shoots at this time - a situation which contrasts with the emergence of bracken shoots in spring.

High concentrations of soluble carbohydrates and low concentrations of cell wall materials (Table 3.5) suggest that rhizomes of butterbur would make a good substrate for anaerobic digestion, if harvesting were feasible. The large and mobile pool of soluble carbohydrates in the rhizomes, together with the possibly insignificant end-of-season translocation of soluble carbohydrates from shoots to rhizome, suggests that the harvesting of shoots at peak standing crop would exert little effect on subsequent re-growth - a fact casually observed in the field over 3 years.

The energy contents of the dry matter of shoots of butterbur vary little over the growing season (Figure 3.7), and the mean energy content over the growing season is 20.0 $\pm$ 0.24 KJ $g^{-1}$, compared with 18.9 $\pm$ 0.26 KJ $g^{-1}$ for the rhizomes. If shoots of butterbur were harvested at peak standing crop, over 140 x $10^9$ J $ha^{-1}$ would result, but other species at the site could increase this to ca 180 x $10^9$ J $ha^{-1}$, while the harvesting of rhizomes would further increase the energy yield to ca 340 x $10^9$ J $ha^{-1}$. However, the latter figure could not be sustained on an annual basis.

## 3.7 A summary of the potential of butterbur as an energy crop

3.7.1 Butterbur could be managed as an opportunity energy crop but, because of its limited distribution in England, Scotland and Wales (ca 33.5 $km^2$), it would only be important in a few areas such as the Scottish Islands where it is abundant. Elsewhere, it may be harvested for fuel in the vegetation of riversides and roadsides.

3.7.2 Butterbur leaves and petioles would be harvested at peak standing crop (25 July at the Chisworth site in 1979) as they collapse at the end of season and decompose rapidly .

3.7.3 Dry matter yields of shoots were 7.2 t $ha^{-1}$ (142 x $10^9$ J $ha^{-1}$) at the Chisworth site, and other species associated with butterbur increased the yield to 8.2 t $ha^{-1}$ (ca 162 x $10^9$ J $ha^{-1}$).

3.7.4 Shoots of butterbur harvested at peak standing crop should form an extremely good substrate for anaerobic digestion, as the water content is over 85% of the fresh weight, concentrations of N, P and K are high (1.8, 0.24 and 4.4% dry weight respectively), concentrations

TABLE 3.5 Concentrations (% dry weight) of organic plant fractions in the rhizomes of butterbur collected from the Chisworth site.

| COMPOUND | CONCENTRATION | | |
|---|---|---|---|
| | 30 March | 19 September | 14 December |
| Soluble carbohydrates | 53.7 | 57.7 | 68.3 |
| Starch | 0.27 | 0.48 | 0.68 |
| Crude fat | 2.1 | 1.9 | 1.9 |
| Lignin | < 1.0 | < 1.0 | < 1.0 |
| Holocellulose | 31.0 | 25.7 | 24.0 |

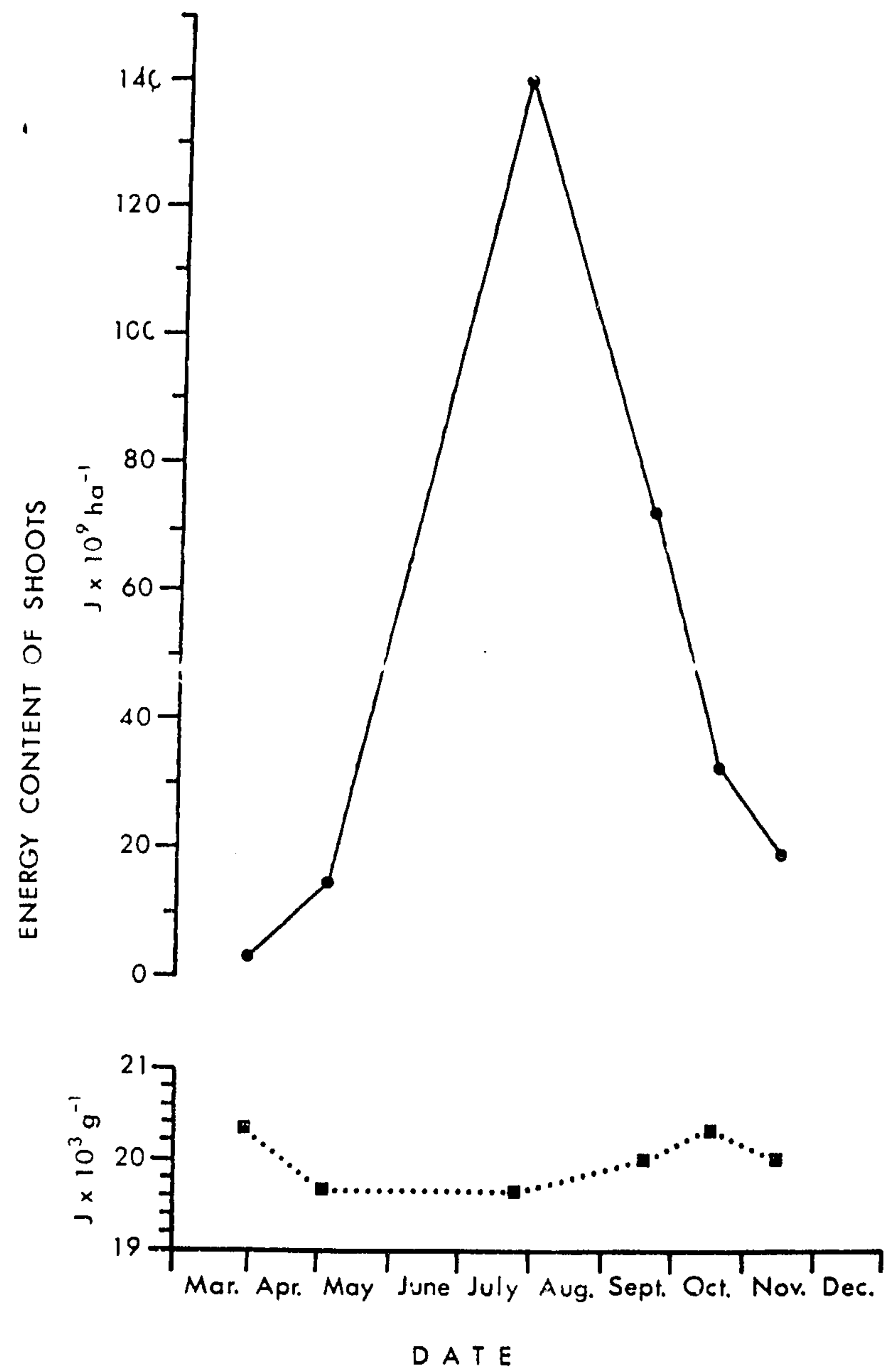


Figure 3.7 The energy content of shoots of butterbur throughout the growing season expressed on a land area basis and on a unit dry weight basis.

of soluble carbohydrates are much higher than in the other species investigated (35% dry weight), and compounds more resistant to digestion (holocellulose and lignin) occur in only small concentrations (37 and 3% dry weight respectively). An ash concentration of 13.9% would remain in the residues produced by a chemical conversion process.

3.7.5 The re-growth of butterbur in the year after harvesting should not be significantly affected by removing biomass, as the soluble carbohydrates in the shoots appear to be decomposed on the soil surface rather than translocated into the rhizomes at the end of season. Indeed, re-growth within a season occurs and 2 cuts can increase total yield by 1 t $ha^{-1}$. However, long-term effects of harvesting biomass can only be evaluated in long-term experiments.

3.7.6 Application of N and P to areas of harvested butterbur would be in the range of those currently applied to agricultural crops, if the N and P removed in biomass (131 and 17 kg $ha^{-1}$ respectively) were to be replaced. Applications of K, however (315 kg $ha^{-1}$) would be far greater than traditional applications (29 to 183 kg $ha^{-1}$) of this element in agriculture.

3.7.7 Butterbur appears to re-cycle its nutrients externally (through decomposition) rather than internally (through translocation), as in bracken. It should, therefore, be efficient in taking up and utilizing nutrients added to the soil, and there may be significant potential for increasing yields by adding fertilizer.

3.7.8 Although it is technologically feasible to harvest butterbur from waterlogged habitats by using equipment similar to that developed in Sweden for harvesting reeds, this would probably only be efficient in the large stands of butterbur on the Scottish Islands.

3.7.9 If rhizomes of butterbur were harvested in, for example, a programme of land improvement for agriculture, a yield of 8.7 t $ha^{-1}$ ($164 \times 10^9$ J $ha^{-1}$) could be expected, and this material should be amenable to anaerobic digestion as the soluble carbohydrate concentration reaches 68% dry weight.

## 3.8 Conclusion

Butterbur would be harvested at peak standing crop, as shoots quickly collapse at the end of season. The shoots should provide a readily digestible substrate for chemical conversion, but the high nutrient contents would require high fertilizer applications to maintain yield.

# 4 *SPARTINA ANGLICA* - CORD-GRASS

## 4.1 General description

This grass is a stout perennial which reaches a height of 50 to 130 cm (Clapham *et al.* 1962). It reproduces vegetatively in established clones, but sexually fertile plants are widespread (Clapham *et al.* 1962).

## 4.2 Distribution and extent

*Spartina anglica* is thought to be a vigorous descendant of the sterile hybrid *S.* x *townsendii*, which arose in Southampton water where it was first recorded in 1870 (Hubbard 1968). *Spartina anglica* was first collected at Lymington, Hampshire, in 1892 but by 1907 many thousands of hectares of tidal mud-flats between Sussex and east Dorset had been covered (Hubbard 1968). It is now abundant on tidal mud-flats up to southern Scotland (Figure 4.1, in which *S.* x *townsendii* and *S. anglica* have not been distinguished), and, although frequently planted as a mud-binder, its vigorous growth is controlled by herbicides in areas where it is regarded as scenically undesirable.

Cord-grass forms dense and extensive stands (Plate 1c), and it is thought to occupy 120 $km^2$ of land around Great Britain's coast (Ranwell 1967).

## 4.3 Rate of development

Leaf emergence in spring is comparatively late at the Rampside site, occurring in late May and early June. The subsequent development of the plant is also slow, so that a maximum standing crop is obtained in late autumn or early winter when seed-set occurs (Figure 4.2). After peak standing crop has been achieved, the rate of death of the above-ground tissues increases over winter, but green tissue is still present in the new year. No green material is evident in March of the second year, and much standing dead material persists until July of that year (Figure 4.2). The late development of cord-grass contrasts markedly with the early development of butterbur (Figure 3.3).

## 4.4 Productivity

Previous estimates of the annual productivity of cord-grass shoots and rhizomes vary from 9.6 to 9.8 t $ha^{-1}$ $yr^{-1}$ (Ranwell 1961; Jefferies 1972), with a peak above-ground standing crop of 7.5 t $ha^{-1}$, to 41 t $ha^{-1}$ (Dunn & Long 1980). The latter figure, however, makes a large allowance for leaf turn-over. The intensive site at Rampside (site number 2, Appendix II) used during the present study showed a peak standing crop of the current year's above-ground growth of 6.1 t $ha^{-1}$ (Figure 4.2), but at Southport (site number 21, Appendix II) the species was far more extensive and vigorous with a maximum standing crop of 16.8 ± 0.61 t $ha^{-1}$ on 10 October 1979 and a high standing crop of 11.4 ± 0.53 t $ha^{-1}$ on 20 December 1979.

Although development was slow at the Rampside site, a standing crop of at least 4.3 t $ha^{-1}$ was maintained for 4 months (Figure 4.2). After death of the above-ground tissues, standing dead matter was persistent, yielding 2.0 ± 0.2 and 2.4 ± 0.3 t $ha^{-1}$ on 5 June and 6 July, respectively.

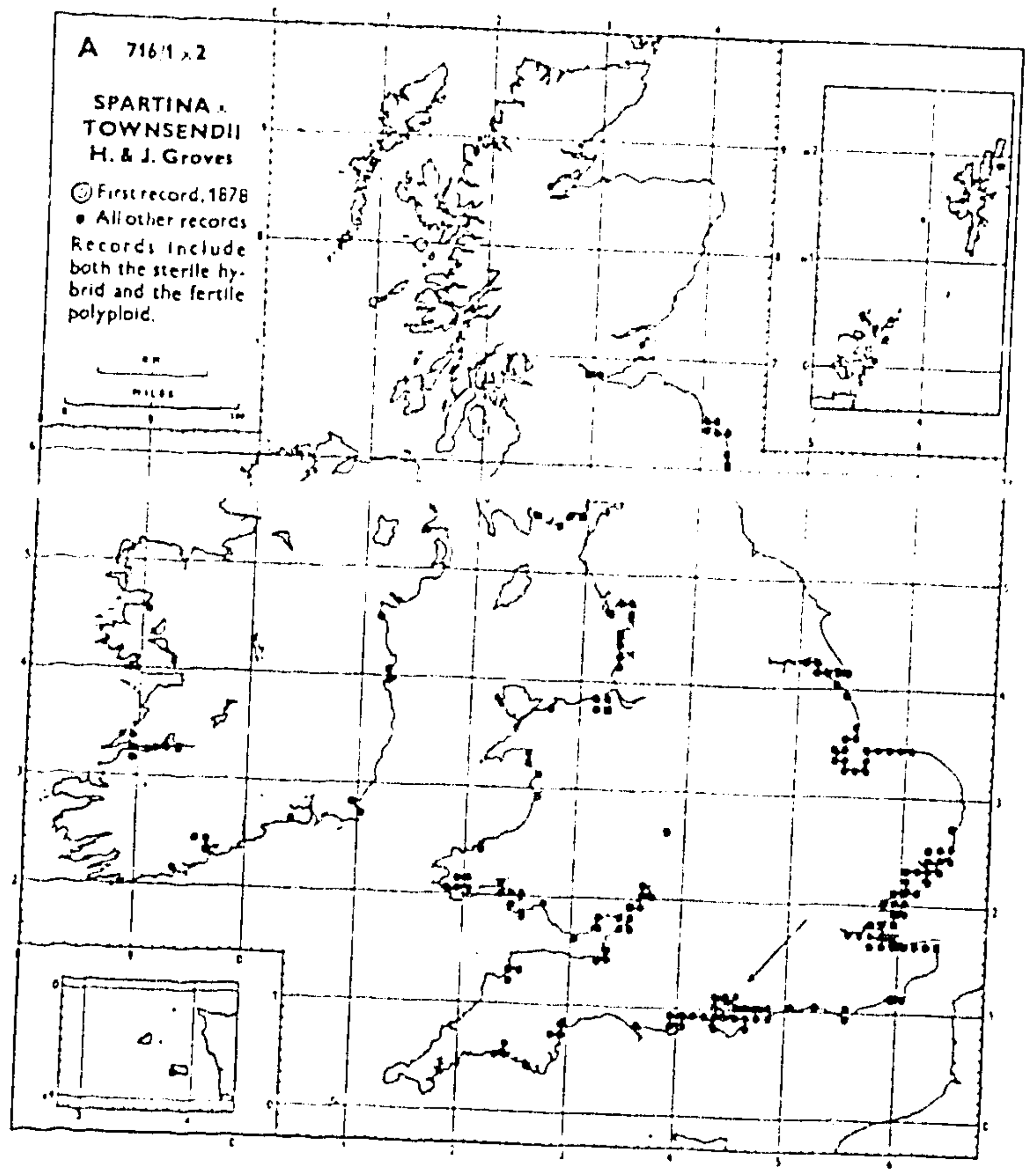


Figure 4.1 The distribution of cord-grass in Great Britain and Ireland; from Perring & Walters (1962).

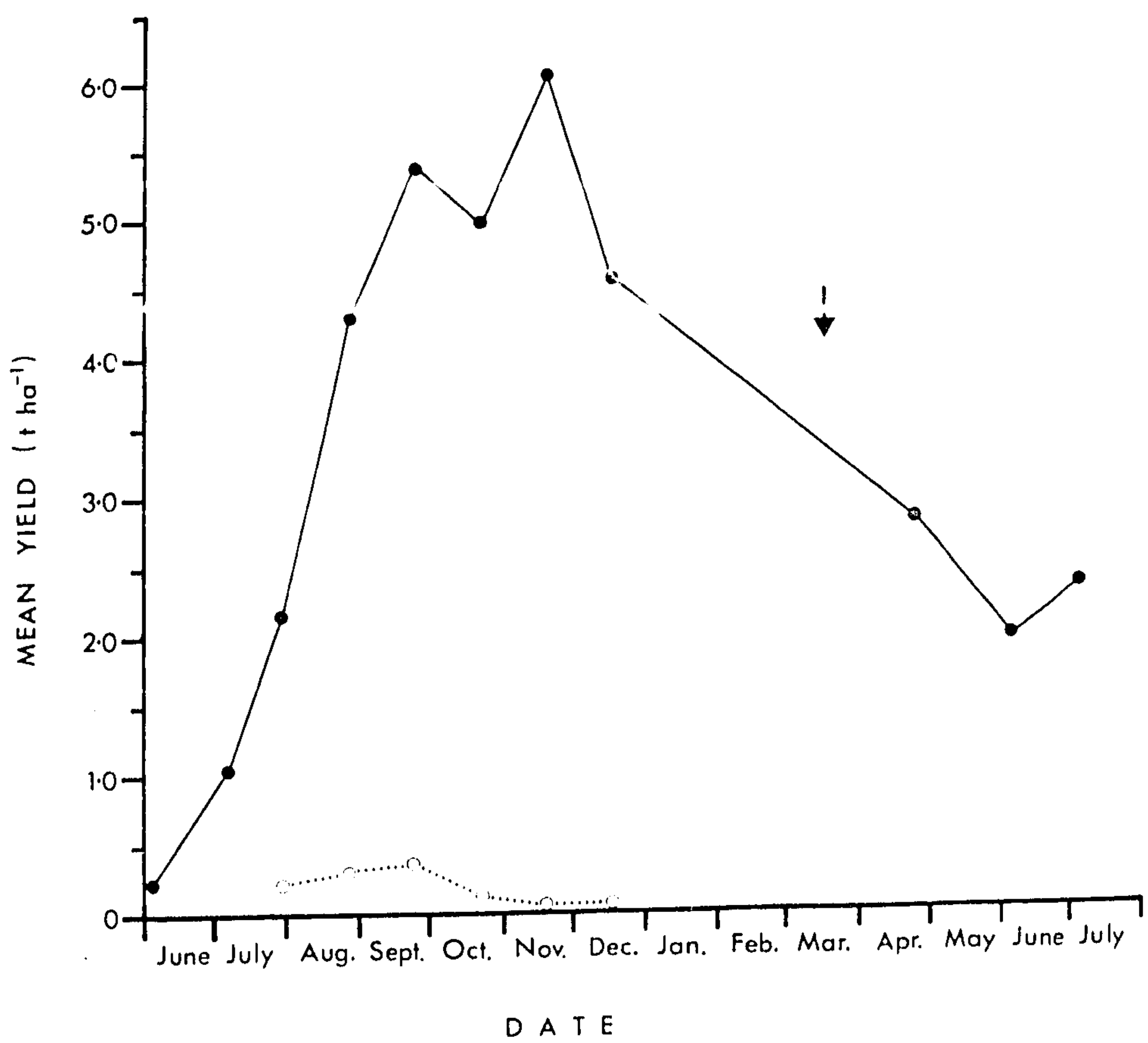


Figure 4.2 Seasonal trends of above-ground standing crops of cord-grass (solid line and solid circles) and other species at the Rampside site (dotted line and open circles). The arrow denotes the date by which all of the cord-grass leaves and stems had turned brown.

The water content of living leaves of cord-grass is about 60% with fresh weight/dry weight ratios of 3.0 ± 0.03 on 6 July and 3.4 ± 0.10 on 23 October. In the following year, when the leaves were dead, the water content was only 30 to 35% with fresh weight/dry weight ratios of 1.64 ± 0.08 on 25 April and 1.48 ± 0.04 on 6 July.

Standing crops of rhizomes vary considerably throughout the season from 4.1 ± 0.3 t $ha^{-1}$ on 5 June to 10.6 and 14.2 t $ha^{-1}$ on 20 November and 18 December, respectively. Unfortunately, no sample replication could be obtained at the end of season due to practical difficulties in extracting rhizomes from tidal mud-flats.

Other species growing at the site (mainly *Puccinellia maritima*, Appendix II) contributed very little to site yield as the maximum standing crop was only 0.36 t $ha^{-1}$ (Figure 4.2).

## 4.5 Re-growth after cutting

Grass leaves are usually produced continuously throughout the growing season and the potential for re-growth should be high. Indeed, Beddows (197[illegible]) showed that a maximum annual yield of *Lolium perenne* could be obtained by cutting 4 times in the growing season. It is surprising, therefore, that the re-growth of cord-grass is only 1.[illegible] t $ha^{-1}$ at its maximum (Table 4.1), following an early season cut. Re-growth after later cuts is so small that the energy input via harvesting is probably greater than the energy contained in the harvested material. The maximum standing crop of cord-grass is consistently greater than the standing crops at earlier stages in the plant's development, plus the re-growth after an earlier cut (Table 4.1). Thus, the potential for harvesting cord-grass more than once in the growing season is even less than that in the case of bracken, although fertilizer treatments during re-growth trials may alter these conclusions.

## 4.6 Nutrient content of cord-grass

### 4.6.1 Inorganic nutrients

Concentrations of N, P and K in leaves and stems showed a characteristic exponential decrease over the growing season, with K showing the slowest rate of decrease (Figure 4.3, A). Concentrations of N and P are within the range shown by bracken (Figure 2.3, A) and butterbur (Figure 3.4, A), but concentrations of K are generally much lower than those in the other 2 species. However, Na and K may be physiologically interchangeable in some species and high concentrations of Na occur in the saline environment of cord-grass, which might compensate for low concentrations of K. Unfortunately, Na analyses were not carried out.

Concentrations of Ca and Mg in stems and leaves show an increase over the growing season (Figure 4.3, B) and, again, this is typical of many species (Lawson *et al.* 1980). This trend is also evident in the rhizomes, but the concentrations of Ca and Mg are generally higher in the rhizomes than in the above-ground tissues (Figure 4.3, B). In contrast, concentrations of N, P and K in the rhizomes show slight decreases over the growing season (Table 4.2) and levels are lower than in the above-ground tissues (Figure 4.3, A). Concentrations of ash in the rhizomes (Table 4.2) and shoots (which can be calculated from Figure 3.2 and Table 4.3) are exceptionally high, reaching 44%.

TABLE 4.1 The re-growth of cord-grass leaves and stems after cutting at various times in the growing season. Units are t $ha^{-1}$.

| | 6 JULY | 31 JULY | 28 AUGUST | 25 SEPTEMBER | 23 OCTOBER | 20 NOVEMBER |
|---|---|---|---|---|---|---|
| Yield at specified date: | 1.04 | 2.17 | 4.30 | 5.39 | 4.95 | 6.06 |
| Re-growth after specified date: | 1.41 | 0.85 | 0.29 | 0.10 | 0.06 | - |
| Total yield: | 2.45 | 3.02 | 4.59 | 5.49 | 5.01 | 6.06 |

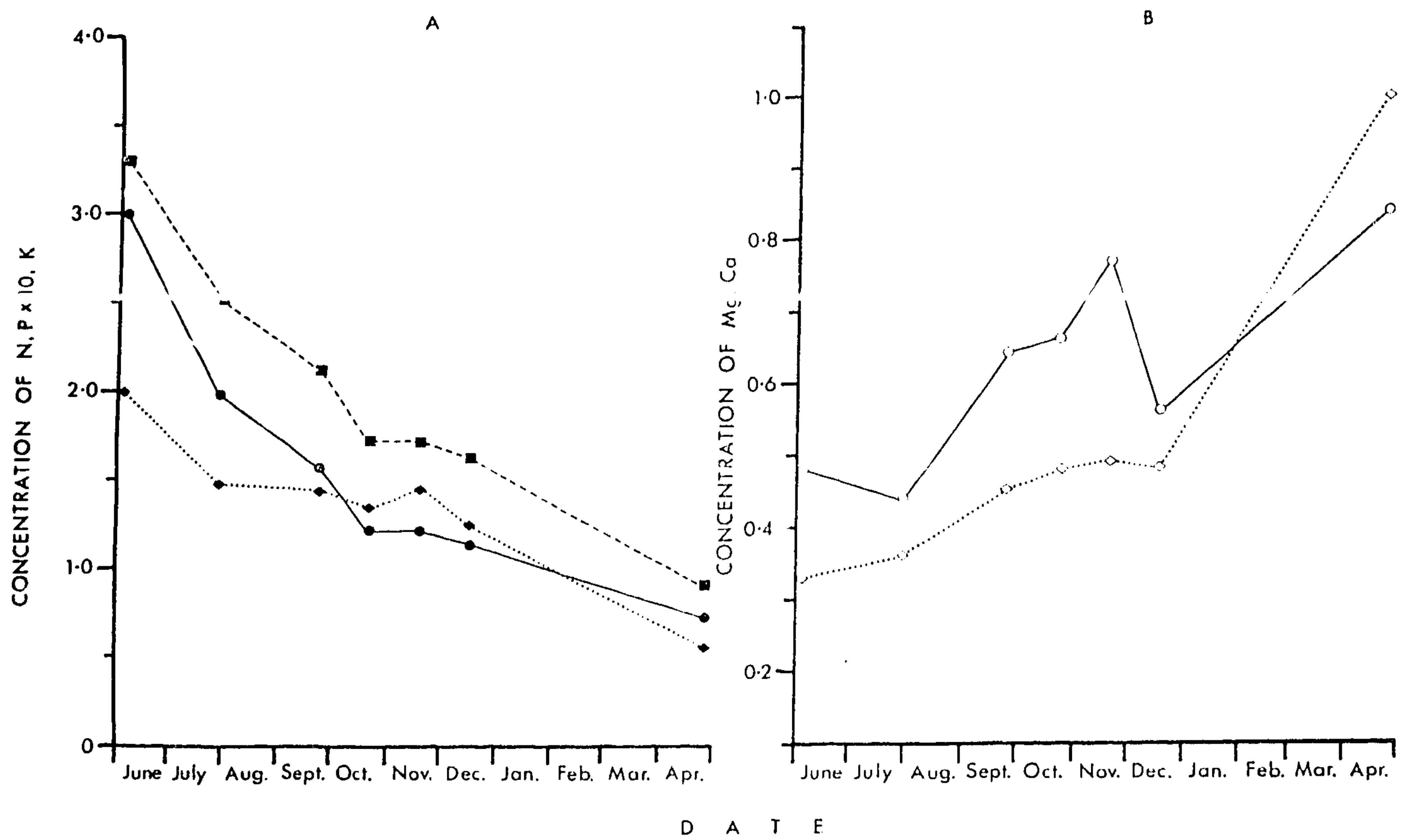


Figure 4.3 The seasonal trends of concentrations of inorganic nutrients (% dry weight) in shoots of cord-grass from the Rampside site.

A Concentrations of N (solid line and solid circles), P (broken line and solid squares) and K (dotted line and solid diamonds).

B Concentrations of Ca (solid line and open circles) and Mg (dotted line and open diamonds).

NB Concentrations of P are 1/10th of those of N and K.

TABLE 4.2 Concentrations and contents (concentration x dry weight) of inorganic nutrients in rhizomes of cord-grass.

| ELEMENT | CONCENTRATION (% dry weight) | | | CONTENT (kg ha$^{-1}$) | | |
|---|---|---|---|---|---|---|
| | 5 June | 20 November | 18 December | 5 June | 20 November | 18 December |
| N | 1.50 | 0.84 | 1.00 | 62.1 | 88.7 | 141.8 |
| P | 0.15 | 0.12 | 0.12 | 6.33 | 12.67 | 17.02 |
| K | 1.40 | 1.30 | 1.40 | 58.0 | 137.3 | 198.5 |
| Ca | 0.71 | 1.34 | 1.20 | 29.4 | 141.5 | 170.2 |
| Mg | 0.47 | 0.53 | 0.47 | 19.5 | 56.0 | 66.7 |
| Ash | 31.0 | 44.0 | 42.0 | 1283 | 4646 | 5956 |

The total amounts of N, P, K, Ca, and Mg in the rhizomes increase over the growing season (Table 4.2) as a result of increased standing crop at the end of season. However, because of lack of replication of rhizome biomass samples, few inferences can be made about nutrient content.

Although concentrations of N, P and K in cord-grass shoots decrease over the growing season (Figure 4.3, A), total N, P and K increase during the growing season (Table 4.3), due to the seasonal increase in standing crop (Figure 4.2). Similar trends are shown by contents of Ca and Mg although higher contents are evident in dead material which has over-wintered (Table 4.3).

Nutrient contents (Table 4.3) and dry weights (Figure 4.2) of cord-grass show relatively little variation between 25 September and 18 December. Harvesting above-ground tissues within this period would give a yield of between 4.6 and 6.1 t $ha^{-1}$ and would remove far less N, P and K than harvesting bracken and butterbur at peak standing crop. Removing the peak living standing crop of cord-grass would remove less N, P and K from the site than is traditionally applied to grassland and root-crops (Church 1975).

If the above-ground tissues of cord-grass were harvested after they had died, fewer nutrients would be removed (Figure 4.4). Whereas there is a very close relationship between the seasonal increase in dry weight and the contents of N, P and K, dry weight decreases at a slower rate than contents of N, P and K in senescing and dead tissues (Figure 4.4). This is the pattern previously described for bracken and probably represents translocation of N, P and K into the below-ground perennating tissues and eventually into new above-ground growth. If a harvest were taken on 25 April, 77% of the total N, 78% of the total P and 82% of the total K would have been naturally re-cycled, with a loss of 54% of the maximum standing crop (Figure 4.4). Harvesting dead cord-grass leaves and stems would therefore, probably affect re-growth less than harvesting green tissues, and would remove only small amounts of N, P and K which tend to be naturally replenished each year in the estuarine environment of cord-grass (Lawson *et al.* 1980).

Unfortunately, a large residue of ash would result from the chemical conversion of cord-grass, and this could be as high as 1.9 t $ha^{-1}$ (Table 4.3).

### 4.6.2 Organic fractions

Concentrations of the energy-storing compounds in the shoots of cord-grass show no clear seasonal trends (Figure 4.5, A), and concentrations of soluble carbohydrates are quite low when compared with those in bracken and butterbur. Concentrations of the cell wall materials also show no clear seasonal trends (Figure 4.5, B) and, whereas concentrations of holocellulose are similar to those in other species, concentrations of lignin are very low. However, the low levels of lignin may, to some extent, be an artefact resulting from the method of determination (see Appendix I). In general, the nature of the leaves of cord-grass is similar to that of other grass leaves, and conversion to fuels by, for example, anaerobic digestion, should be as efficient as in herbage grasses.

TABLE 4.3 The nutrient content (concentration x dry weight) of cord-grass leaves and stems during the annual cycle. Units are kg $ha^{-1}$.

| ELEMENT | 5 JUNE | 31 JULY | 25 SEPTEMBER | 23 OCTOBER | 20 NOVEMBER | 18 DECEMBER | 25 APRIL |
|---|---|---|---|---|---|---|---|
| N | 6.9 | 42.8 | 84.6 | 59.4 | 72.7 | 50.9 | 19.9 |
| P | 0.76 | 5.43 | 11.32 | 8.42 | 10.30 | 7.20 | 2.46 |
| K | 4.6 | 31.9 | 77.1 | 65.8 | 86.7 | 55.4 | 15.3 |
| Ca | 1.10 | 9.55 | 34.50 | 32.67 | 46.66 | 25.20 | 23.60 |
| Mg | 0.76 | 7.81 | 24.26 | 23.76 | 29.69 | 21.60 | 28.84 |
| Ash | 50.6 | 362 | 1256 | 1337 | 1859 | 1080 | - |

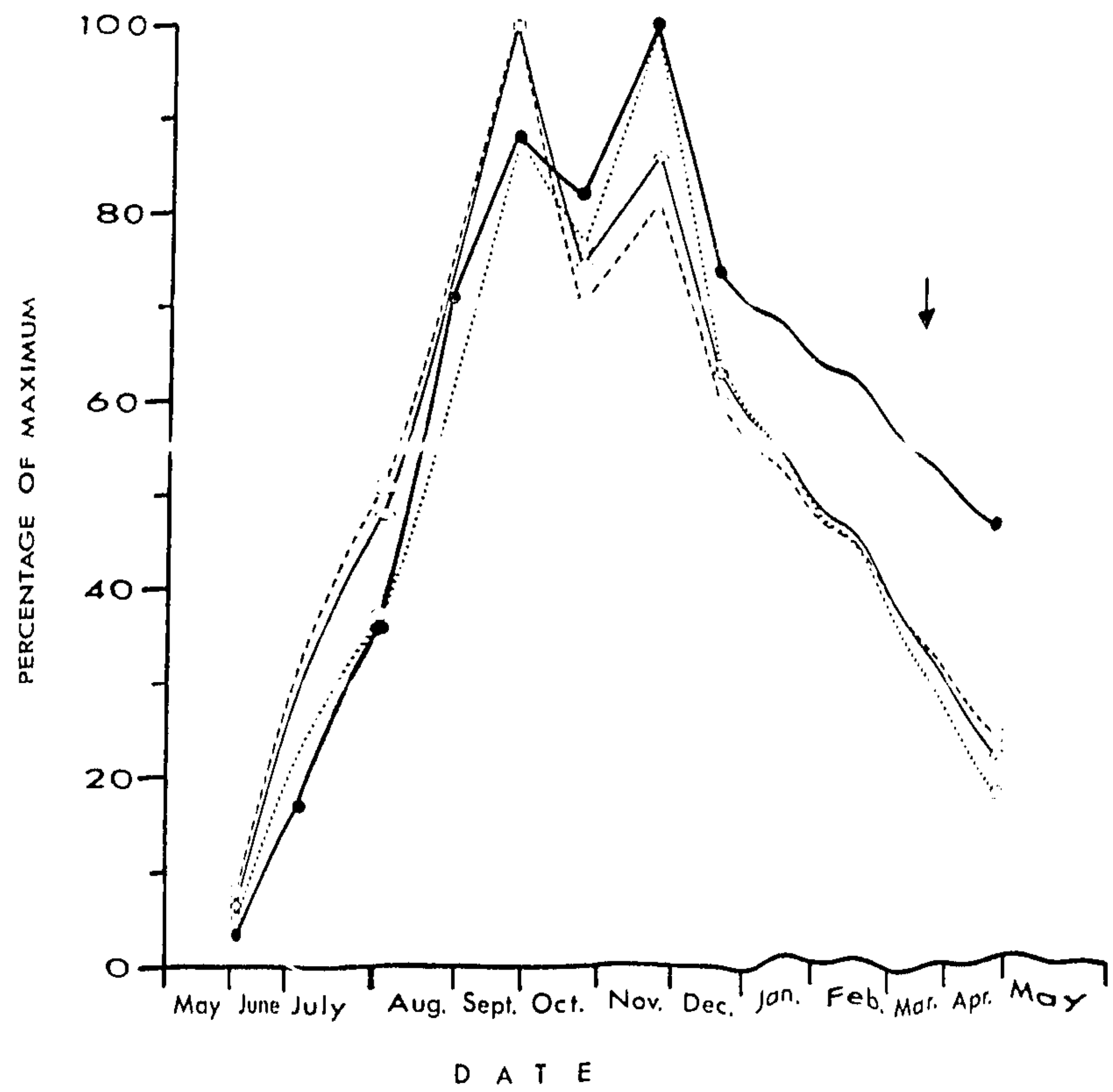


Figure 4.4 The relationship between the seasonal trend of standing crop (thick solid line and solid circles) and the total contents of N (broken line and open squares), P (thin solid line and open diamonds) and K (dotted line and open circles) in leaves and stems of cord-grass from the Rampside site. All values are expressed as percentages of the maxima to standardise the vertical axis. The arrow denotes the date by which the above-ground tissues had died.

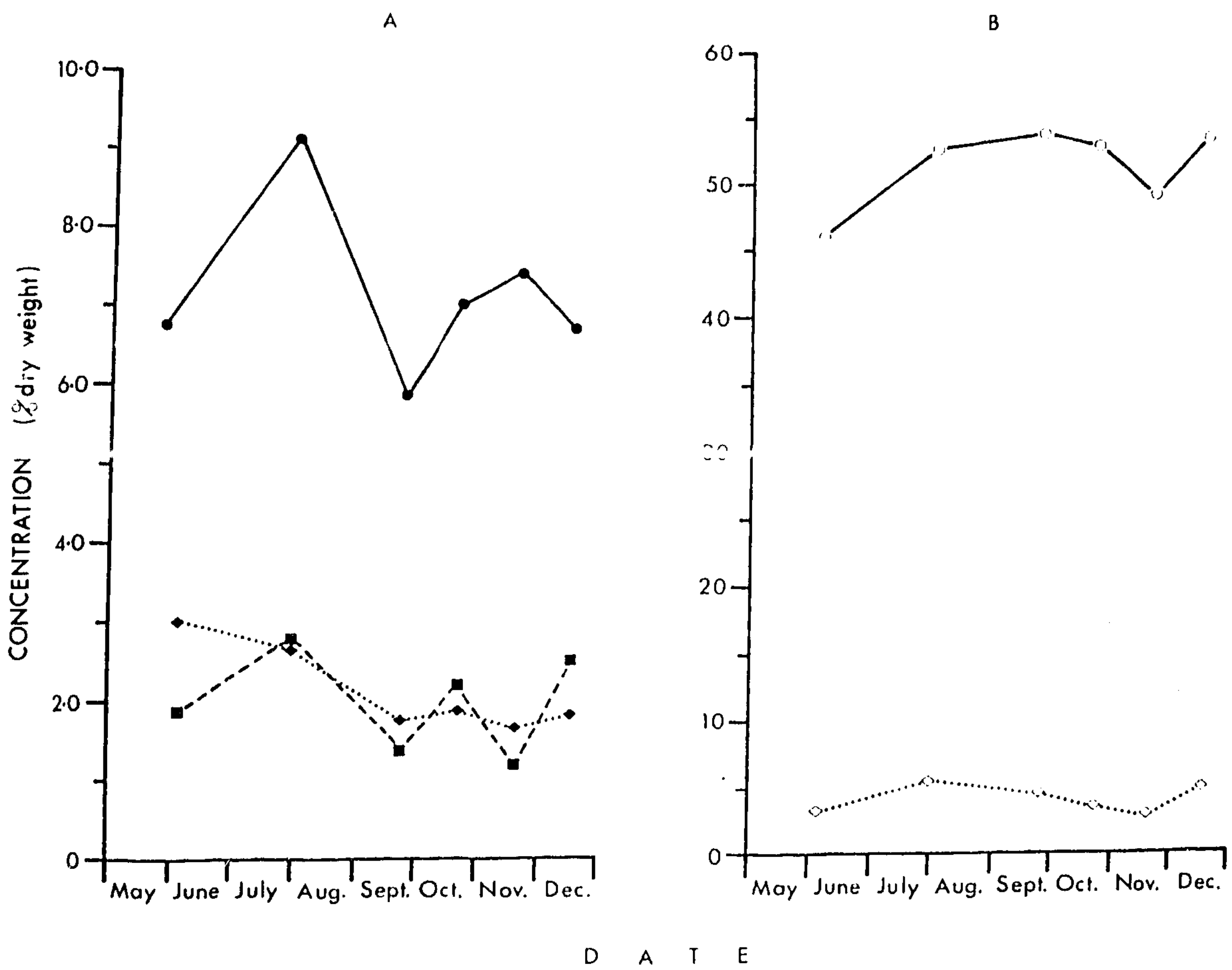


Figure 4.5 The seasonal trends of concentrations of organic plant fractions in shoots of cord-grass collected from the Rampside site.

A Soluble carbohydrates (solid circles and line), crude fat (solid diamonds and dotted line) and starch x 10 (solid squares and broken line).

B Holocellulose (open circles and solid line) and lignin (open diamonds and dotted line)

NB Concentrations of starch are 1/10th of the values on the Y axis.

The absence of seasonal trends in the concentrations of the organic plant fractions suggests that marked translocation of energy-storing compounds into the rhizomes is absent, and it follows that harvesting at peak standing crop would exert little effect on subsequent re-growth. Indeed, the concentrations of energy-storing compounds in the rhizomes are very low (Table 4.4) when compared with those in other species, and the shoots are probably self-sufficient in energy terms soon after their production in spring.

The energy contents of shoots on a dry weight basis are similar to those in other species and show no clear seasonal trends (Figure 4.6). An overall mean of 20.7 ± 0.18 KJ $g^{-1}$ is shown by the shoots and a similar value (20.6 ± 0.30 KJ $g^{-1}$) by the rhizomes.

If shoots were harvested at peak standing crop, an energy yield of 126 x $10^9$ J $ha^{-1}$ would be obtained (Figure 4.6) whereas shoots harvested during senescence (eg during March, Figure 4.2) would yield 73 x $10^9$ J $ha^{-1}$, assuming a mean energy content of 20.7 KJ $g^{-1}$ dry weight. Shoots harvested during senescence, however, would probably require a thermal conversion method for fuel production.

## 4.7 A summary of the potential of cord-grass as an energy crop

4.7.1 Cord-grass would be managed as an opportunity energy crop as it grows in estuaries where there is little competition for other forms of land use. It presently occupies 120 $km^2$ of Great Britain's coast, and expensive control measures are being taken to restrict its spread. However, if used for energy, cord-grass could be allowed to increase its distribution under the control of harvesting programmes.

4.7.2 The maximum dry matter yield of shoots at an intensively studied site was 6.1 t $ha^{-1}$ (127 x $10^9$ J $ha^{-1}$), but this figure was low when compared with records in the literature and results from a less intensively studied site which yielded 16.8 t $ha^{-1}$ (353 x $10^9$ J $ha^{-1}$). Cord-grass is, therefore, potentially a high yielding species.

4.7.3 Shoots of cord-grass harvested at peak standing crop should not be resistant to anaerobic digestion, as water content is about 60% of the fresh weight, concentrations of N, P, K and soluble carbohydrates are moderate (1.2, 0.17, 1.4 and 7.4% dry weight respectively), and concentrations of holocellulose and lignin (50 and 2.9% dry weight respectively) are low. Unfortunately, however, the chemical conversion of cord-grass to a fuel would generate considerable quantities of ash, as the ash concentration is 31% of the shoot dry weight.

4.7.4 The re-growth of shoots of cord-grass is poor within the season of harvesting, but re-growth in subsequent years should be good as it does not appear to depend on any marked end of season translocation of soluble carbohydrates from shoots to rhizomes. The removal of soluble carbohydrates in harvested biomass should not, therefore, significantly affect re-growth.

4.7.5 It may not be necessary to apply fertilizer to replace nutrients removed in harvested biomass, as the estuarine environment of cord-grass is naturally flushed with nutrients. However, if it were necessary to apply replacement amounts of N, P and K (73, 10 and 87 kg $ha^{-1}$ respectively) to areas of cord-grass harvested at peak standing crop, the required amounts would be lower than those currently applied to agricultural crops.

TABLE 4.4 Concentrations (% dry weight) of organic plant fractions in the rhizomes of cord-grass collected from the Rampside site.

| COMPOUND | CONCENTRATION | | |
|---|---|---|---|
| | 5 June | 20 November | 18 December |
| Soluble carbohydrate | 2.03 | 8.87 | 8.9 |
| Starch | 0.21 | 0.17 | 0.18 |
| Crude fat | 1.27 | 0.60 | 0.73 |
| Lignin | 4.61 | < 1.0 | < 1.0 |
| Holocellulose | 51.7 | 42.7 | 43.0 |

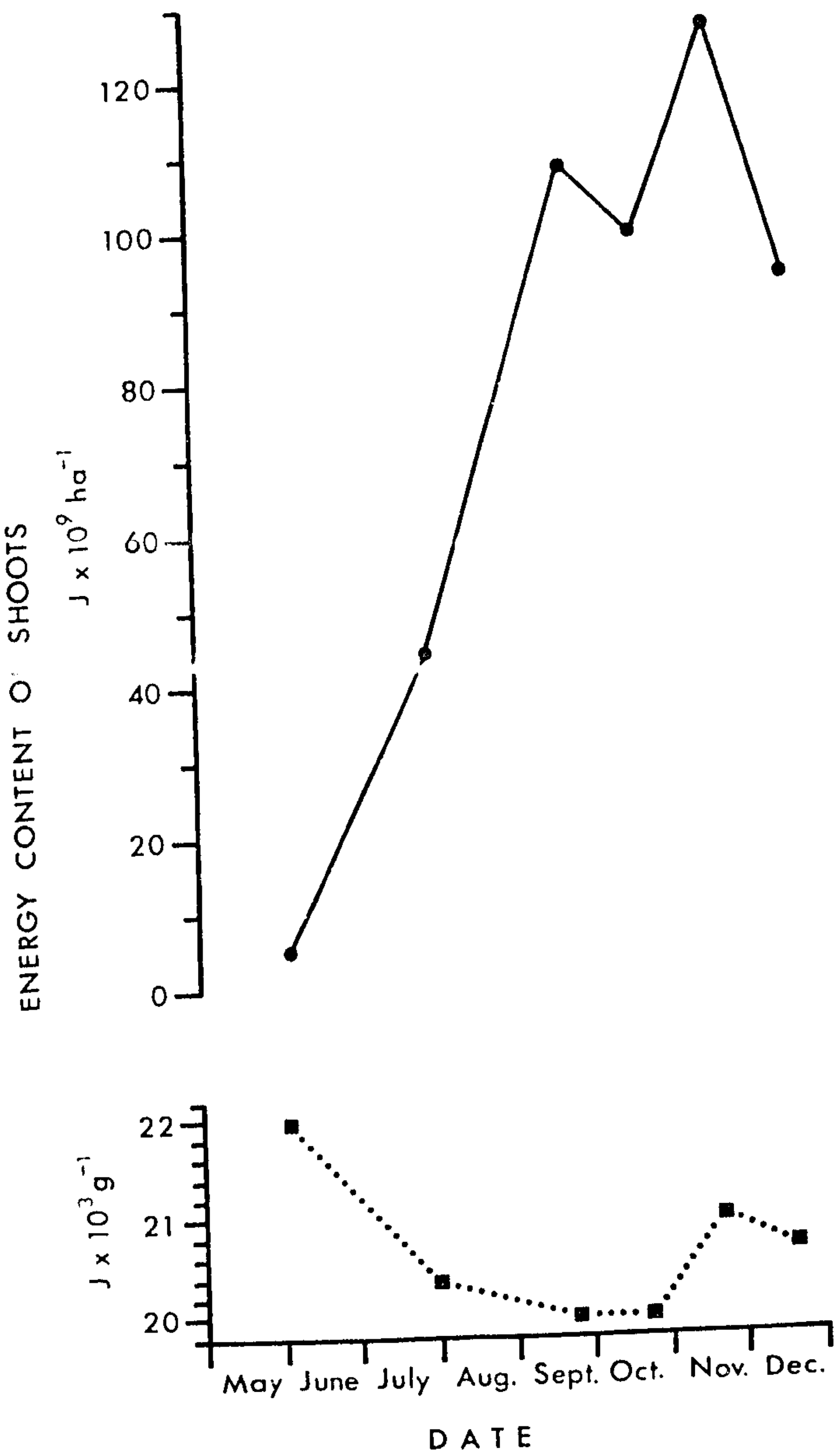


Figure 4.6 The seasonal trends of the energy contents of shoots of cord-grass expressed on a land area basis and on a unit dry weight basis.

4.7.6 If shoots of cord-grass were harvested when senescent, it would be possible to harvest throughout the winter months, but a thermal conversion process would probably be required to produce fuel from the biomass. A yield of at least 4 t $ha^{-1}$ (83 x $10^9$ J $ha^{-1}$) should be obtained, while a yield of 11.4 t $ha^{-1}$ (237 x $10^9$J $ha^{-1}$) was obtained in late December at one site.

4.7.7 The harvesting of senescent shoots of cord-grass should have no significant effect on re-growth (dead leaves are often removed by the tide), and fertilizer applications would be unnecessary as about 80% of the N, P and K in the shoots is re-cycled naturally. Using this harvesting strategy, therefore, it should be possible to obtain good annual yields of cord-grass indefinitely.

4.7.8 It is improbable that rhizomes of cord-grass would be harvested for energy purposes because of practical problems, but some harvesting may be necessary if new areas were to be planted with the species.

4.7.9 It is technologically feasible to plant new areas and harvest cord-grass using equipment and methods developed in Sweden, the Netherlands and the USA.

## 4.8 Conclusion

Like bracken, cord-grass could be harvested when green or when senescent. Yields of senescent material would be about 50% lower than those at peak standing crop, however, and a thermal conversion process would be required to generate a fuel. Both harvesting strategies are feasible and the choice would depend upon the type of fuel required or if the necessity to control the spread of the species exists. Re-growth following both types of harvesting should be good, and cord-grass must, therefore, represent an opportunity energy crop of high potential.

# 5 *POLYGONUM CUSPIDATUM* (JAPANESE KNOTWEED) AND *P. SACHALINENSE*

## 5.1 General description

Japanese knotweed is a stout, rhizomatous perennial which may reach a height of 2.5 m (Bailey 1971). Leaves and stems are deciduous, but the stems remain erect over the winter months and persist until the following summer. The species spreads quickly, as a result of rhizome extension and proliferation, forming dense stands (Plate 1d). In this country, sexual reproduction appears to be unsuccessful in most years, although flowers are always produced. *Polygonum sachalinense* (Plate 1e) resembles Japanese knotweed but achieves a height of about 4 m and possesses larger leaves (up to 30 cm long) which have been used for forage in other countries (Bailey 1971).

## 5.2 Distribution and extent

It appears that Japanese knotweed was introduced into this country as a garden plant during the last century (Conolly 1977). Since then, it has become naturalised in many places, particularly on waste land such as derelict cemeteries and railway embankments in urban areas. At present, it occurs from Cornwall to the northern-most part of the Outer Hebrides (Figure 5.1, A), but it does not usually occur at altitudes over 300 m. It covers approximately 3.1 km$^2$ of Great Britain at the moment (Bunce pers comm).

*Polygonum sachalinense* has had a similar history of introduction and naturalisation to Japanese knotweed, but shows a far more restricted distribution (Figure 5.1, B).

## 5.3 Rate of development

Japanese knotweed was studied intensively at a large site in Manchester (Queen's Park Cemetery Site - site number 4, Appendix II) and at a smaller site in Grange-over-Sands (Kents Bank site - site number 3, Appendix II).

Stems appear above ground in April, and by mid-May there are over 30 m$^{-2}$ at the Queen's Park Cemetery site (Figure 5.2, A). Stem density increases over the growing season at this site until a maximum of over 70 stems m$^{-2}$ is reached at the end of July, after which density decreases (Figure 5.2, A). At the Kents Bank site, the initial increase in stem density was not measured as the growing season started particularly early here, but a slow decrease in stem density was measured over the summer.

As stem density increase, stem height increases and leaves are produced. At the Queen's Park Cemetery site, the mean number of leaves per stem increases from 5 in early May to 50 in July, but mean number of leaves per stem is much higher (between 85 and 105) at the Kents Bank site, where samples showed more variation (Figure 5.2, B) because of habitat heterogeneity and edge effects.

The expansion of the leaf surface starts slowly during May at the Queen's Park Cemetery site, but there is a rapid phase of expansion in June at both sites (Figure 5.2.C). Maximum leaf area development is achieved during early July at both sites, and mean area per leaf remains unaltered until leaves are shed in November (Figure 5.2, C). Larger leaves are produced at the Kents Bank site than at the Queen's Park Cemetery site.

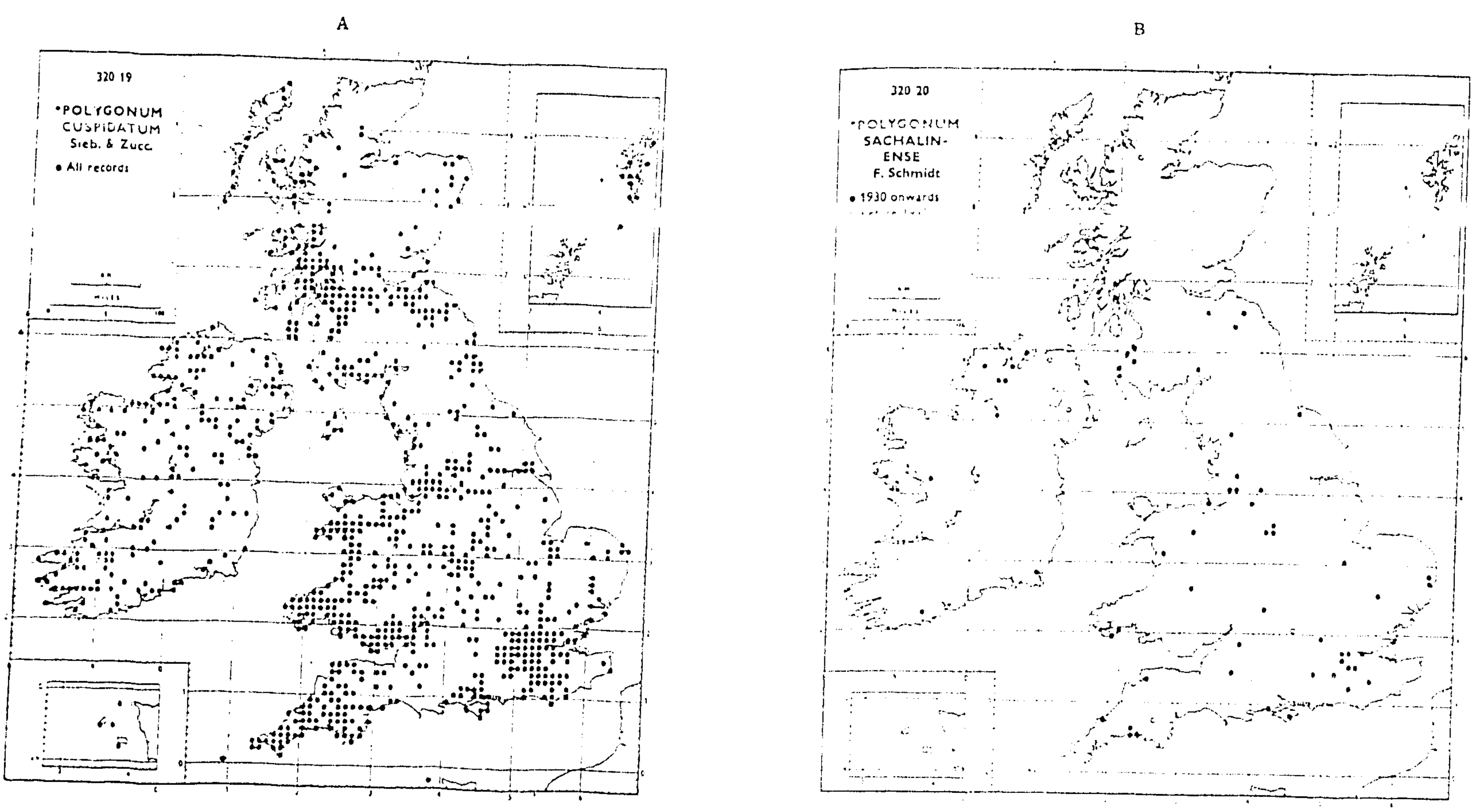


Figure 5.1 The distribution of *Polygonum cuspidatum* (A) and *P. sachalinense* in (B) in Great Britain and Ireland from Perring & Walters (1962).

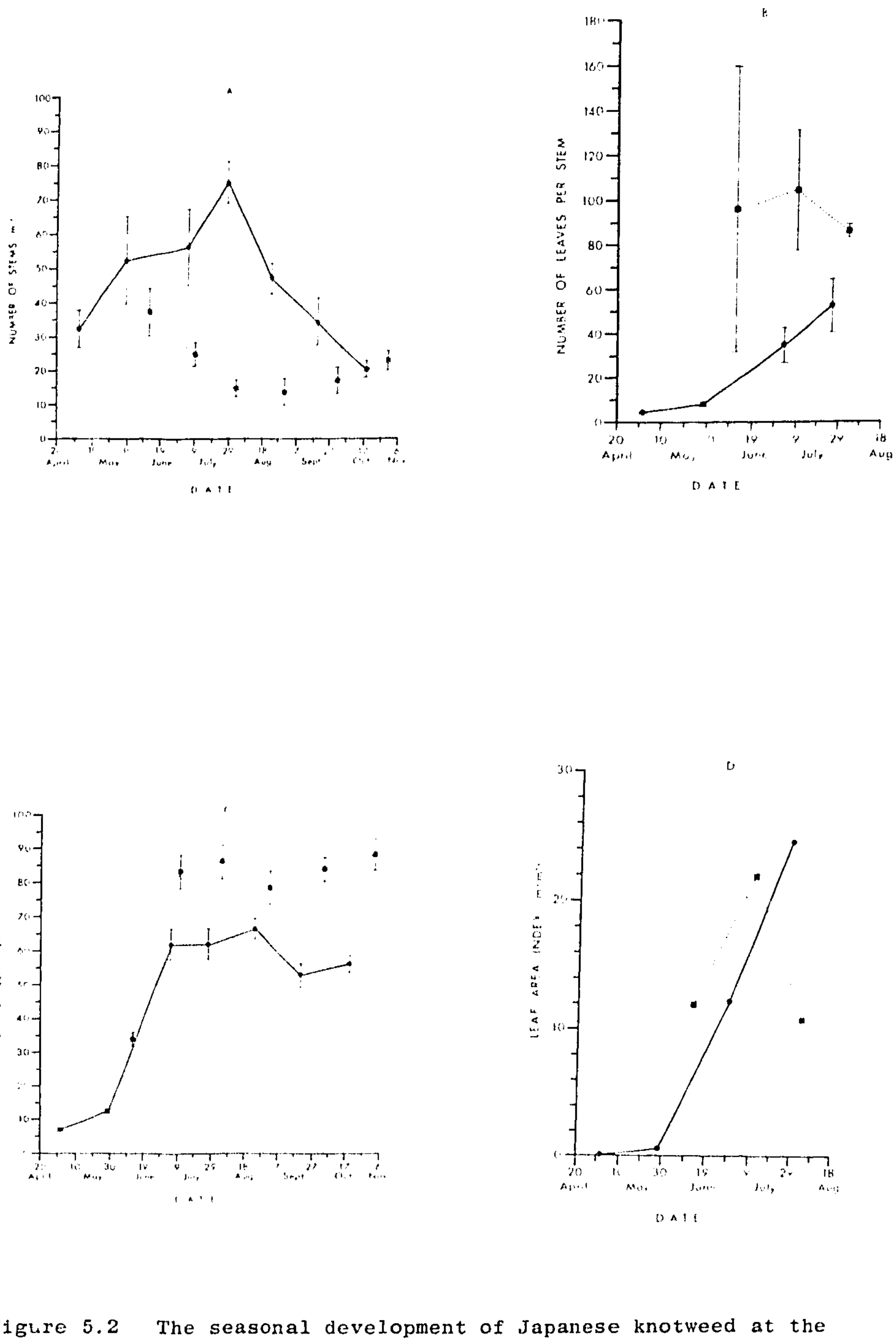


Figure 5.2 The seasonal development of Japanese knotweed at the Queen's Park Cemetery site (solid line and circles) and Kents Bank site (dotted line and squares).
A Stem density; B Number of leaves per stem;
C Mean area per leaf; D leaf area index.

The development of the whole photosynthetic canopy of a stand of Japanese knotweed is an interaction between stem density, the number of leaves per stem, and the area per leaf. This interaction gives Leaf Area Index in $m^2$ of leaf per $m^2$ of ground, and values calculated for Japanese knotweed reach exceptionally high levels (up to 24 $m^2$ $m^{-2}$, Figure 5.2, D) when compared with butterbur (5 $m^2$ $m^{-2}$), and even agricultural crops which show optimal (not maximal) values between 3 and 11 (Sestak *et al.* 1971). A clear seasonal increase during June, July and August was shown at the Queen's Park Cemetery but no clear trend was evident at Kents Bank because of the great variability at this site.

## 5.4 Productivity

The above-ground standing crop of Japanese knotweed was measured at one site on only one occasion and without replication by Callaghan *et al.* (1978). A high standing crop of 25.3 t $ha^{-1}$ was recorded, and no other values have been traced in the literature.

During the present study, peak standing crops were lower than previously recorded and ranged from 7.45 to 22.58 t $ha^{-1}$ (Table 5.1). The closely related species, *Polygonum sachalinense*, shows a very high standing crop in Scotland of 37.5 t $ha^{-1}$ (Table 5.1), and this species merits further investigation.

At the intensive site in Manchester (Queen's Park Cemetery), Japanese knotweed showed a clear seasonal trend of growth with above-ground standing crops of between 7 and 10 t $ha^{-1}$ persisting for August, September and October (Figure 5.3). On the other hand, at the Kents Bank site, this species did not show a significant seasonal trend during the period of sampling (Figure 5.3, Appendix III), but a high standing crop (7 t $ha^{-1}$) was measured as early as 12 June (Figure 5.3). At both sites the maximum standing crop was lower than had been expected or recorded earlier, and this is probably due to the difficulty of finding large stands of Japanese knotweed which have not been damaged by trampling, etc. Indeed, the site at Manchester had been treated with herbicides in previous years.

A significant proportion of the total plant biomass is below-ground in Japanese knotweed, and standing crops of 15.4 ± 3.7 and 30.1 ± 7.9 t $ha^{-1}$ were measured at the Queen's Park Cemetery site on 2 May and 20 December respectively. At the Kents Bank site rhizome standing crops of 20.34 ± 8.28, 11.92 ± 3.36 and 18.61 ± 8.52 t $ha^{-1}$ were recorded on 12 June, 1 October and 26 November respectively. The variation between samples at each harvest date was great, however, and a seasonal trend was not apparent at the Kents Bank site (Appendix III).

Although Japanese knotweed was dominant at both of the intensive sites, some other species did occur. At the Queen's Park Cemetery site, these species did not occur in sufficient quantity to merit harvesting, but at the Kents Bank site a maximum of 1.5 t $ha^{-1}$ was produced above-ground by species other than Japanese knotweed (Figure 5.3). At peak standing crop (1 October), the above-ground standing crop of species associated with Japanese knotweed raised site standing crop from 11.39 to 12.55 t $ha^{-1}$.

Fresh weight/dry weight ratios do no vary significantly over the growing season (Appendix III) and the water content is within the range of 67 to 83% of the fresh weight (Table 5.2). Unfortunately, data are not available for the end of season when above ground tissues die and dry out.

TABLE 5.1 Between-site variation in the above ground standing crop (t $ha^{-1}$) of *Polygonum cuspidatum* and *P. sachalinense*. Standard errors are given and full site descriptions are presented in Appendix I.

| SITE | SITE No. | COMMUNITY | SAMPLE DATE | STANDING CROP |
|---|---|---|---|---|
| A. *Polygonum cuspidatum* | | | | |
| Southport, Lancashire | 21 | coastal waste land | 10 October | 7.5 ± 0.79 |
| Queen's Park, Manchester | 4 | overgrown graveyard | 18 September | 9.8 ± 1.44 |
| Kents Bank, Cumbria | 3 | derelict land | 1 October | 11.4 ± 3.21 |
| Dornie, Ross & Cromarty | 7 | roadside | 14 September | 15.6 ± 0.99 |
| Coldstream, Berwickshire | 14 | riverbank | 14 September | 22.6 ± 4.98 |
| B. *Polygonum sachalinense* | | | | |
| Lynton, Devon | 32 | roadside | 9 September | 12.6 ± 2.60 |
| Lock Locky, Inverness | 8 | roadside | 14 September | 37.5 ± 1.16 |

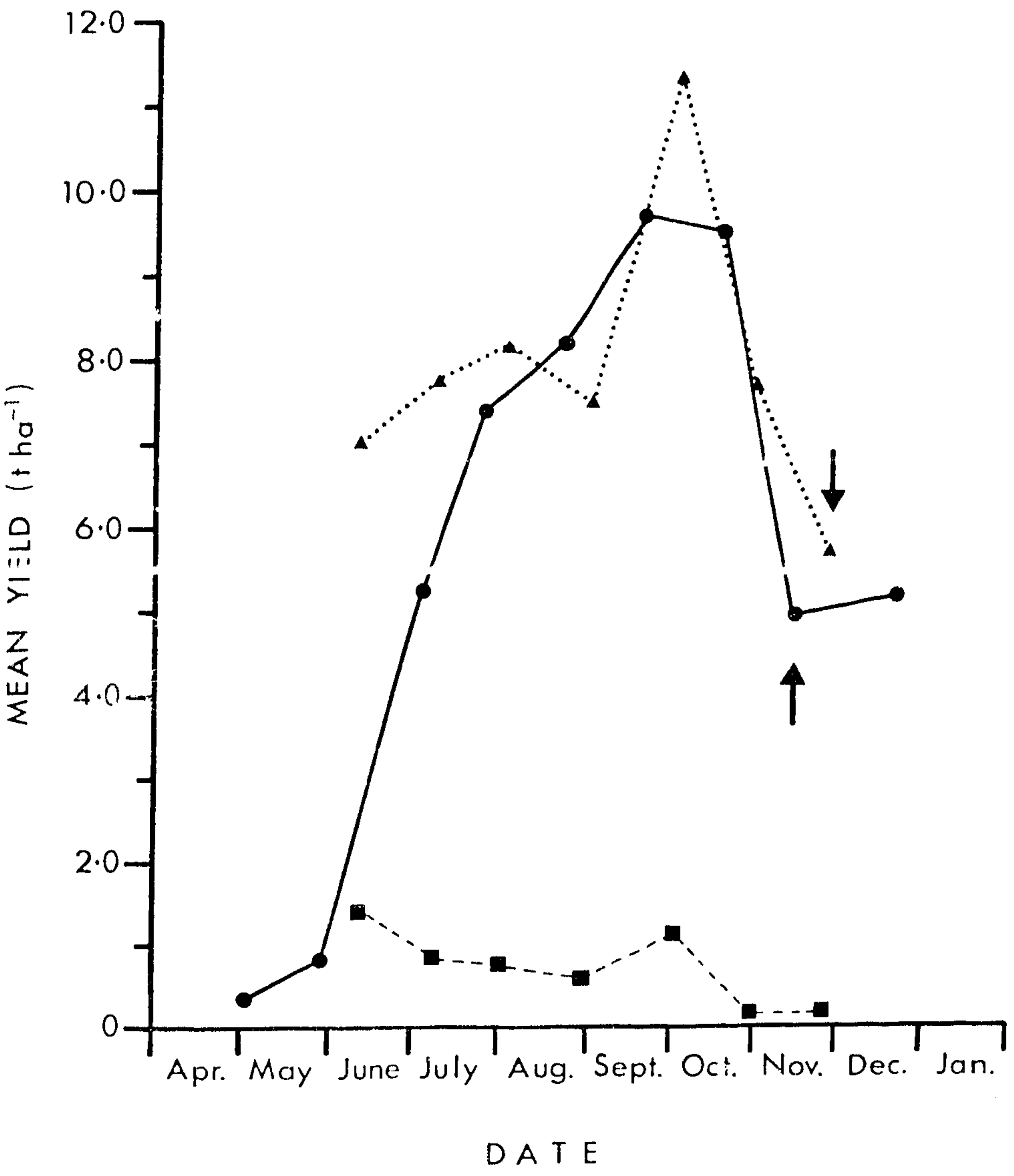


Figure 5.3 The seasonal growth of shoots of Japanese knotweed from the Queen's Park Cemetery site (solid line and circles), Japanese knotweed from the Kents Bank site (dotted line and triangles) and species associated with Japanese knotweed at the Kents Bank site (broken line and squares). The arrows denote the date by which the above-ground tissues had died.

TABLE 5.2 Fresh weight/dry weight ratios of leaves and stems of Japanese knotweed. Water contents, as a % of the fresh weight, are given in brackets and standard errors are included.

| SITE | 12 JUNE | 4 JULY | 9 JULY | 14 SEPT | 1 OCT | 10 OCT | 17 OCT | 30 OCT |
|---|---|---|---|---|---|---|---|---|
| Kents Bank | 5.7 ± 1.38 (83%) | - | 4.19 ± 0.17 (76%) | - | 4.28 ± 1.19 (77%) | - | - | 4.65 ± 0.33 (79%) |
| Queen's Park Cemetery | - | [illegible].02 ± 1.34 (67%) | - | - | - | - | 3.64 ± 0.06 (73%) | - |
| Coldstream | - | - | - | 3.86 ± 0.17 (74%) | - | - | - | - |
| Southport | - | - | - | - | - | 4.35 ± 0.14 (77%) | - | - |

## 5.5 Re-growth after cutting

At the Queen's Park Cemetery site, the production after a first harvest clearly decreased as the date of the first harvest became later in the season (Table 5.3), and the re-growth at this site was considerably better than at the Kents Bank site, or, indeed, at the bracken, butterbur and cord-grass site. Re-growth at the Kents Bank site also showed a significant decrease as the date of the first harvest became later in the season.

The dry matter production achieved by harvesting above-ground tissues of Japanese knotweed at 2 times in the growing season was less than that achieved by harvesting only once at peak standing crop, at both sites (Table 5.3). The potential for re-growth within the growing season is, therefore, insignificant under the present experimental design.

Rhizome biomass appears to be unaffected by harvesting above-ground tissues of Japanese knotweed from the Kents Bank site early in the season, but the data, like those for above-ground tissues, are variable at this site (Table 5.4). However, the data suggest that re-growth during the following year will be relatively unimpaired.

## 5.6 Nutrient content of Japanese knotweed

### 5.6.1 Inorganic nutrients

Concentrations of inorganic nutrients follow seasonal trends typical of most plant species, with decreases in concentrations of N, P and K (Figure 5.4, A) and high mid-season values of Ca and Mg (Figure 5.4, B).

The concentrations are generally within the range shown by the species discussed above, although concentrations of Ca are high (Figure 5.4, B). After the death of the above-ground tissues in November (Figure 5.3), concentrations of all nutrients are low, with the concentration of P only 5% of the early season level.

Concentrations of N, P, K, Ca and Mg in the rhizomes are remarkably constant throughout the growing season and only Ca showed a significant seasonal trend (Table 5.5, Appendix III). Concentrations of N, P and K in the rhizomes are similar to those in the above-ground tissues at the end of season, ie the lowest concentrations in the above-ground tissues, but there is little difference in Ca and Mg concentrations between rhizomes and above-ground tissues (Table 5.5, Figure 5.4).

Contents of N, P, K, Ca and Mg in the rhizomes show no significant seasonal trends (Table 5.5). In general, the underground tissues possess a large pool of inorganic nutrients in excess of the pool held by the above-ground tissues (Table 5.5).

The pools of inorganic nutrients other than Ca in the above-ground tissues at the time of maximum standing crop are similar to those in the other species considered so far, but the Ca content of Japanese knotweed is much higher (Table 5.6). After the death of the above-ground tissues, the pools of N, P and K are reduced to 10, 7 and 25%, respectively, of their maximum values in the season, whereas the standing crop of leaves and stems is only reduced by 47% (Figure 5.5). It appears, therefore, that some translocation of N, P and K occurs during the senescence of leaves and stems as in bracken and cord-grass,

TABLE 5.3 The re-growth of above-ground tissues of Japanese knotweed measured on the 18 September (Queen's Park Cemetery Site) and 1 October (Kents Bank Site) after cutting at earlier times in the growing season. Yields are t ha$^{-1}$. Dates refer to the Queen's Park Cemetery site or, where bracketed, the Kents Bank site.

| | 2 MAY | 29 MAY (12 JUNE) | 4 JULY (9 JULY) | 26 JULY (2 AUGUST) | 22 AUGUST (31 AUGUST) | 18 SEPT (1 OCTOBER) |
|---|---|---|---|---|---|---|
| <u>Queen's Park Cemetery Site</u> | | | | | | |
| yield at specified date: | 0.35 | 0.78 | 5.27 | 7.44 | 8.21 | 9.77 |
| re-growth after specified date: | 4.88 | 3.70 | 2.00 | 1.73 | 0.51 | - |
| total yield: | 5.23 | 4.48 | 7.27 | 9.17 | 8.72 | 9.77 |
| <u>Kents Bank Site</u> | | | | | | |
| yield at specified date: | - | 7.07 | 7.77 | 8.25 | 7.50 | 11.39 |
| re-growth after specified date: | - | 1.18 | 0.44 | 0.51 | 0.04 | - |
| total yield | - | 8.25 | 8.21 | 8.76 | 7.54 | 11.39 |

TABLE 5.4 The effect of harvesting the above-ground tissues of Japanese knotweed from the Kents Bank site on rhizome biomass (t $ha^{-1}$) at the end of season.

| | SAMPLES COLLECTED ON 1 OCTOBER WITH LEAVES AND STEMS REMOVED ON: | | | | UNDISTURBED SAMPLES COLLECTED ON: |
|---|---|---|---|---|---|
| | 12 June | 9 July | 2 August | 31 August | 1 October |
| Oven dry wt. (t $ha^{-1}$) | 4.64 | 17.23 | 11.39 | 10.95 | 11.93 |

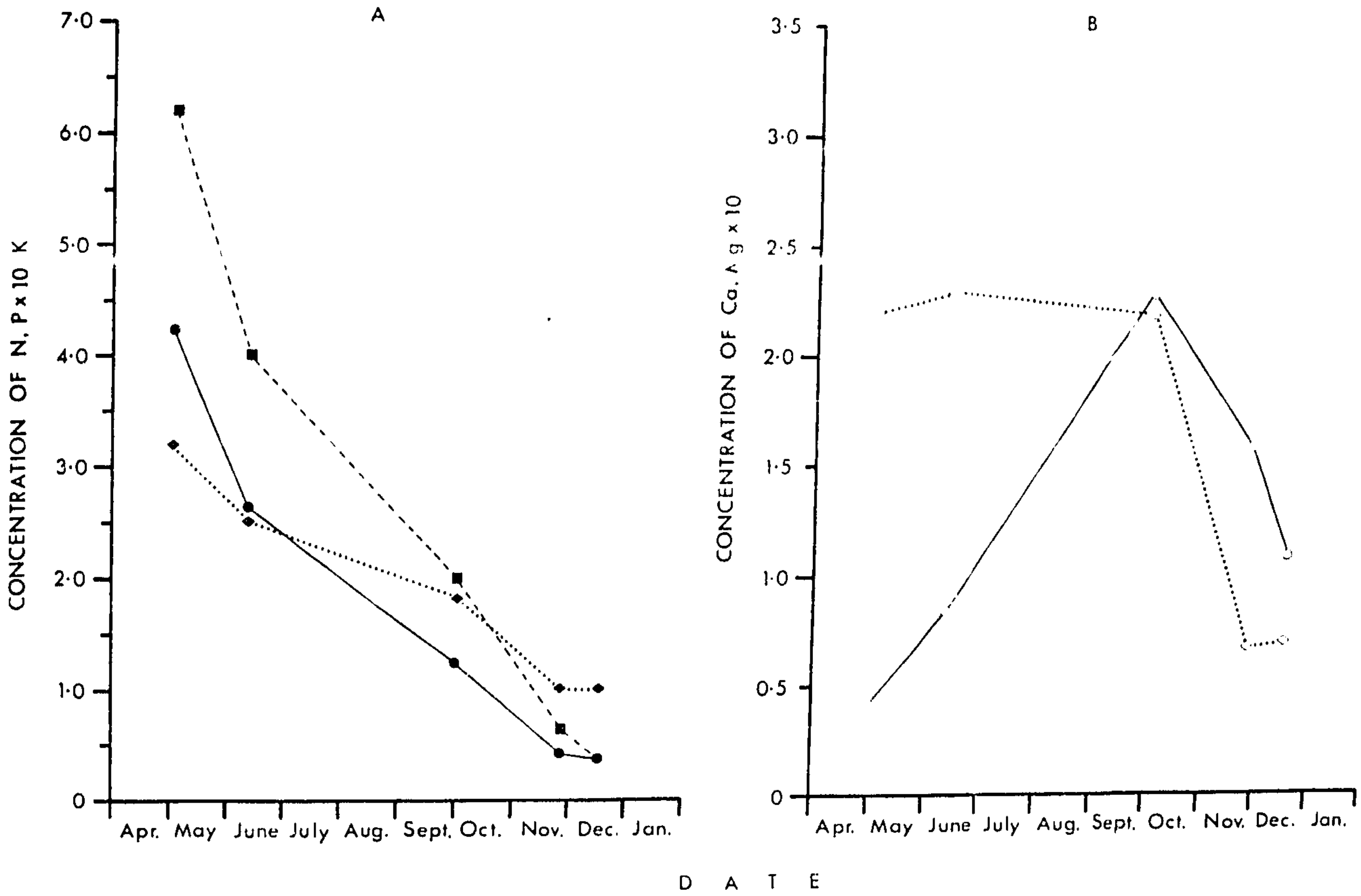


Figure 5.4 The seasonal trends of concentrations of inorganic nutrients (% dry weight) in shoots of Japanese knotweed from the Queen's Park Cemetery site (May and December) and Kents Bank site (other dates).

A Concentrations of N (solid line and solid circles), P (broken line and solid squares) and K (dotted line and solid diamonds).

B Concentrations of Ca (solid line and open circles and Mg (dotted line and open diamonds).

NB Concentrations of P are 1/10th of those of N and K while concentrations of Mg are 1/10th of those of Ca.

TABLE 5.5 Concentrations and content (concentration x dry weight) of inorganic nutrients in Japanese knotweed rhizomes from the Queen's Park Cemetery site (2 May and 17 December) and Kents Bank site (12 June, 1 October and 26 November).

| ELEMENT | CONCENTRATION (% dry weight) | | | | | CONTENT (kg ha$^{-1}$) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2 May | 12 June | 1 October | 26 November | 17 December | 2 May | 12 June | 1 October | 26 November | 17 December |
| N | 1.30 | 0.96 | 1.15 | 1.30 | 1.27 | 200.1 | 195.3 | 137.1 | 241.9 | 382.8 |
| P | 0.18 | 0.15 | 0.18 | 0.21 | 0.19 | 27.7 | 30.5 | 21.5 | 39.1 | 57.3 |
| K | 0.63 | 0.64 | 0.95 | 0.93 | 0.92 | 97.0 | 130.2 | 113.2 | 173.1 | 277.3 |
| Ca | 1.10 | 2.60 | 1.87 | 2.10 | 1.04 | 169.3 | 528.8 | 222.9 | 390.8 | 313.5 |
| Mg | 0.14 | 0.13 | 0.14 | 0.17 | 0.13 | 21.6 | 26.4 | 16.7 | 31.6 | 39.2 |
| Ash | 8.5 | 9.8 | 8.7 | 16.4 | 7.3 | 1308 | 1993 | 1037 | 3052 | 2200 |

TABLE 5.6 The nutrient content (concentration x dry weight) of stems and leaves of Japanese knotweed from the Queen's Park Cemetery site (2 May and 17 December) and Kents Bank site (12 June, 1 October and 26 November). Units are kg $ha^{-1}$.

| ELEMENT | 2 MAY | 12 JUNE | 1 OCTOBER | 26 NOVEMBER | 17 DECEMBER |
|---|---|---|---|---|---|
| N | 14.8 | 185.9 | 142.4 | 24.6 | 19.6 |
| P | 2.17 | 28.3 | 22.8 | 3.61 | 1.91 |
| K | 11.2 | 176.8 | 205.0 | 57.9 | 51.2 |
| Ca | 1.47 | 60.1 | 262.0 | 91.7 | 56.9 |
| Mg | 0.77 | 16.3 | 25.1 | 3.95 | 3.62 |
| Ash | 39.9 | 552 | 1093 | 3610 | 248 |

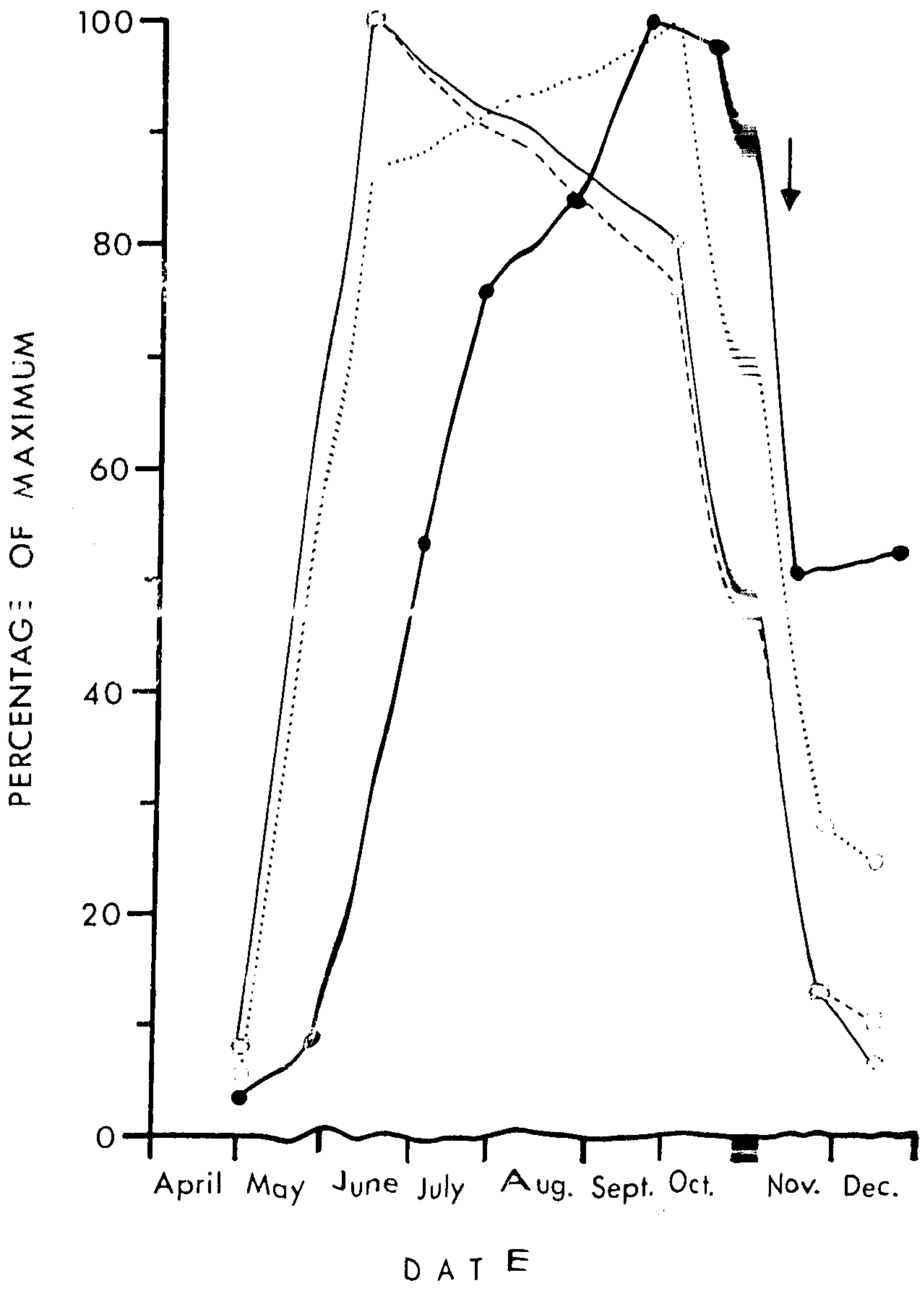


Figure 5.5 The relationship between the seasonal trends of standing crop (thick solid line and solid circles) and the total contents of N (broken line and open squares), P (thin solid line and open diamonds) and K (dotted line and open circles) in leaves and stems of Japanese knotweed from the Queen's Park Cemetery site (May and December) and Kents Bank site (other dates). All values are expressed as percentages of the maxima to standardise the vertical axis. The arrow denotes the date by which the above-ground tissues had died.

and a harvesting regime designed to remove dead leaves and stems in winter would result in a yield of between 5 and 6 t $ha^{-1}$ while removing only very small amounts of N, P and K from site. If living leaves and stems were harvested at peak standing crop, yield would be doubled, and the amounts of N, P and K removed from site would be increased by factors of between 4 and 11, thus making expensive annual fertilizer applications essential. Concentrations and contents of ash (Tables 5.5, 5.6) are low, however, and an ash residue of about 1.1 t $ha^{-1}$ would result, if shoots were harvested at peak biomass.

### 5.6.2 Organic plant fractions

Concentrations of the energy-storing compounds - soluble carbohydrates, starch and crude fat - show clear decreases over the growing season in the shoots of Japanese knotweed (Figure 5.6, A), but there is no mid-season peak concentration as in the case of bracken (Figure 2.5, A). The maximum concentration of soluble carbohydrates is low when compared with bracken and, in particular, butterbur. However, concentrations of starch are quite high when compared with other species. The comparatively low concentrations of the energy-storing compounds during the period when maximum standing crop is achieved suggest that harvesting at this time would not significantly affect re-growth in the following year, and this has been observed in the field. In this species, therefore, it should be possible to harvest at peak standing crop, although inorganic nutrient levels may need to be supplemented.

At the end of season, the stems of Japanese knotweed become dry and hard and they persist until the following summer. This pattern of development is reflected in the concentrations of lignin which are higher than those in the species considered earlier, and in the increasing concentrations of holocellulose throughout the season, which reach a very high value of ca 74% dry weight in December (Figure 5.6, B). If shoots of Japanese knotweed were harvested at the end of season, therefore, they would be a suitable substrate for a thermal chemical conversion processs.

Concentrations of holocellulose are considerably lower in the rhizomes of Japanese knotweed than in the shoots (Table 5.7, Figure 5.6, B), but lignin concentrations in the rhizomes are high, reflecting the tough and woody nature of these persistent organs. The concentrations of the organic plant fractions in general show no clear seasonal patterns in the rhizomes, with the exception of starch wich shows higher concentrations at the end of season than in mid-season (Figure 5.6, B). This, together with decreasing concentrations of soluble carbohydrates in the shoots at the end of season (Figure 5.6, A), suggests translocation of energy reserves below ground. The rhizomes appear, in fact, to be efficient storage organs and up to 35% of their dry weight consists of energy-storing compounds. This energy storage capacity of the rhizomes explains to some extent the extremely efficient regeneration of this species from rhizome fragments, while suggesting that the rhizomes should be considered as a substrate for a chemical conversion process. Indeed, in terms of re-growth, it appears to be feasible to harvest a considerable proportion of the below-ground organs without replanting in following years, and the technical feasiblity should be assessed as very high yields would be obtained.

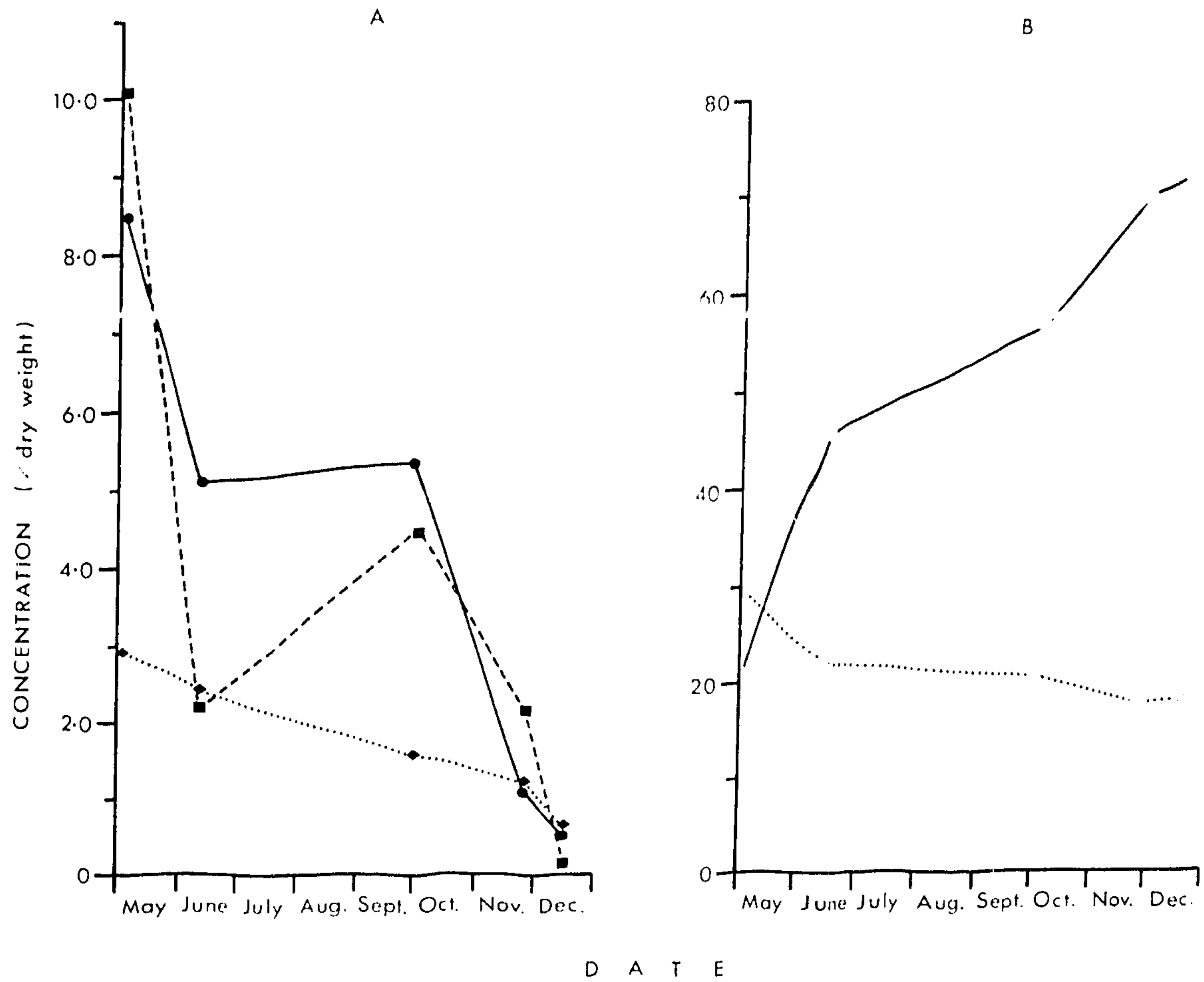


Figure 5.6 The seasonal trends of concentrations of organic plant fractions in shoots of Japanese knotweed from the Queen's Park Cemetery site (May and December) and Kents Bank site (other dates).
A Soluble carbohydrates (solid circles and line), crude fat (solid diamonds and dotted line) and starch x 10 (solid squares and broken line).
B Holocellulose (open circles and solid line) and lignin (open diamonds and dotted line).
NB Concentrations of starch are 1/10th of the values on the Y axis.

TABLE 5.7 Concentrations (% dry weight) of organic plant fractions in the rhizomes of Japanese knotweed collected from the Queen's Park Cemetery site (2 May and 17 December) and Kents Bank site (12 June, 1 October and 26 November).

| COMPOUND | CONCENTRATION | | | | |
|---|---|---|---|---|---|
| | 2 May | 12 June | 1 October | 26 November | 17 December |
| Soluble carbohydrate | 14.7 | 10.1 | 15.3 | 8.0 | 14.7 |
| Starch | 13.8 | 9.1 | 15.3 | 14.4 | 19.3 |
| Crude fat | 0.89 | 1.07 | 1.33 | 0.97 | 0.87 |
| Lignin | 27.0 | 34.0 | 28.9 | 33.2 | 23.5 |
| Holocellulose | 36.7 | 36.3 | 34.0 | 39.0 | 40.0 |

The energy content of shoots of Japanese knotweed show a slight decrease over the growing season, with values between 22 and 19.3 KJ $g^{-1}$ dry weight (Figure 5.7). Over the whole growing season, the energy content of shoots (20.4 ± 0.27 KJ $g^{-1}$) exceeds that of the rhizomes (19.4 ± 0.13 KJ $g^{-1}$). The seasonal trends of energy contents and yield of shoots combine to give a maximum energy yield of green shoots of *ca* 230 x $10^9$ J $ha^{-1}$ and an energy of senescent shoots of *ca* 115 x $10^9$ J $ha^{-1}$ (Figure 5.7). If rhizomes were harvested in addition to shoots, a total energy yield of *ca* 504 x $10^9$ J $ha^{-1}$ would be achieved in the year of harvesting (assuming a mean rhizome standing crop of 19.3 t $ha^{-1}$ and a mean energy content of 19.4 KJ $g^{-1}$), but the subsequent yield of rhizomes will certainly be reduced. It may, however, be possible to harvest rhizomes on a longer rotation than the annual rotation of shoot harvesting.

## 5.7 A summary of the potential of Japanese knotweed as an energy crop

5.7.1 Japanese knotweed would be managed mainly as a dedicated energy crop as it occurs naturally only in small stands (covering only 3.1 $km^2$ of Great Britain), but is capable of growing throughout Great Britain up to an alitude of 300 m and can be easily transplanted.

5.7.2 Dry matter yields of green shoots should be at least 9.8 t $ha^{-1}$ $yr^{-1}$ (199 x $10^9$ J $ha^{-1}$) and values up to 25.3 t $ha^{-1}$ (514 x $10^9$ J $ha^{-1}$) have been recorded, while a yield of 37.5 t $ha^{-1}$ (761 x $10^9$ J $ha^{-1}$) was recorded for the related species *Polygonum sachalinense*. Although the highest yields may reflect the increased light interception by the sides of leaf canopies in small stands, it is certain that *P. cuspidatum* (Japanese knotweed) and *P. sachalinense* are very productive species.

5.7.3 Shoots of Japanese knotweed harvested at peak standing crop should not be resistant to anaerobic digestion, as water content is 77% of the fresh weight, concentrations of N, P, K and soluble carbohydrates are 1.3, 0.2, 1.8 and 5.4% dry weight respectively, but concentrations of compounds more resistant to digestion, holocellulose and lignin, occur in relatively high concentrations (57 and 21% dry weight respectively). An ash content of only 9.6% dry weight would remain in the residues produced by conversion.

5.7.4 Japanese knotweed has a considerable potential for re-growth within the season of harvesting (although 2 cuts per season do not yield more than one cut per season), and low concentrations of soluble carbohydrates in the shoots together with experience in the field suggest that re-growth in years following harvesting would not be greatly affected by removing biomass at peak standing crop. Long-term experiments are required to test the effect of harvesting on subsequent yields, and it should be possible to harvest this species in such a way as to maximise annual yield.

5.7.5 Application of N and P (142 and 23 kg $ha^{-1}$ respectively) to areas of Japanese knotweed harvested at peak standing crop would be within the range currently applied in agriculture, but replacement applications of K (205 kg $ha^{-1}$) would be greater than those traditionally applied to agricultural crops. High concentrations of Ca in the shoots of Japanese knotweed may necessitate the application of lime to areas of Japanese knotweed after repeated harvesting.

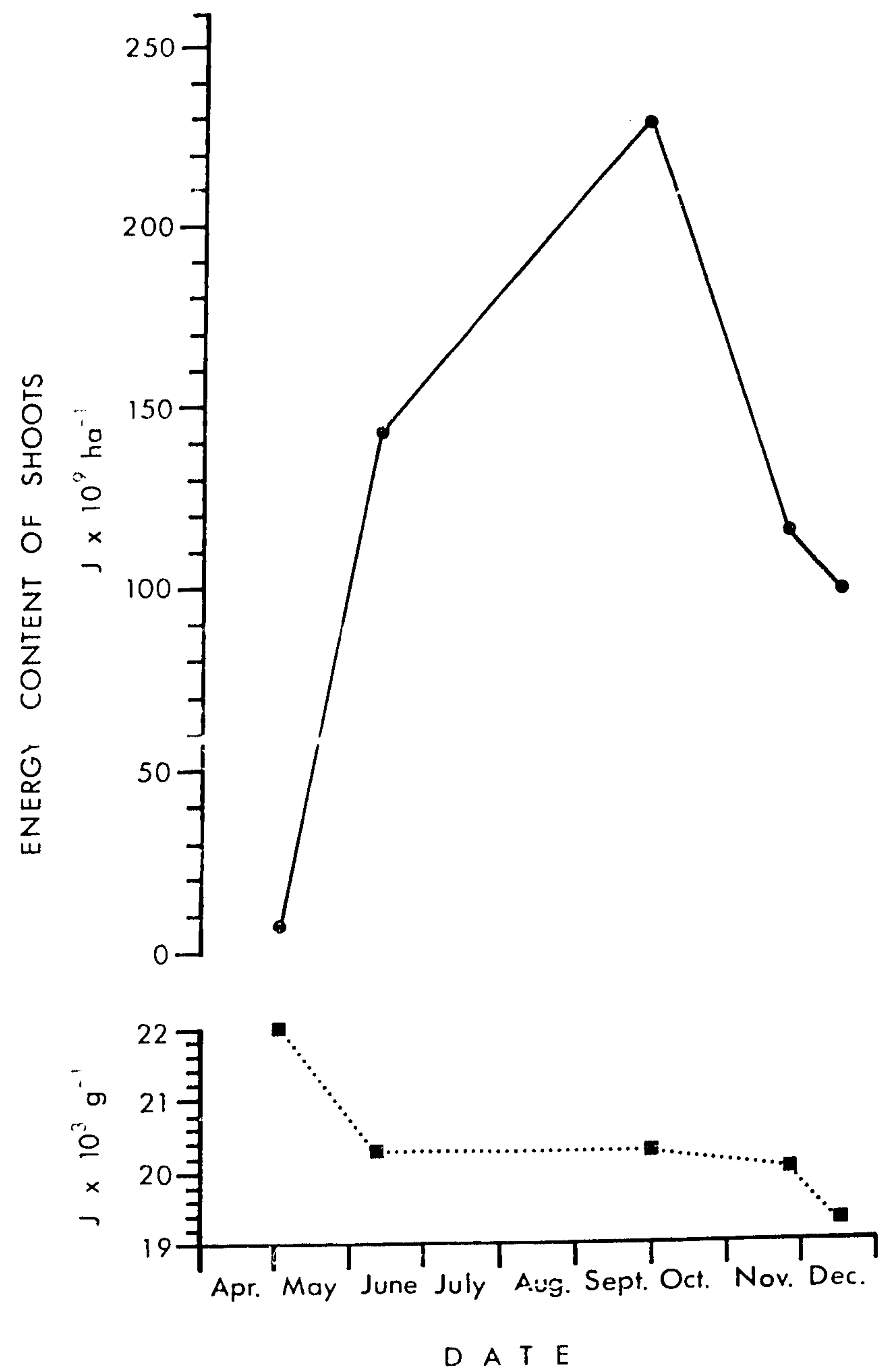


Figure 5.7 The seasonal trends of the energy contents of shoots of Japanese knotweed expressed on a land area basis and on a unit dry weight basis.

5.7.6 If shoots of Japanese knotweed were harvested when senescent, dry matter yields of at least 5 t $ha^{-1}$ (97 x $10^9$ J $ha^{-1}$) could be obtained over the winter period, and the dry fibrous tissues (with concentrations of holocellulose and lignin of 73 and 19% dry weight respectively) could be used as feed-stock for a thermal chemical conversion process.

5.7.7 If shoots of Japanese knotweed were harvested when senescent, re-growth in following years should not be significantly affected, and 90, 93 and 75% of the N, P and K in the shoots would be recycled naturally making fertilizer applications minimal.

5.7.8 It may be possible to harvest the rhizomes of Japanese knotweed on a long-term rotation basis as this appears to rejuvenate old stands of the species. Additional yields of between 12 and 30 t $ha^{-1}$ (232 and 579 x $10^9$ J $ha^{-1}$) could be expected in the initial year of harvesting. The rhizomes are rich in soluble carbohydrates and starch, which together represent 30% of the rhizomes' dry weight.

5.7.9 The harvesting of shoots of Japanese knotweed should present no problems to conventional harvesting equipment.

## 5.8 Conclusion

Japanese knotweed and *P. sachalinense* could be harvested when green or when senescent, the harvesting strategy depending upon the nature of the fuel required. Both harvesting strategies could produce high yields and re-growth should be very efficient. These species of *Polygonum* must, therefore, represent dedicated energy crops of high potential which could be planted easily on areas of good agricultural land, or on railway embankments and roadsides where they occur naturally.

# 6 *IMPATIENS GLANDULIFERA* - POLICEMAN'S HELMET

## 6.1 General description

Unlike the species considered earlier, policeman's helmet is an annual species which does not reproduce vegetatively. It possesses stout, hollow stems which may reach a height of 3 m, and it regularly produces vast quantities of seeds which are dispersed violently from an "exploding" fruit.

## 6.2 Distribution and extent

Policeman's helmet is a native of the Himalaya which was introduced into Britain and is now completely naturalised (Clapham *et al.* 1962). It is found in damp woodlands and along banks of rivers and streams, particularly in industrial areas where it appears to tolerate high levels of pollution (Plate 2a). The species has already spread to the north of Scotland, but its centre of distribution is in the industrial midlands and north-west (Figure 6.1), and, at present, it covers only about 0.6 $km^2$ of Great Britain (Bunce pers comm).

## 6.3 Rate of development

Seeds germinate in March and quickly produce 2 cotyledons and a pair of leaves, but this state appears to be maintained for many weeks with most of the annual growth occuring between May and July (Figure 6.2). Flowering occurs in July, August and September, and seeds are shed after leaf death has occurred. Loss of dry weight takes place while stems are still standing (at a density of $46.2 \pm 3.61$ stems $m^{-2}$), and the outer tissues of the stems show considerable putrefaction before stem turgor is lost and the stems collapse. At the end of season, all stems collapse and decomposition is very fast. Winter floods redistribute the stem litter.

## 6.4 Productivity

No previous estimates of the productivity of policeman's helmet have been found in the literature, and it appears that little is known about its autecology. At the Chorlton Brook site (site number 5, Appendix II), a maximum above-ground standing crop of 10.5 t $ha^{-1}$ was achieved in August and standing crop remained quite constant at this high level until October (Figure 6.2). During October, the small root systems and stem bases were excavated and found to have a standing crop of $0.93 \pm 0.09$ t $ha^{-1}$. Total productivity at the site is, therefore, approximately 11.5 t $ha^{-1}$ $yr^{-1}$.

The ratio of root to shoot standing crop in policeman's helmet is very small (0.092), and contrasts strongly with the ratios in the perennial species considered earlier. For example, ratios of 1.5 can be calculated for bracken, cord-grass and Japanese knotweed.

## 6.5 Re-growth after cutting

Because of the annual nature of policeman's helmet, re-growth after cutting is impossible in the context discussed earlier. However, as peak standing crop is achieved on 13 August, it may be possible to produce 2 crops of the species from seed in one growing season, and this potential should be explored.

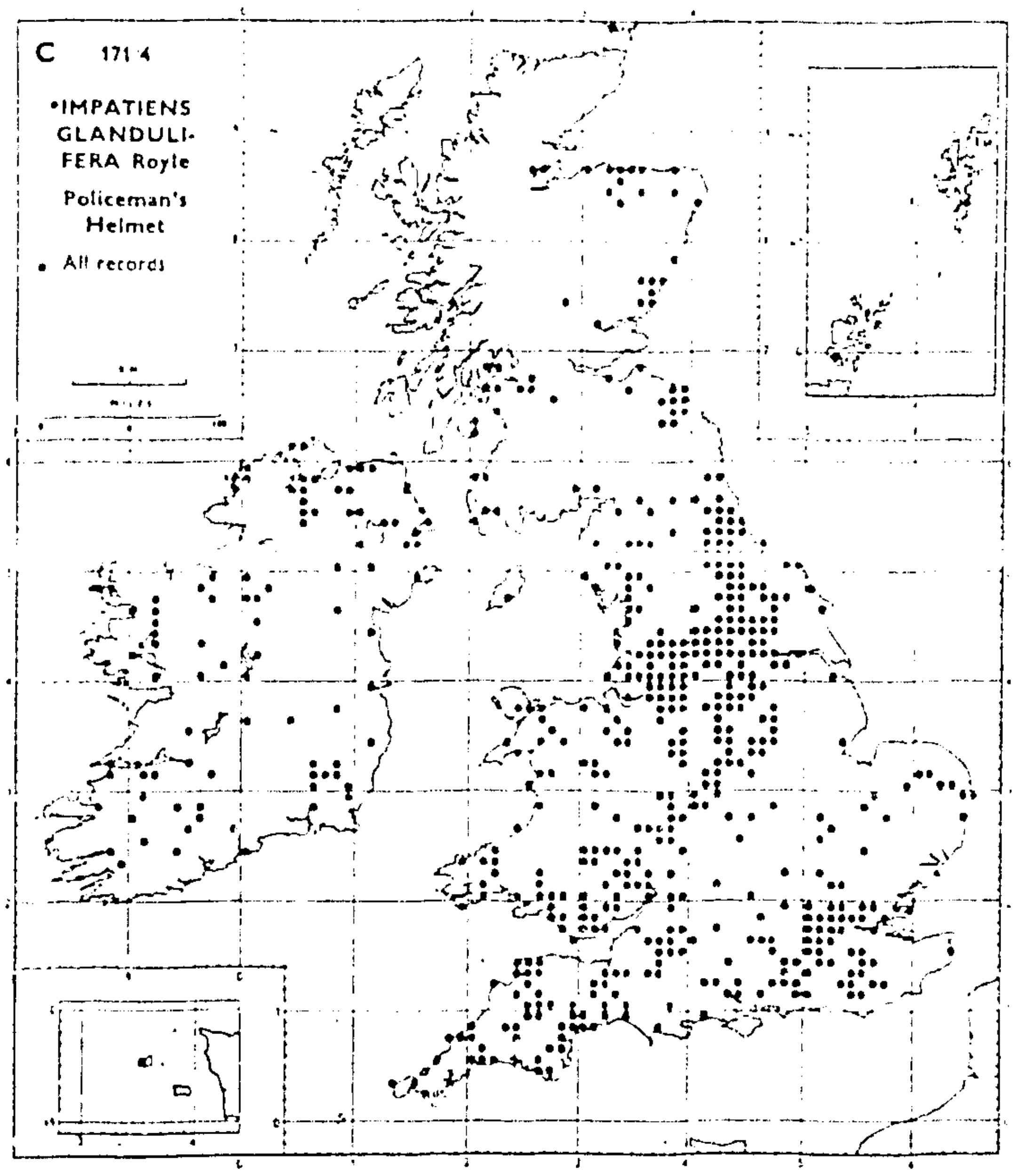


Figure 6.1 The distribution of policeman's helmet in Great Britain and Ireland; from Perring & Walters (1962).

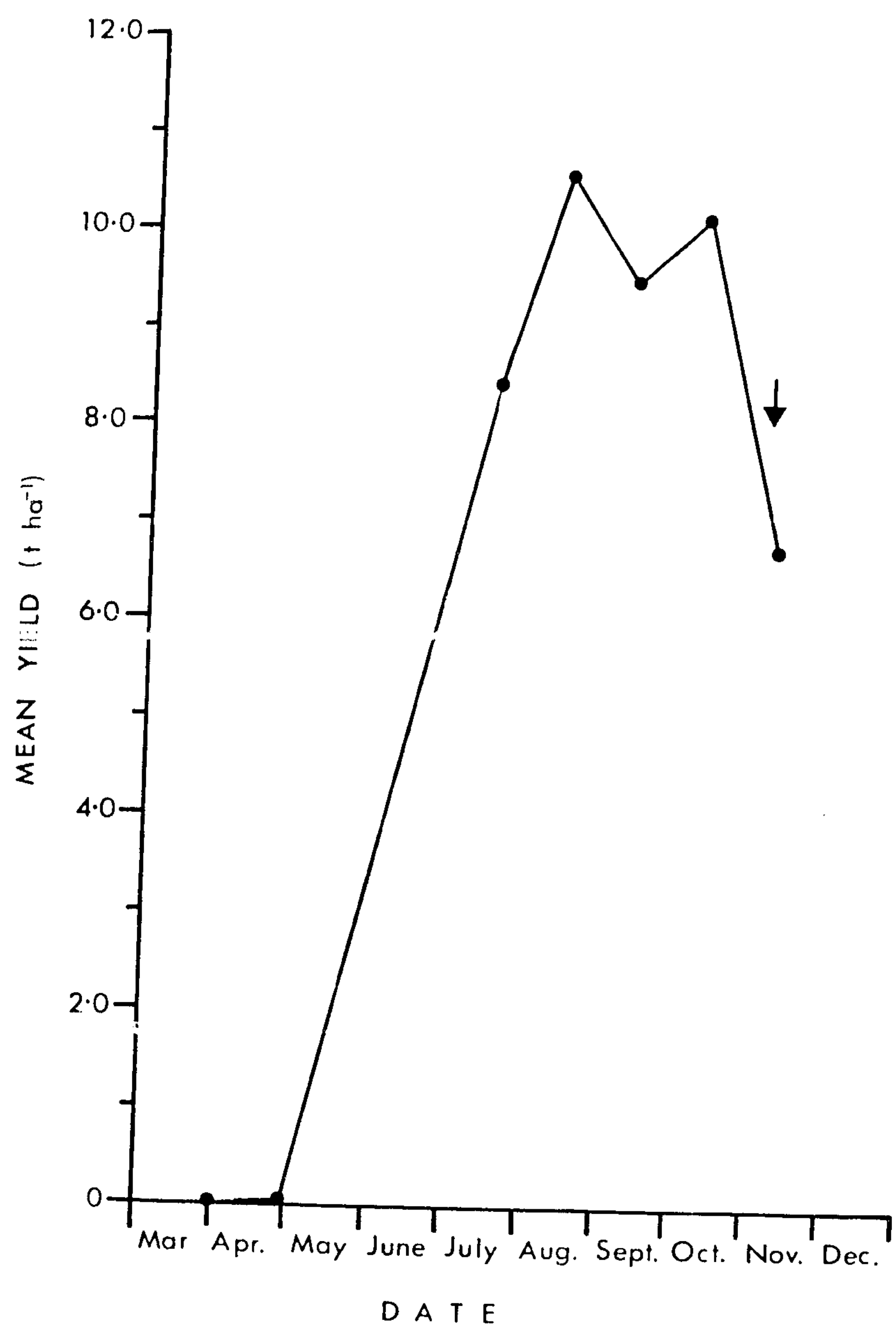


Figure 6.2 The seasonal growth of shoots of policeman's helmet at the Chorlton Brook site. The arrow denotes the date by which all the shoots had died.

## 6.6 Nutrient content of policeman's helmet

### 6.6.1 Inorganic nutrients

Concentrations of N, P and K in leaves and stems of policeman's helmet show decreases over the summer and autumn months (Figure 6.3, A), and concentrations are within the ranges shown by these nutrients in the perennial species described above. Concentrations of Ca, however, decrease over the growing season and are much higher than those found in bracken, cord-grass and butterbur, showing a greater similarity to concentrations found in Japanese knotweed (Figure 5.4, B). Magnesium concentrations in above-ground tissues also show a seasonal decrease (Figure 6.3, B), which contrasts with the trends shown by this element in the other species.

Within the below-ground tissues, concentrations of all the inorganic nutrients analysed show similar values to those in above-ground tissues on the same date (Table 6.1), but ash concentrations are twice those in the shoots. Because of the small size of the below-ground standing crop, however, the pools of inorganic nutrients in below-ground tissues are extremely small (Table 6.1), and only approximately one-tenth of those found in the perennating tissues of the species described above.

If policeman's helmet were harvested at peak standing crop (13 August, Figure 6.2), a considerable pool of inorganic nutrients would be removed from site (Table 6.2), and this pool would exceed those represented in the peak above-ground standing crops of bracken, butterbur, cord-grass and Japanese knotweed. Thus, there would be a considerable effect on site fertility if policeman's helmet were harvested as an energy feed-stock, and long-term nutrient replacement would involve applications of levels of N, P and K in excess (particularly in the case of K) of those currently applied to root crops and cereals. Unfortunately, this annual species cannot be harvested when it is dead as stems collapse and whole plants die. It is interesting in this annual species, that the contents of N, P and K in the stems and leaves decrease faster than dry weight (Figure 6.4). Whereas this difference represents translocation in the perennial species, in policeman's helmet it is probably the result of leaching as nutrient-rich leaves fall to the ground, leaving stems with lower nutrient concentrations which are themselves decomposing on the outside while still standing.

Concentrations of ash in the shoot (calculated from Table 6.2 and Figure 6.2) vary between 10 and 15% and would contribute ca 1.5 t $ha^{-1}$ to the residues of a chemical conversion process (Table 6.2).

### 6.6.2 Organic fractions

Policeman's helmet is an annual species, and therefore, cannot accumulate energy-storing compounds to be used for a period of rapid vegetative growth followed by flowering and seed-set. Consequently, concentrations of soluble carbohydrates, starch and crude fat are very low at the end of the season in both shoots (Figure 6.5, A) and stem bases (Table 6.3). However, at the time of peak standing crop (August), concentrations of crude fat and starch are maximal, while concentrations of soluble carbohydrates are highest immediately before peak standing crop when photosynthetic rates are probably greatest. Concentrations of the 3 energy-storing components are high (Figure 6.5, A) when compared with those in other species, while concentrations of

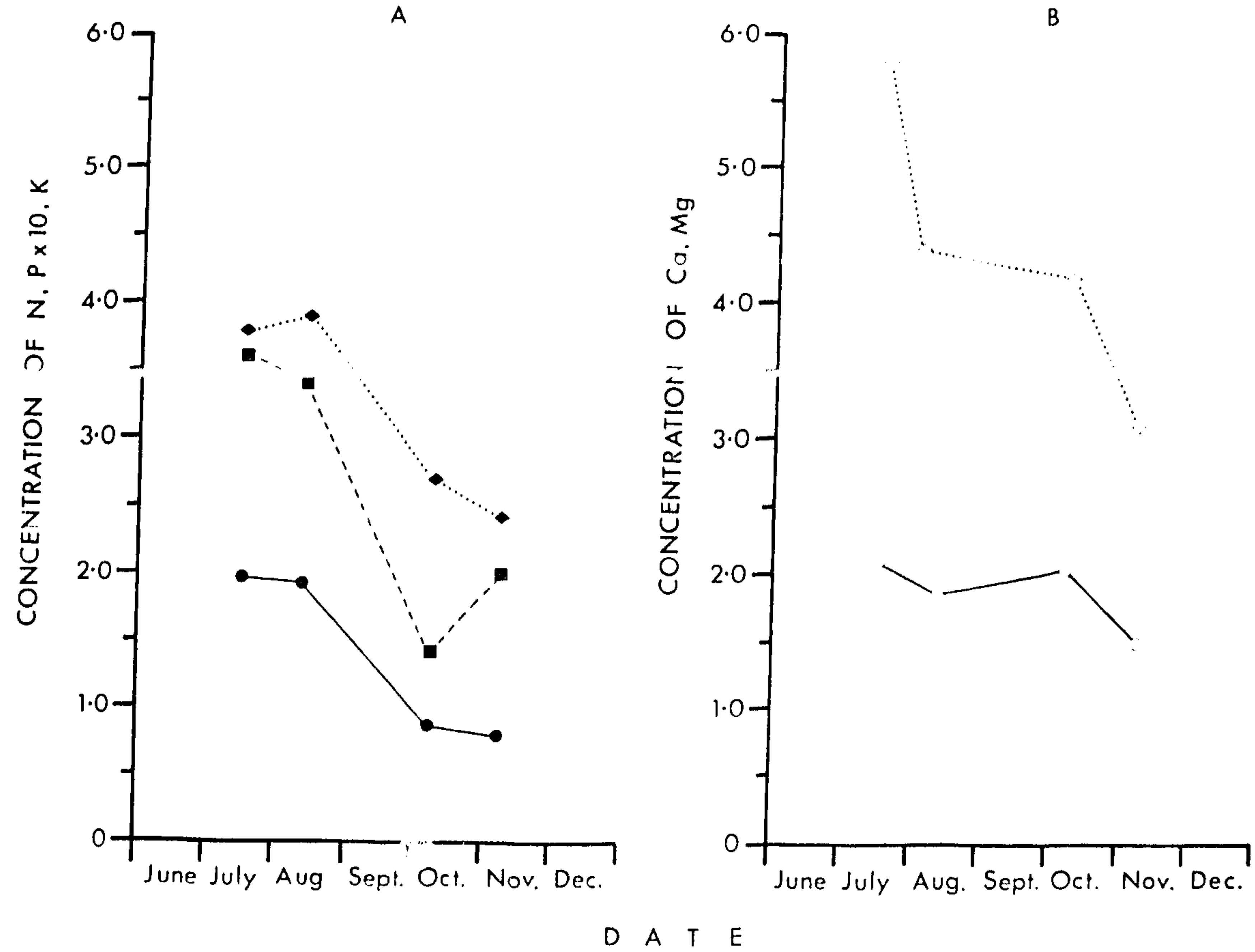


Figure 6.3 The seasonal trends of concentrations (% dry weight) of inorganic nutrients in leaves and stems of policeman's helmet from the Chorlton Brook site.
A Concentrations of N (solid line and solid circles), P broken line and solid squares) and K (dotted line and solid diamonds).
B Concentrations of Ca (solid line and open circles) and Mg (dotted line and open diamonds).
NB Concentrations of P are 1/10th those of N and K.

TABLE 6.1 Concentrations and contents (concentrations x dry weight) of inorganic nutrients in roots and stem bases of policeman's helmet collected from the Chorlton Brook site on 9 October 1979. Standard errors are presented.

| Element | N | P | K | Ca | Mg | Ash |
|---|---|---|---|---|---|---|
| Concentration (% dry weight) | 0.90 ± 0.09 | 0.26 ± 0.02 | 2.77 ± 0.49 | 1.43 ± 0.09 | 0.36 ± 0.032 | 31.0 ± 2.65 |
| Content (kg $ha^{-1}$) | 8.37 ± 1.36 | 2.39 ± 0.15 | 25.76 ± 6.45 | 13.30 ± 1.51 | 3.35 ± 3.94 | 288 ±10.56 |

TABLE 6.2 The nutrient content (concentration x dry weight) of stems and leaves of policeman's helmet from the Chorlton Brook site. Units are kg $ha^{-1}$.

| ELEMENT | 18 JULY | 13 AUGUST | 9 OCTOBER | 8 NOVEMBER |
|---|---|---|---|---|
| N | 165.5 | 203.4 | 86.8 | 53.5 |
| P | 30.2 | 35.5 | 14.0 | 13.4 |
| K | 319.2 | 407.9 | 272.4 | 157.9 |
| Ca | 176.4 | 197.1 | 204.8 | 100.4 |
| Mg | 49.0 | 46.1 | 42.4 | 20.7 |
| Ash | 1176 | 1370 | 1483 | 662 |

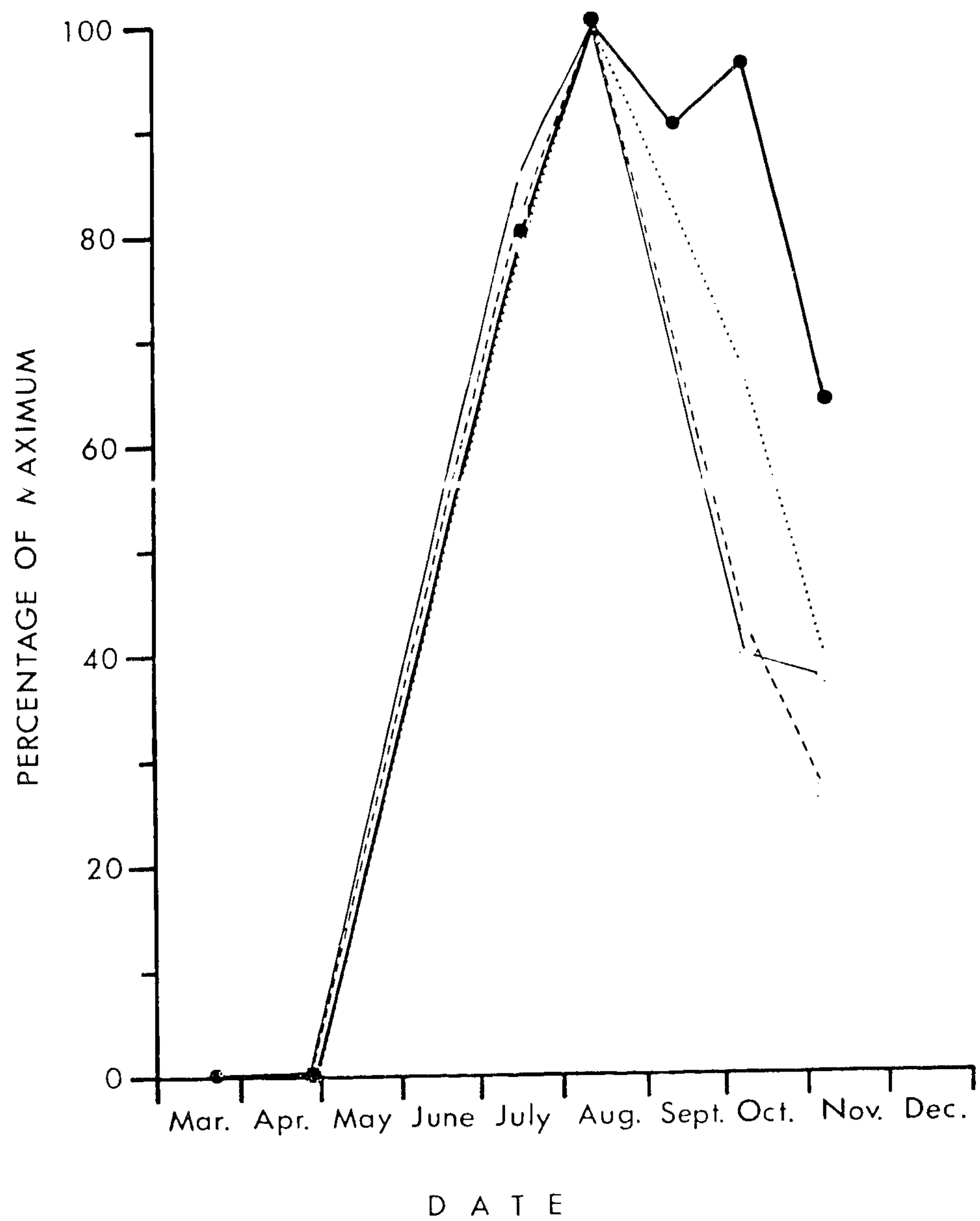


Figure 6.4 The relationship between the seasonal trends of standing crop (thick solid line and solid circles) and the total contents of N (broken line and open squares), P (thin solid line and open diamonds) and K (dotted line and open circles) in leaves and stems of policeman's helmet from the Chorlton Brook site. All values are expressed as percentages of the maxima to standardise the vertical axis.

of lignin are low (Figure 6.5, B). This combination of organic compounds suggests that shoots of policeman's helmet harvested at peak standing crop would decompose rapidly in an anaerobic digestor. Shoots harvested later in the season would be more resistant to digestion, because of the lower concentrations of the energy-storing compounds and the higher concentrations of holocellulose (Figure 6.5, B).

Re-growth is improbable in an annual species and the whole plant, including stem bases and roots - which are easily extractable from the soil - could be harvested with the stems. Although the chemical composition of the underground organs was determined on only one occasion, at the end of the season low concentrations of lignin and holocellulose (Table 6.3) suggest that the stem bases and roots could be digested together with the shoots. The low concentrations of soluble carbohydrates and, in particular, starch (Table 6.3) contrast with the high concentrations found in perennating root systems.

The energy content of shoots of policeman's helmet shows a slight mid-season maximum (Figure 6.6) and an overall value of $19.5 \pm 0.15$ KJ $g^{-1}$, which is not significantly different from the value of $19.3 \pm 0.33$ KJ $g^{-1}$ for the stem bases and roots. Shoots of policeman's helmet, if harvested at peak standing crop, would yield $210 \times 10^9$ J $ha^{-1}$ (Figure 6.6), and the harvesting of roots could increase this to ca $238 \times 10^9$ J $ha^{-1}$.

## 6.7 A summary of the potential of policeman's helmet as an energy crop

6.7.1 Policeman's helmet could be managed as an annual dedicated energy crop as it occurs naturally only in small stands (covering only 0.6 $km^2$ of Great Britain), although it is capable of growing throughout lowland Britain. It may also have potential as an energy catch crop, if its high growth rates are maintained after late plantings.

6.7.2 Whole plants would be harvested, as the root system is small and easily extracted from the soil.

6.7.3 Policeman's helmet would be harvested when standing crops are at a maximum, as the shoots of this annual species quickly lose dry weight and collapse.

6.7.4 Dry matter yields of shoots of 10.5 t $ha^{-1}$ ($210 \times 10^9$ J $ha^{-1}$) plus 0.9 t $ha^{-1}$ ($18 \times 10^9$ J $ha^{-1}$) of roots could be obtained by harvesting at peak standing crop (13 August in 1979).

6.7.5 Shoots and roots of policeman's helmet should be digested easily as the shoots (which contribute 91% of the total biomass) show high water contents, and moderate concentrations of N, P, K and soluble carbohydrates (1.9, 0.3, 3.9 and 10.2% of dry weight respectively) occur while the concentrations of holocellulose and lignin (51 and 10% of dry weight respectively) are quite low. An ash concentration of 13% of dry weight should reduce the size of the residues resulting from chemical conversion processes.

6.7.6 Vegetative re-growth does not occur in this annual species, but it remains to be proved that seeds of policeman's helmet can successfully be planted and seedlings established at various times during the growing season.

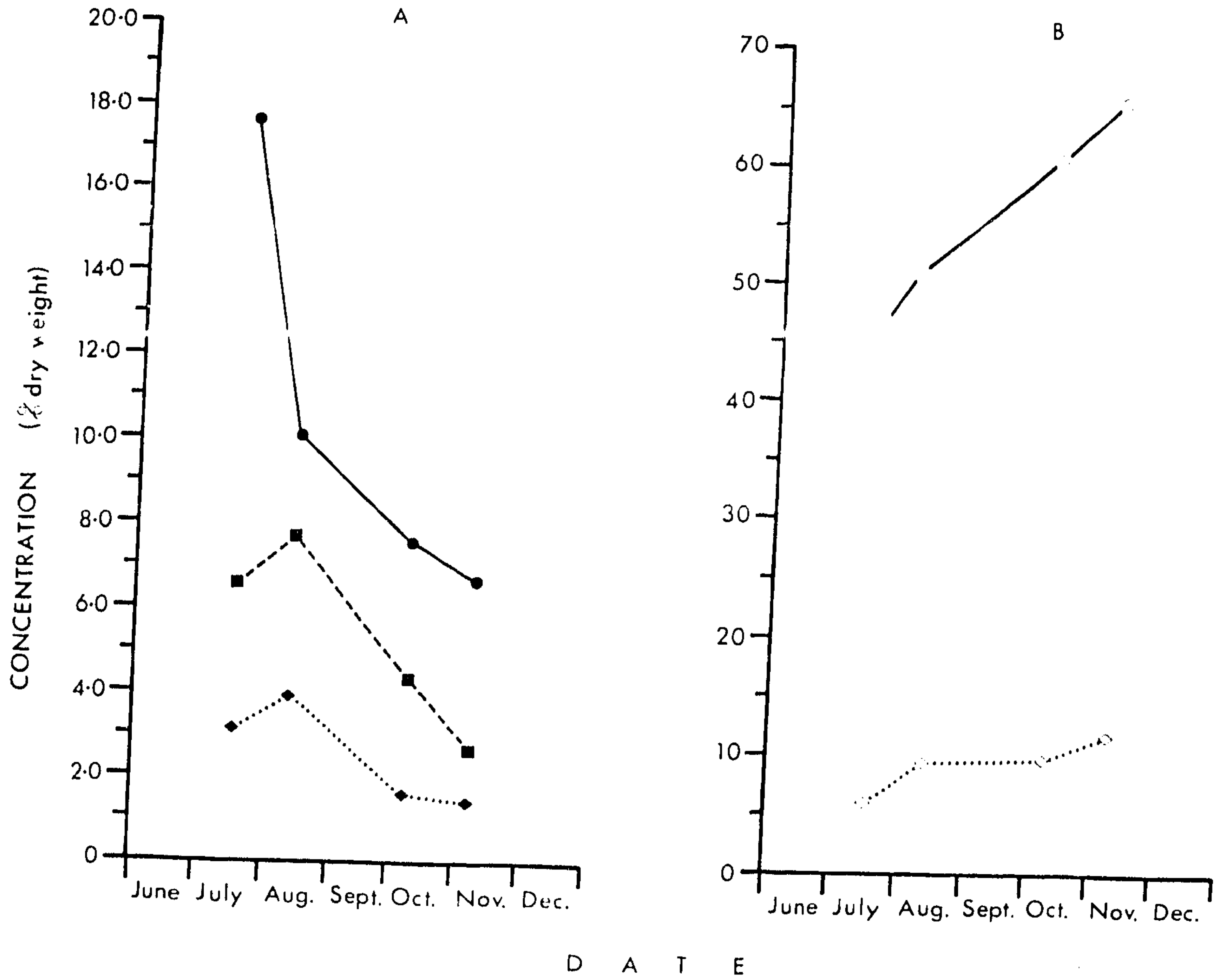


Figure 6.5 The seasonal trends of concentrations of organic plant fractions in shoots of policeman's helmet from the Chorlton Brook site.

A Soluble carbohydrates (solid circles and line), crude fat (solid diamonds and dotted line) and starch x 10 (solid squares and broken line).

B Holocellulose (open circles and solid line) and lignin (open diamonds and dotted line).

NB Concentrations of starch are 1/10th of the values on the Y axis.

TABLE 6.3 Concentrations (% dry weight) of organic plant fractions in the stem bases and roots of policeman's helmet collected from the Chorlton Brook site on 9 October 1979. Standard errors are presented.

| COMPOUND | CONCENTRATION |
|---|---|
| Soluble carbohydrates | 2.59 ± 0.87 |
| Starch | 0.70 ± 0.14 |
| Crude fat | 1.43 ± 0.09 |
| Lignin | 8.50 ± 0.76 |
| Holocellulose | 50.7 ± 0.89 |

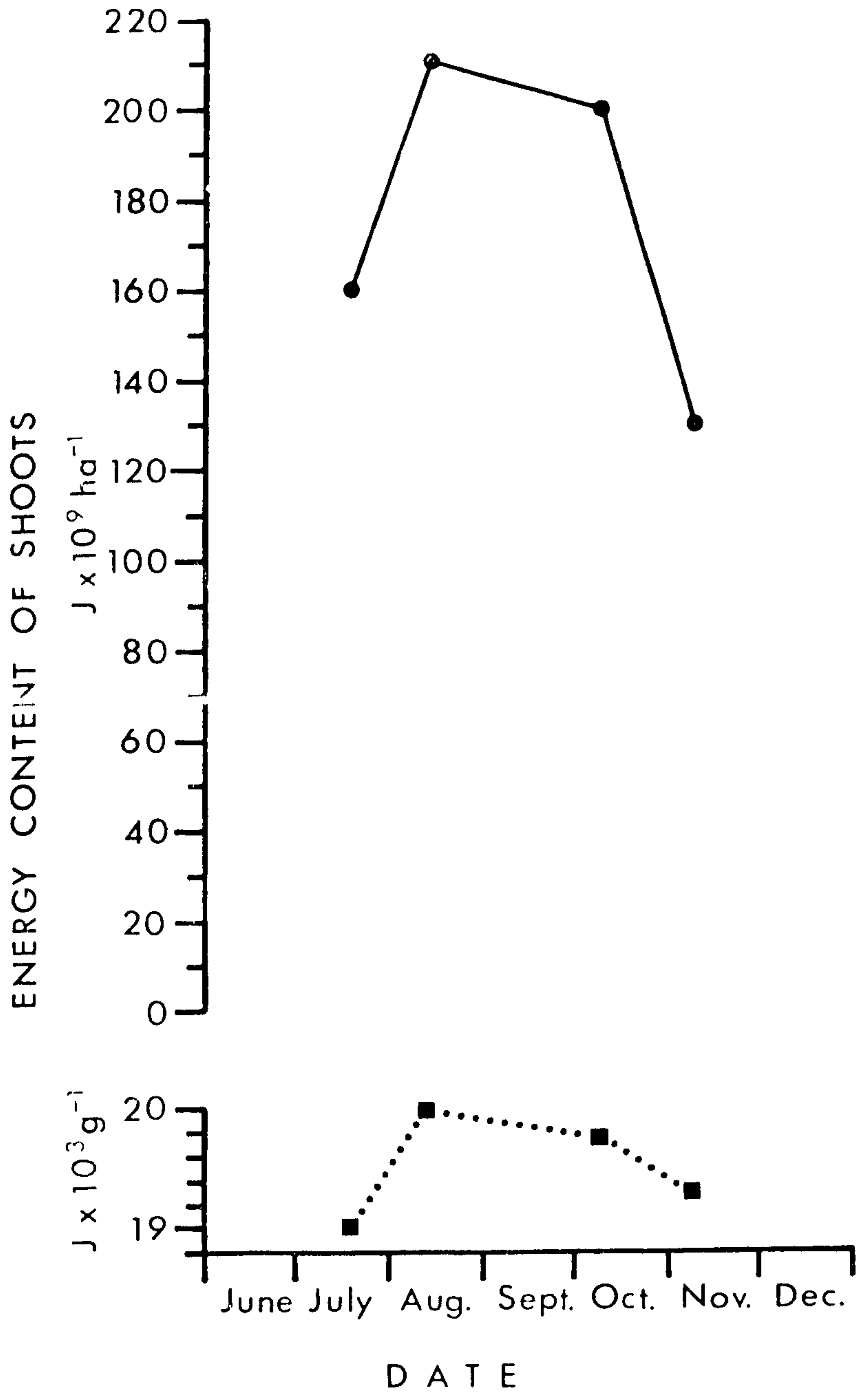


Figure 6.6 Seasonal trends of the energy content of shoots of policeman's helmet expressed on a land area basis and on a unit dry weight basis.

6.7.7 Applications of N, P and particularly K to areas of land dedicated to the growth of policeman's helmet (211, 38 and 434 kg $ha^{-1}$ respectively) would be greater than those currently applied in agriculture, if nutrients removed in the crop were to be replaced, but its tolerance to pollution may make it suitable for growing in sewage effluent, in which case the nutrients in the harvested material could be reclaimed for use elsewhere.

6.7.8 The management of artificial monocultures of policeman's helmet should be technologically feasible using existing equipment, although high soil water deficits may seriously affect the establishment of this energy crop.

## 6.8 Conclusion

Policeman's helmet is an annual species which could be managed as a dedicated energy crop, and, possibly, as an energy catch crop, if its high growth rates are maintained after late plantings. Harvesting time would be at peak standing crop and the biomass should digest easily.

# 7 *FILIPENDULA ULMARIA* - MEADOW SWEET

## 7.1 General description

Meadow sweet is a perennial herb which can reach a height of 120 cm (Plate 2b). It flowers prolifically and also reproduces vegetatively by rhizomes.

Meadow sweet is found throughout the United Kingdom (Figure 7.1) in swamps, marshes, fens, wet woods and meadows extending to nearly 914 m (Clapham *et al.* 1962). Although it often dominates the vegetation where it occurs, it rarely forms pure stands, and other plant species make important contributions to site productivity. It covers approximately 110 $km^2$ of Great Britain (Bunce pers comm).

## 7.2 Productivity

Previous estimates of the above-ground productivity of stands of meadow sweet were 4 t $ha^{-1}$ (Al-Mufti *et al.* 1979) and 7.1 t $ha^{-1}$ (Callaghan *et al.* 1978) for total herbaceous shoot standing crop and 3 t $ha^{-1}$ (Al-Mufti *et al.* 1979) for the meadow sweet component. More intensive sampling during 1979 at the site used by Callaghan *et al.* (1978) in 1978 gave very similar results, ie a peak standing crop for all herbaceous shoot material of 6.5 t $ha^{-1}$ (Figure 7.2). Above-ground standing crop reached a maximum for the site in July, but meadow sweet and its associated species showed separate peaks of standing crop in July and June respectively (Figure 7.2). The maximum above-ground standing crop of meadow sweet was 5.6 t $ha^{-1}$, and it appears that the site studied is far more productive than that studied by Al-Mufti *et al.* (1977). In comparison with neighbouring sites, however, the above-ground standing crop of the meadow sweet is low.

Biomass of below-ground organs is very high. In 1978, Callaghan *et al.* recorded a below-ground standing crop of 12.6 t $ha^{-1}$ and, in 1979, standing crops of 10.7 ± 1.8 and 12.6 ± 3.1 t $ha^{-1}$ were recorded on 25 May and 14 December respectively.

The water content of the aerial shoots of the meadow sweet site varied little over the growing season, being 81% in May and 74% in October. The fresh weight/dry weight ratios were 5.3 ± 0.4 (25 May), 3.3 ± 0.1 (26 June) and 3.9 ± 0.1 (9 October).

## 7.3 Nutrient content of meadow sweet

### 7.3.1 Inorganic nutrients

The concentrations of all the inorganic nutrients analysed showed a decrease over the growing season (Table 7.1). This trend is characteristic of N, P and K, but the decrease in the concentrations of Ca and Mg contrast strongly with, for example, the pattern found in cord-grass. Concentrations of N, P and K in meadow sweet are low when compared with the concentrations of these elements in other species at similar stages of development. The combination of low concentrations of N, P and K together with comparatively

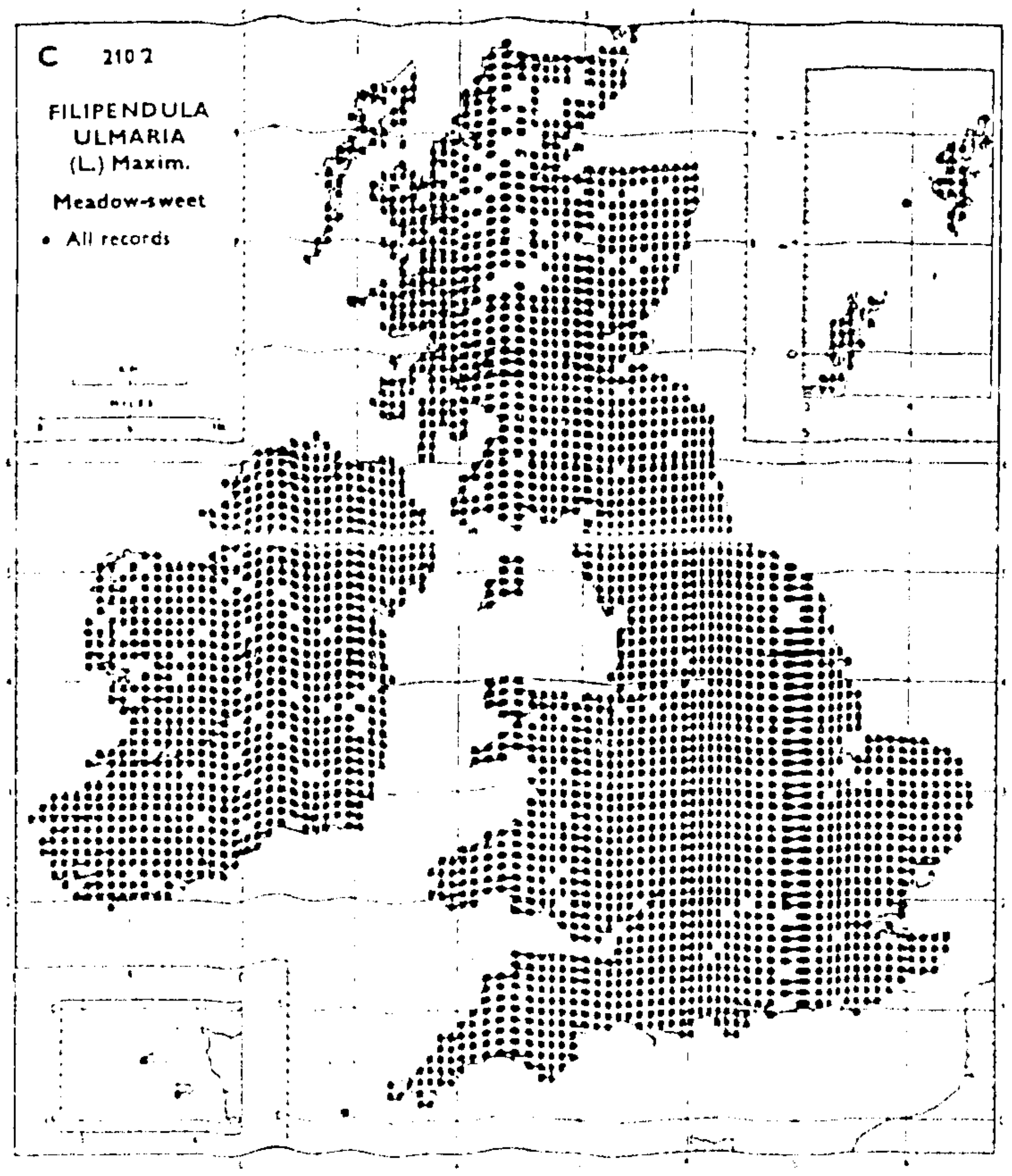


Figure 7.1 The distribution of meadow sweet in Great Britain and Ireland; from Perring & Walters (1962).

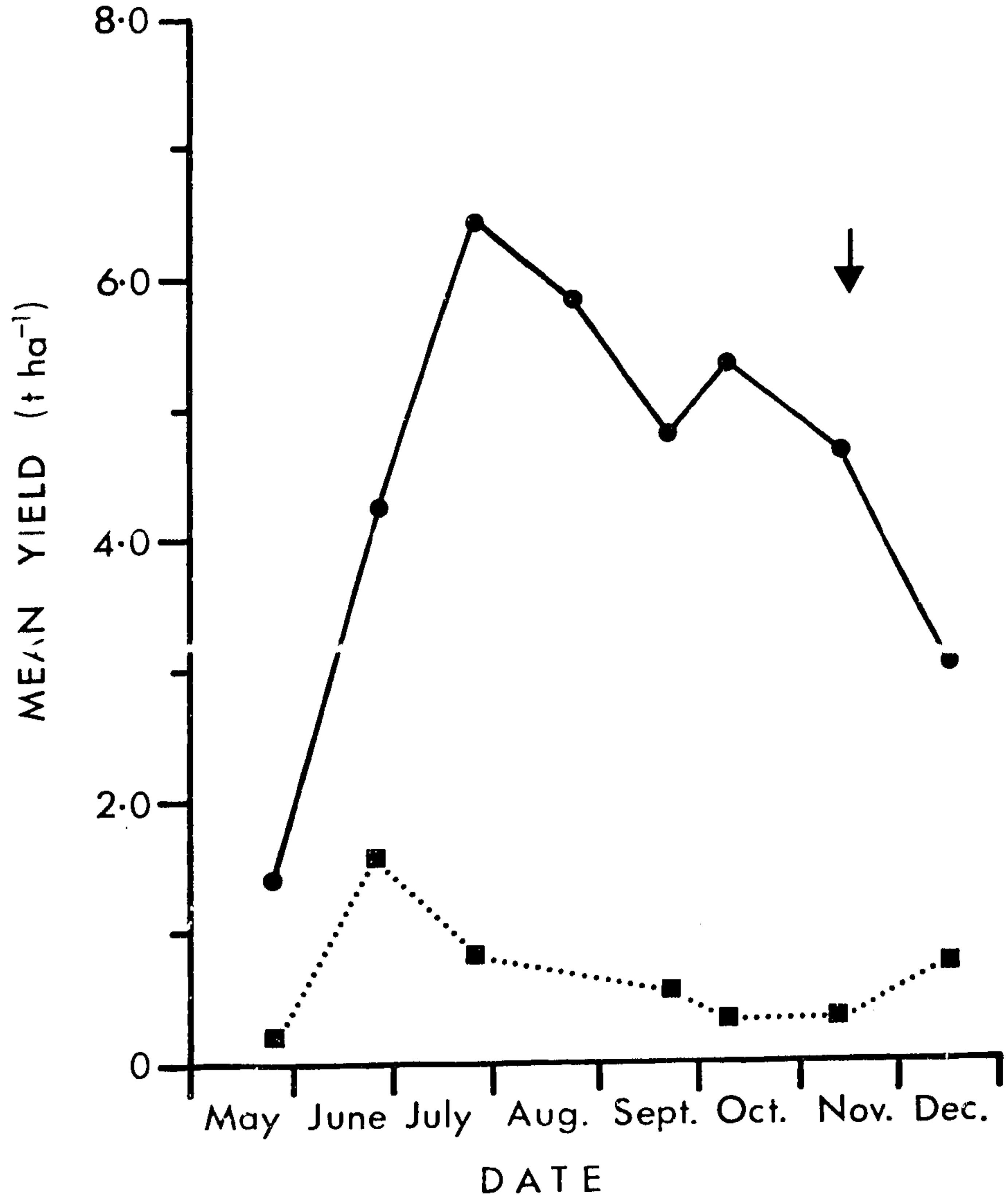


Figure 7.2 The seasonal growth of shoots of meadow sweet (solid circles and line) and associated species (squares and dotted line) collected from the Chisworth site. The 2 biomass fractions are plotted cumulatively. The arrow denotes the date by which all shoots were dead.

low standing crops results in low contents of N, P and K (Table 7.1). If this material were harvested for conversion to biofuels, the replacement levels of N, P and K would be lower than those required for other sites and also lower than those currently used in agriculture (Church 1975).

Concentrations of inorganic nutrients in the rhizomes of meadow sweet are generally similar to concentrations in the shoots, except that concentrations of K are lower in the rhizomes than in the shoots. Ca shows the opposite trend (Table 7.1).

The clear seasonal trends shown by the concentrations of inorganic nutrients in the shoots are not evident in the rhizomes, which represent a considerable over-wintering pool of nutrients. In the cases of N, P and Mg, this pool is approximately twice the size of their maximum contents in the shoots (Table 7.1). Only K shows similar values between peak content in above ground tissues and mid-season values in the rhizomes. However, there is a significant increase in the content of K (and in the concentration of K) in the rhizomes during autumn (Table 7.1), and this may represent end of season translocation from shoots to rhizome suggesting a possible economy of this element. Concentrations of ash in the rhizomes (Table 7.1) are approximately twice those in the shoots, but both values are very low and would result in an ash residue of only 319 kg $ha^{-1}$ after conversion of biomass to fuel.

### 7.3.2 Organic plant fractions

Concentrations of soluble carbohydrates and crude fat in the shoots of meadow sweet decrease by over one-half between peak standing crop and the end of season (Table 7.2). In the case of soluble carbohydrates, this decrease in shoots coincides with an increase in concentration in the rhizomes (where starch concentrations also increase over the growing season), and a significant end of season translocationis indicated (Table 7.2). In general, however the concentrations of energy-storing compounds are low in both shoots and rhizomes. On the other hand, concentrations of cell wall materials are quite high in shoots and rhizomes, and it must be inferred that meadow sweet would not be converted to biofuels as easily as the species considered so far, while the removal of soluble carbohydrates during the harvesting of maximum standing crop would probably depress subsequent re-growth.

If meadow sweet were harvested at peak standing crop, an energy yield of 130 x $10^9$ J $ha^{-1}$ would be obtained, and this could be increased to 344 x $10^9$ J $ha^{-1}$ on one occasion by harvesting rhizomes.

## 7.4 A summary of the potential of meadow sweet as an energy crop

7.4.1 It is doubtful if meadow sweet could be efficiently managed even as an opportunity energy crop for the reasons outlined below.

7.4.2 Although meadow sweet grows throughout Great Britain, its maximum standing crop of shoots is only 5.6 t $ha^{-1}$ (112 x $10^9$ J $ha^{-1}$), and other species associated with it increase the yield of shoots to only 6.5 t $ha^{-1}$ (ca 130 x $10^9$ J $ha^{-1}$).

TABLE 7.1 Inorganic nutrient concentrations and contents (concentration x dry weight) of the above- and below-ground tissues of meadow-sweet collected from the Chisworth site.

| | N | P | K | Ca | Mg | Ash |
|---|---|---|---|---|---|---|
| ABOVE-GROUND TISSUES | | | | | | |
| Concentration (% dry weight) | | | | | | |
| 25 July 1979 | 1.80 | 0.150 | 1.75 | 0.60 | 0.35 | 5.7 |
| 14 December 1979 | 0.41 | 0.024 | 0.05 | 0.37 | 0.10 | 2.2 |
| Content (kg $ha^{-1}$) | | | | | | |
| 25 July 1979 | 100.8 | 8.40 | 98.0 | 33.3 | 19.6 | 319 |
| 14 December 1979 | 9.2 | 0.54 | 1.2 | 8.3 | 2.3 | 49.3 |
| BELOW-GROUND TISSUES | | | | | | |
| Concentration (% dry weight) | | | | | | |
| 25 May 1979 | 2.0 | 0.16 | 0.88 | 1.03 | 0.37 | 11.7 |
| 14 December 1979 | 1.6 | 0.14 | 1.12 | 0.97 | 0.37 | 11.0 |
| Content (kg $ha^{-1}$) | | | | | | |
| 25 May 1979 | 214.6 | 17.2 | 94.4 | 110.5 | 39.7 | 1255 |
| 14 December 1979 | 201.8 | 17.3 | 141.2 | 122.3 | 46.7 | 1387 |

TABLE 7.2 Concentrations (% dry weight) of the organic plant fractions and energy contents (KJ $g^{-1}$ dry weight) of shoots and rhizomes of meadow sweet collected from the Chisworth site.

| | Soluble carbohydrate | Starch | Crude fat | Lignin | Holocellulose | Energy content |
|---|---|---|---|---|---|---|
| **Above-ground tissues** | | | | | | |
| 25 July 1979 | 6.25 | 0.50 | 2.05 | 20.1 | 54.5 | 20.0 |
| 14 December 1979 | 3.03 | 0.83 | 0.86 | 14.0 | 77.3 | 20.0 |
| **Below-ground tissues** | | | | | | |
| 25 May 1979 | 6.34 | 1.63 | 1.40 | 36.6 | 31.0 | 20.0 |
| 14 December 1979 | 12.00 | 7.57 | 1.27 | 29.8 | 47.3 | 19.3 |

7.4.3 The wet habitats where meadow sweet usually occurs are often capable of sustaining far greater productivities from species such as *Epilobium hirsutum* (Chapter 9).

7.4.4 It would probably be feasible to harvest meadow sweet only if its habitat were being drained and "improved" for other uses of the land and about to be disturbed.

7.4.5 If the above strategy were adopted, 6.5 t $ha^{-1}$ (130 x $10^9$ J $ha^{-1}$) of shoots could be obtained together with, possibly, 11.7 t $ha^{-1}$ (230 x $10^9$ J $ha^{-1}$) of rhizomes.

7.4.6 Shoots of meadow sweet, if harvested at peak standing crop (23 July in 1979) should not be too resistant to anaerobic digestion, although nutrient concentrations are lower than in the other species investigated, whereas the concentrations of holocellulose and lignin together (75% of the dry weight) are quite high.

## 7.5 Conclusion

It is doubtful if meadow sweet could be efficiently managed as an opportunity energy crop, because its yields are lower than those which could be obtained from other species of similar habitats. It could be harvested during a period of change in land use, although it would not probably digest as easily as the other species considered earlier.

# 8 *CHAMAENERION ANGUSTIFOLIUM* - ROSEBAY WILLOW-HERB

## 8.1 General description

Rosebay willow-herb is a tall perennial herb which may reach a height of 120 cm. It reproduces vegetatively but shows extremely efficient sexual reproduction and seed dispersal, which is responsible for its recent spread (Clapham *et al.* 1968) and success as a ruderal species, often being the first species to colonise cleared woodland or derelict urban areas (Plate 2c). The species occurs naturally in rocky places (up to 975 m) and woodland clearings and it is possible that its present abundance is due to the availability of newly-disturbed areas of land (Clapham *et al.* 1968).

Rosebay willow-herb is found throughout most of Great Britain (Figure 8.1), and may form dense, and almost pure stands. It covers approximately 138 $km^2$ of Great Britain (Bunce pers comm).

## 8.2 Productivity

Al-Mufti *et al.* (1979) recorded standing crops of 8 and 6 t $ha^{-1}$ for total above-ground standing crop and standing crop of the rosebay willow-herb component respectively of a site in Derbyshire, while Callaghan *et al.* (1978) recorded a standing crop of 7.79 t $ha^{-1}$ for another site in Derbyshire. During the present study, a maximum shoot standing crop of 8.4 t $ha^{-1}$ was recorded for the dominant species (Figure 8.2), and above-ground standing crops of all species ranged from 4.35 to 10.6 t $ha^{-1}$ (Table 8.1, Figure 8.2), with a mean value of 8.5 t $ha^{-1}$. At the intensively studied Chisworth site, species associated with rosebay willow-herb showed a peak standing crop of shoots of 2.25 t $ha^{-1}$ one month earlier than the peak standing crop of the dominant species (Figure 8.2).

Below-ground structures yielded 7.5 t $ha^{-1}$ when recorded in 1978 (Callaghan *et al.* 1978), and 10.03 ± 0.63 when measured on the 25 May 1979.

Water contents of shoots from the rosebay willow-herb sites vary between 82% in May and 66% in September.

## 8.3 Nutrient content of rosebay willow-herb

### 8.3.1 Inorganic nutrients

Concentrations of the inorganic nutrients were measured on only one occasion, ie when above-ground standing crop was at a maximum. Concentrations of N, P, K, Mg and ash were generally low (compared with values for meadow sweet), but high productivity resulted in more typical contents of these elements (Table 8.2). However, if rosebay willow-herb were harvested as a biofuel at peak above-ground standing crop, the nutrients removed from site would be less than those currently applied annually to agricultural crops (Church 1975), while a comparatively good yield of 10.5 t $ha^{-1}$ $yr^{-1}$ would be obtained with an ash content of only 420 kg.

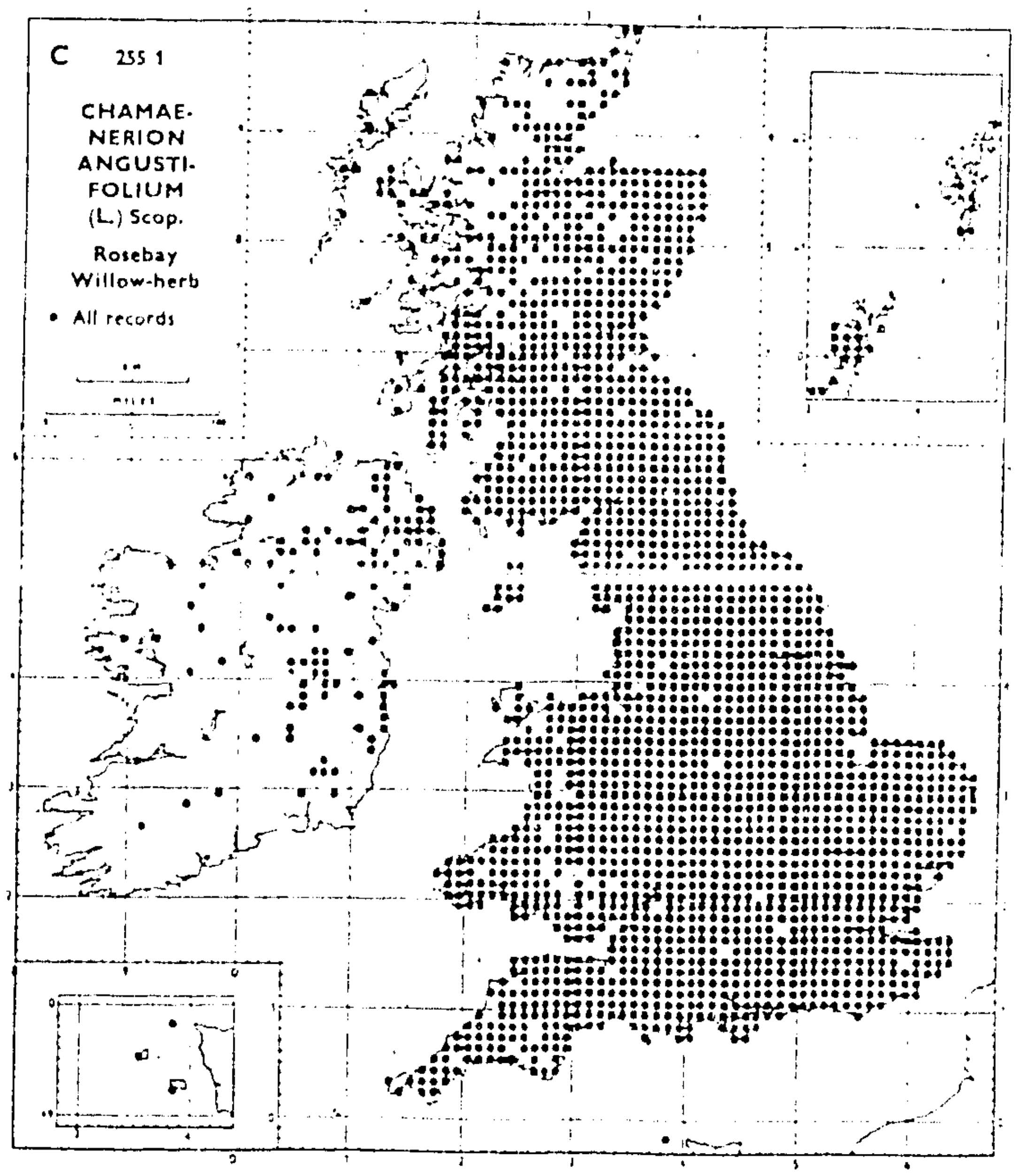


Figure 8.1 The distribution of rosebay willow-herb in Great Britain & Ireland; from Perring & Walters (1962).

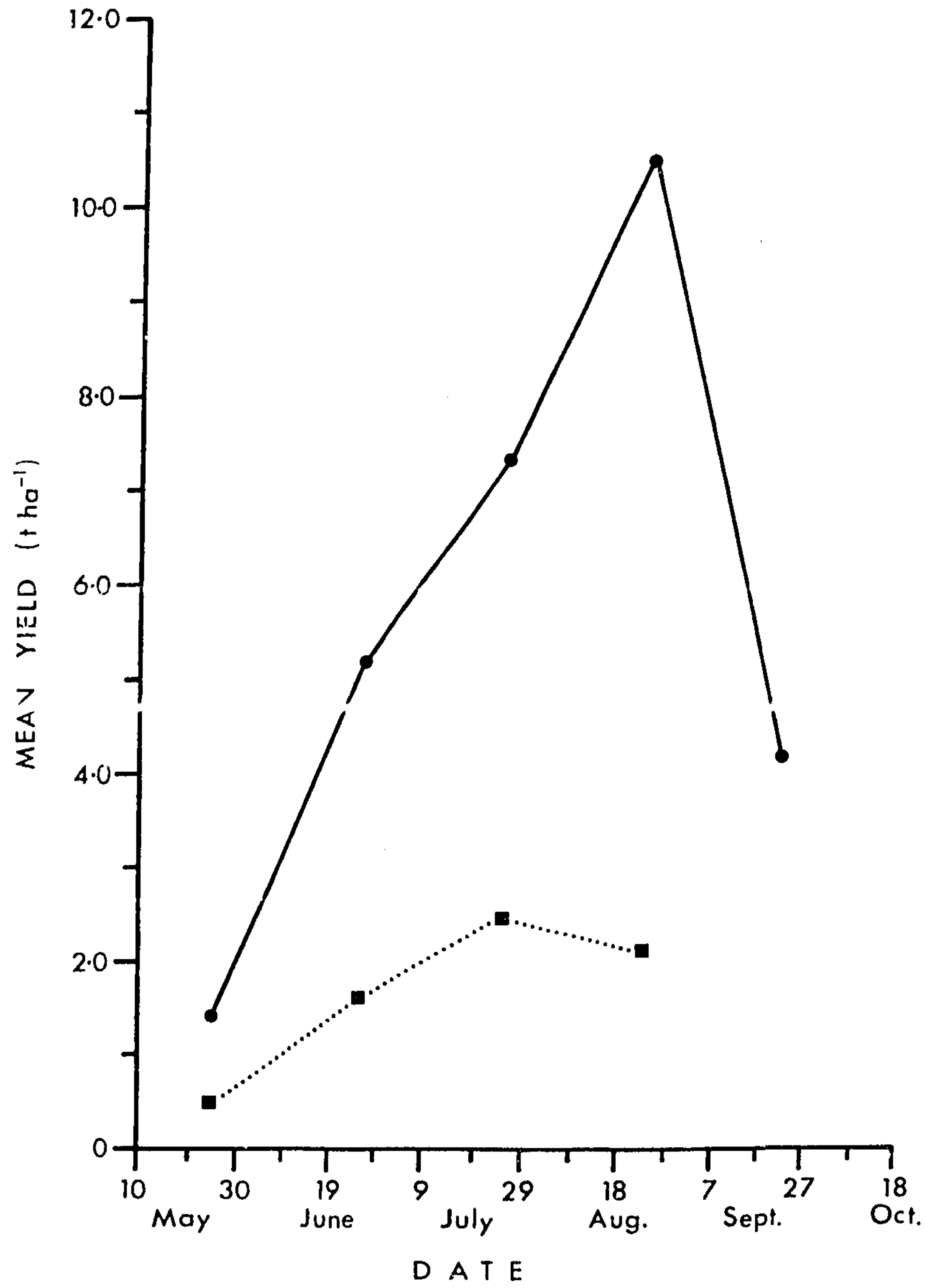


Figure 8.2 The seasonal growth of shoots of rosebay willow-herb (circles and solid line) and species associated with it (squares and dotted line) at the Chisworth site. The 2 yield components are plotted cumulatively. Shoots were still alive on 21 September.

TABLE 8.1 The yield and fresh weight/dry weight ratios of herbaceous shoots from stands of rosebay willow-herb. Standard errors are presented.

| Site | Site No. | Sampling date | Standing crop (t $ha^{-1}$) | Fresh weight/dry weight |
|---|---|---|---|---|
| Bellmuir, Aberdeenshire | 12 | 13 September | 4.35 ± 0.37 | 4.37 ± 0.17 |
| Risedale, Cumbria | 18 | 24 September | 7.33 ± 0.66 | - |
| Dollarbeg, Clackmannanshire | 13 | 14 September | 7.58 ± 0.60 | 4.58 ± 0.09 |
| Holsworthy, Devon | 26 | 9 September | 8.39 ± 0.58 | 2.95 ± 0.08 |
| Chisworth, Derbyshire | 6 | 23 August | 10.56 ± 0.92 | 5.54 ± 0.19 (25 May)<br>5.25 ± 0.15 (26 June) |
| Pontefract, Yorkshire | 15 | 4 September | 10.76 ± 1.13 | - |
| Straition, Ayrshire | 9 | 1 October | 10.79 ± 1.47 | 3.82 ± 0.10 |

### 8.3.2 Organic plant fractions

At peak standing crop (23 August), concentrations of the energy-storing compounds are high when compared with other species, accounting for ca 17.8% of the shoot dry weight (Table 8.2). contrast, concentrations of the cell wall materials are comparatively low. Consequently, shoots of rosebay willow-herb, if harvested at peak standing crop, should provide a good substrate for anaerobic digestion.

An energy content of shoot material of 20.0 KJ $g^{-1}$ dry weight (Table 8.2) would result in a maximum energy yield of 212 x $10^9$ J $ha^{-1}$, which could be increased initially to 422 x $10^9$ J $ha^{-1}$ by harvesting rhizomes

## 8.4 A summary of the potential of rosebay willow-herb as an energy crop

8.4.1 Rosebay willow-herb would be managed as an opportunity energy crop as it grows throughout Great Britain, covering 138 $km^2$ of its surface. It is often a major component of the vegetation of roadsides, railway embankments and waste land, where harvesting would not affect current land use.

8.4.2 Dry matter yields of 8.4 t $ha^{-1}$ (168 x $10^9$ J $ha^{-1}$) of rosebay willow-herb shoots together with 2.2 t $ha^{-1}$ (ca 44 x $10^9$ J $ha^{-1}$) of shoots of associated species could be obtained by harvesting at peak standing crop.

8.4.3 Shoots of rosebay willow-herb harvested at peak standing crop should be easily digested, as water contents are between 66 and 82% of the fresh weight and inorganic nutrients occur in moderate concentrations. Energy-storing compounds occur in quite high concentrations (soluble carbohydrates = 14% of the dry weight), and the concentrations of the cell wall materials are not excessive (holocellulose = 51% and lignin = 17% of the dry weight). Residues from chemical coversion would contain an ash concentration of only 5% of the shoot dry weight.

8.4.4 Applications of N, P and K to areas of harvested rosebay willow-herb (126, 11 and 118 kg $ha^{-1}$ respectively) would be within the ranges currently applied in agriculture, if nutrients removed in harvested biomass were replaced.

8.4.5 The effect of harvesting shoots of rosebay willow-herb at peak standing crop on re-growth in subsequent years cannot be evaluated from the present data base. However, it is certain that re-growth would be better if shoots were harvested when senescent and processed by thermal conversion to fuel. Yields of senescent shoots would be low (4.2 t $ha^{-1}$ = 84 x $10^9$ J $ha^{-1}$), as standing crops quickly decrease in autumn.

8.4.6 If it were possible to harvest the rhizomes of rosebay willow-herb, an additional yield of ca 8.8 t $ha^{-1}$ (176 x $10^9$ J $ha^{-1}$) would be obtained initially.

TABLE 8.2 Concentrations and contents (concentration x dry weight) of inorganic nutrients and organic plant fractions in the shoots of rosebay willow-herb collected from the Chisworth site on 23 August 1979 when maximum standing crop was achieved. Standard errors are given.

| Fraction | Concentration (% dry weight) | Content (kg $ha^{-1}$) |
|---|---|---|
| N | 1.51 ± 0.1 | 125.9 ± 8.39 |
| P | 0.13 ± 0.01 | 10.9 ± 0.56 |
| K | 1.4 ± 0.0 | 117.5 ± 0.00 |
| Ca | 1.7 ± 0.05 | 63.8 ± 3.97 |
| Mg | 0.19 ± 0.01 | 15.9 ± 1.01 |
| Ash | 5.0 ± 0.15 | 419.5 ± 12.19 |
| Soluble carbohydrate | 14.3 ± 0.88 | 1199.8 ± 74.0 |
| Starch | 0.22 ± 0.08 | 18.5 ± 6.73 |
| Crude fat | 3.27 ± 0.19 | 274.4 ± 15.57 |
| Lignin | 17.3 ± 1.22 | 1448.1 ±102.1 |
| Holocellulose | 50.7 ± 4.78 | 4253.7 ±183.4 |
| Energy content | 20.0 ± 0.0 KJ $g^{-1}$ dry weight | 168 x $10^9$ ± J $ha^{-1}$ ± 0.0 |

8.4.6 It is technologically feasible to harvest shoots of rosebay willow-herb, and cutting and collecting should be particularly energy efficient along present transport routes where the species often occurs naturally. In the case of road verges, the vegetation is often controlled already, but by the wasteful processes of mowing or applying herbicides.

## 8.5 Conclusion

Rosebay willow-herb could be an important short-term opportunity energy crop, and could be harvested at peak standing crop from areas where land use is changing or where more productive energy crops are to be introduced.

# 9 *EPILOBIUM HIRSUTUM* - GREAT HAIRY WILLOW-HERB

## 9.1 General description

This species belongs to the same plant family as rosebay willow-herb and is similar in its morphology and ecology. Great hairy willow-herb is taller than rosebay willow-herb (reaching 1.5 m) but shows a more restricted distribution (Figure 9.1), ascending to only 366 m in the hills of Derbyshire (Clapham *et al.* 1962) and covering only about 6 $km^2$ of Great Britain (Bunce pers comm). Great hairy willow-herb grows in wetter areas than rosebay willow-herb and tends to occur in more stable habitats where it may form dense stands (Plate 2d).

## 9.2 Productivity

Callaghan *et al.* (1978) recorded an above-ground standing crop of 7.79 t $ha^{-1}$ for a stand of great hairy willow-herb, but no other estimates have been found in the literature. During the present study, a maximum above-ground standing crop of 12.9 t $ha^{-1}$ was recorded for the site, with the dominant species contributing 8.6 t $ha^{-1}$ (Figure 9.2). Thus, species associated with great hairy willow-herb make a major contribution to site productivity, reaching a maximum above-ground standing crop of 5.9 t $ha^{-1}$ (Figure 9.2).

High productivity values were also recorded at other sites where above-ground standing crops varied between 8.72 and 15.33 t $ha^{-1}$ (Table 9.1).

Below-ground standing crops at the Chisworth site yield 5.09 ± 0.14 t $ha^{-1}$ on 25 May and 8.08 ± 1.53 t $ha^{-1}$ on 14 December. This species shows, therefore, a much greater allocation of dry weight to the shoots than meadow sweet which grows at an adjacent site.

Water contents of great hairy willow-herb vary between 88% on 26 June to 76% on 17 October, and these figures are high compared with values for rosebay willow-herb.

## 9.3 Nutrient content of great hairy willow-herb

### 9.3.1 Inorganic nutrients

Concentrations of inorganic nutrients in the above-ground tissues of great hairy willow-herb are not available for the time of peak standing crop. However, Table 9.2 presents concentrations and contents of nutrients for 17 October when the yield was 10.8 t $ha^{-1}$, and for later in the season when the above-ground tissues were dead.

Concentrations of the inorganic nutrients are generally low on 17 October (Table 9.2), and the harvesting of biomass at this time would remove quantities of N, P and Mg similar to those removed by harvesting the peak standing crop of meadow sweet (Table 6.1), but the yield of great hairy willow-herb would be almost double that of meadow sweet. It would appear, therefore, that great hairy willow-herb has an efficient economy of N, P and Mg. Concentrations and contents of K and Ca are, however, high and the replacement applications of K would be as great as those conventionally applied to agricultural crops.

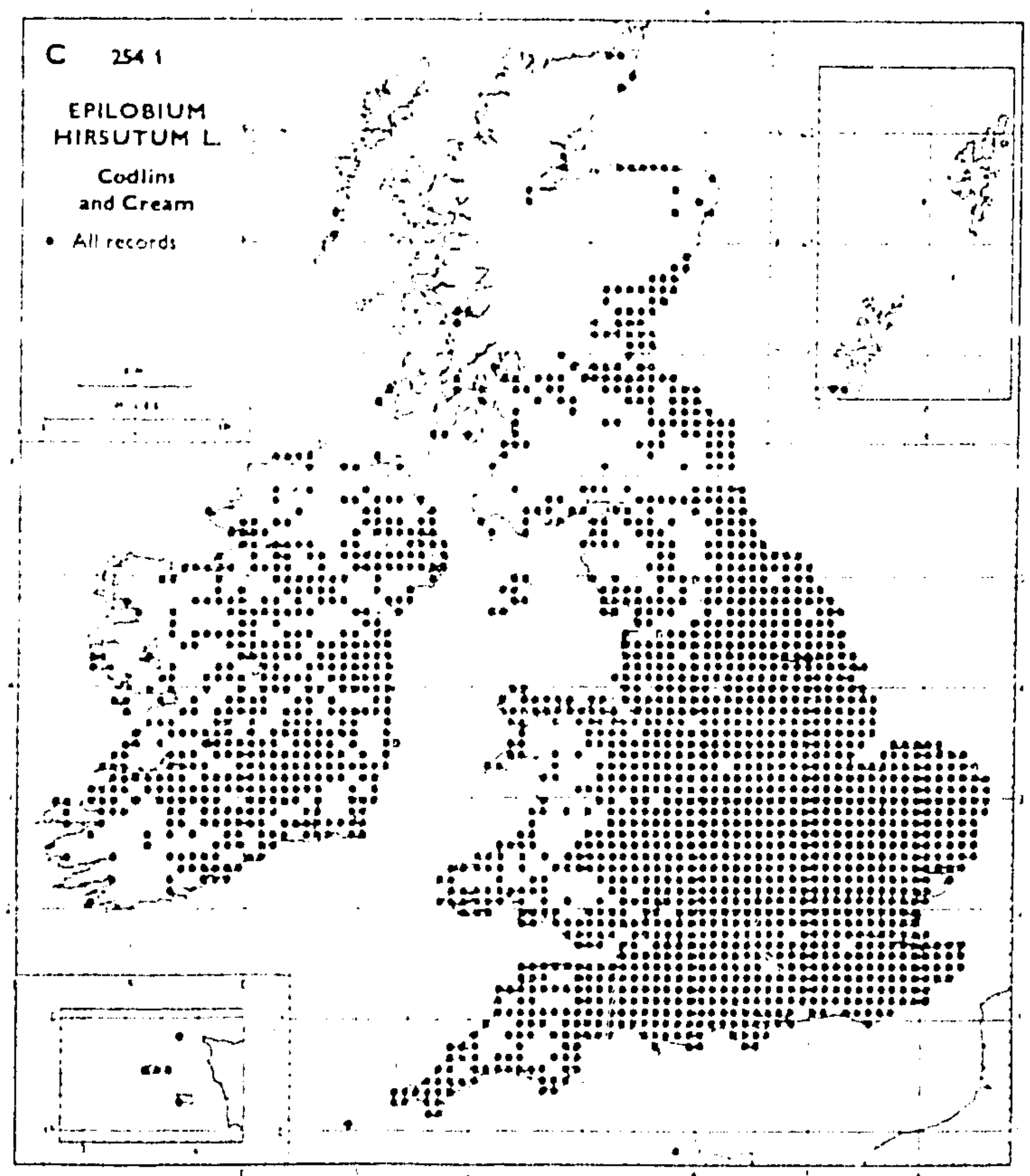


Figure 9.1 The distribution of great hairy willow-herb in Great Britain and Ireland; from Perring & Walters (1962).

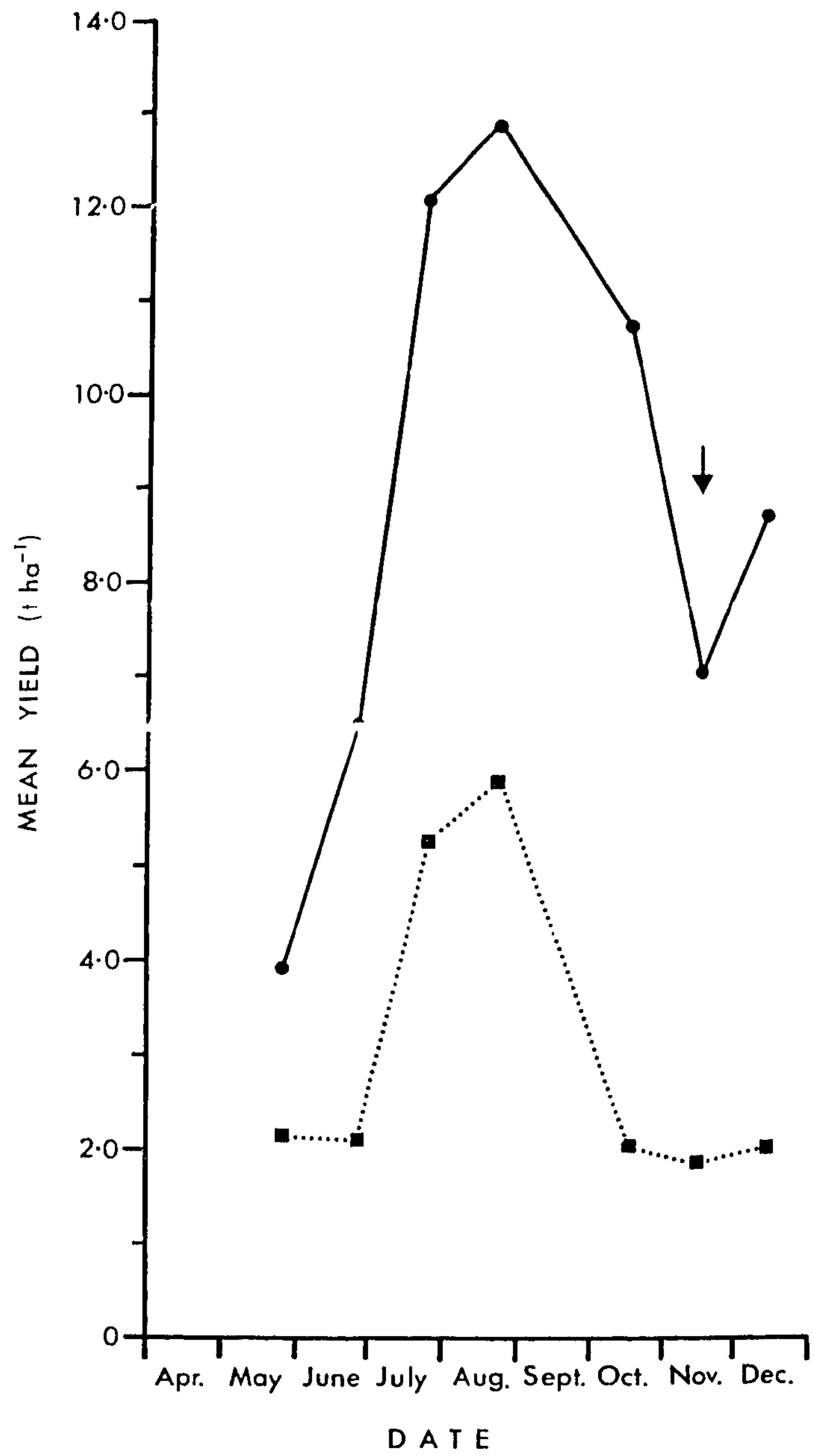


Figure 9.2 The seasonal growth of shoots of great hairy willow-herb (circles and solid line) and species associated with it (squares and dotted line) at the Chisworth site. The 2 yield components are plotted cumulatively. The arrow denotes the date on which all of the shoots of great hairy willow herb were apparently dead.

TABLE 9.1 Above-ground standing crops of stands of great hairy willow-herb

| Site | Site No. | Sampling date | Standing crop (t $ha^{-1}$) |
|---|---|---|---|
| Kettleburgh, Suffolk | 25 | 3 September | 8.72 ± 1.13 |
| Chisworth, Derbyshire | 6 | 23 August | 12.85 ± 1.41 |
| Sheepy Magna, Leicestershire | 28 | 16 August | 13.59 ± 0.77 |
| Plucks Gutter, Kent | 29 | 4 September | 15.33 ± 0.43 |

Concentrations of inorganic nutrients in the rhizomes of great hairy willow-herb decrease by a factor of up to 50% over the growing season, but increased rhizome dry weight at the end of season results in similar contents of inorganic nutrients (Table 9.2). The pools of K, Ca and Mg in the rhizomes are quite small compared with the contents of these elements in the shoots (Table 9.2), which reflects a low root/shoot ratio. However, the rhizomes appear to represent a pool of P as the content of this element is almost 4 times greater in the rhizomes than in the shoots.

### 9.3.2 Organic plant fractions

Concentrations of the organic plant fractions in the shoots of great hairy willow-herb show that the shoots are fibrous structures with only small amounts of energy-storing compounds (Table 9.3). This woody nature would probably make the shoots resistant to anaerobic digestion (compared with the species considered so far) and necessitate a thermal method of producing a usable fuel from senescent and dry shoots. Surprisingly, the rhizomes appear to be far less fibrous than the shoots and are rich in energy-storing compounds at the end of the season (Table 9.3). High end of season concentrations of soluble carbohydrates and starch, which shows a 10-fold increase over the season, suggest that the rhizomes of great hairy willow-herb are efficient storage organs and should be amenable to anaerobic digestion.

The energy contents of this species are typical, in that there is little variation within the season and the rhizomes show slightly lower values than the shoots (Table 9.3). If shoots of great hairy willow-herb were harvested at peak standing crop, an energy yield of ca 257 x $10^9$ J $ha^{-1}$ would result, which would increase to about 387 x $10^9$ J $ha^{-1}$ if rhizomes could be harvested.

## 9.4 A summary of the potential of great hairy willow-herb as an energy crop

9.4.1 Great hairy willow-herb would be managed mainly as an opportunity energy crop, although it only covers about 6 $km^2$ of Great Britain (Bunce pers comm). Like rosebay willow-herb, it is often an important component of railway embankments, roadside ditches and damp waste land. Thus, harvesting would not affect current land use.

9.4.2 Dry matter yields of 7.0 t $ha^{-1}$ (140 x $10^9$ J $ha^{-1}$) of shoots of great hairy willow-herb could be obtained together with 5.9 t $ha^{-1}$ (ca 118 x $10^9$ J $ha^{-1}$) of the shoots of its associated species, if harvesting were carried out at peak standing crop. A total yield of 15.3 t $ha^{-1}$ (306 x $10^9$ J $ha^{-1}$) was recorded for a less intensively studied site.

9.4.3 Shoots of great hairy willow-herb harvested at peak standing crop would probably be suitable for anaerobic digestion as between 76 and 88% of their fresh weight is water. However, the nutrient content of shoots harvested at this time is not known.

9.4.4 The effects of harvesting shoots of great hairy willow-herb at peak standing crop on re-growth in subsequent years cannot be evaluated from the present data base. However, re-growth would probably be better if shoots were harvested when senescent (between 17 October and 14 November) and processed by thermal conversion

TABLE 9.2 Inorganic nutrient concentrations and contents (concentration x dry weight) of above- and below-ground tissues of great hairy willow-herb collected from the Chisworth site

| | N | P | K | Ca | Mg | Ash |
|---|---|---|---|---|---|---|
| ABOVE-GROUND | | | | | | |
| Concentration (% dry weight) | | | | | | |
| 17 October 1979 | [illegible] | [illegible] | [illegible] | 1.40 | 0.28 | 7.1 |
| 14 November 1979 | 0.88 | 0.073 | 0.41 | 1.27 | 0.21 | 4.4 |
| Content (kg ha$^{-1}$) | | | | | | |
| 17 October 1979 | 78.6 | 5.94 | 135.2 | 120.5 | 24.1 | 611 |
| 14 November 1979 | 45.0 | 3.73 | 21.0 | 64.9 | 10.7 | 225 |
| BELOW-GROUND | | | | | | |
| Concentration (% dry weight) | | | | | | |
| 25 May 1979 | 2.20 | 0.42 | 2.57 | 1.73 | 0.37 | 15.7 |
| 14 December 1979 | 1.67 | 0.27 | 1.36 | 0.93 | 0.22 | 6.1 |
| Content (kg ha$^{-1}$) | | | | | | |
| 25 May 1979 | 112.0 | 21.4 | 130.8 | 88.1 | 18.8 | 290 |
| 14 December 1979 | 134.9 | 21.8 | 109.9 | 75.1 | 17.8 | 210 |

TABLE 9.3 Concentrations (% dry weight) of the organic plant fractions in the above- and below-ground tissues of great hairy willow-herb collected from the Chisworth site

| FRACTION | ABOVE-GROUND TISSUES | | BELOW-GROUND TISSUES | |
|---|---|---|---|---|
| | 17 October | 14 November | 25 May | 14 December |
| Soluble carbohydrate | 4.3 | 3.6 | 4.5 | 14.0 |
| Starch | 0.04 | 0.15 | 0.77 | 7.23 |
| Crude fat | 2.30 | 2.13 | 1.60 | 1.20 |
| Lignin | 18.58 | 16.68 | 28.59 | 22.21 |
| Holocellulose | 62.0 | 67.67 | 35.7 | 41.7 |
| Energy content (KJ $g^{-1}$) | 20.0 | 20.3 | 18.3 | 19.7 |

methods to fuel. Yields of senescent shoots would be 7 t $ha^{-1}$ (ca 142 x $10^9$ J $ha^{-1}$) and only 4.4% of the shoot dry weight would be ash.

9.4.5 Amounts of N, P and K removed in senescent biomass harvested in November (45, 3.7 and 31 kg $ha^{-1}$) would be low and replacement applications would be much lower than conventional levels of fertilizer applied to agricultural crops.

9.4.6 If it were possible to harvest the rhizomes of great hairy willow-herb, an additional yield of 6.6 t $ha^{-1}$ (ca 130 x $10^9$ J $ha^{-1}$) would be obtained initially.

9.4.7 The mechanical harvesting of great hairy willow-herb would be quite feasible and could employ methods similar to those for rosebay willow-herb.

## 9.5 Conclusion

Great hairy willow-herb and its associated vegetation are very productive and high yields of dry shoots could probably be obtained each autumn. This species has, therefore, considerable potential as an opportunity energy crop and methods of increasing its distribution should be considered.

# 10. *URTICA DIOICA* - STINGING NETTLE

## 10.1 General description

Stinging nettle is a familiar perennial species of hedges, woods and disturbed ground. It is particularly abundant on sites rich in N and P where it may form almost pure stands up to 1.5 m high (Plate 3a). It reproduces successfully both vegetatively and sexually, and is distributed throughout Great Britain (Figure 10.1), where it reaaches an altitude of 838 m (Clapham *et al.* 1962) and covers approximately 331 $km^2$ of land (Bunce pers comm).

## 10.2 Productivity

Al-Mufti *et al.* (1977) recorded an above-ground standing crop of ca 6.5 t $ha^{-1}$ for a site dominated by stinging nettle, with the dominant species contributing 4.5 t $ha^{-1}$. Callaghan *et al.* (1978) recorded a higher total above-ground standing crop of 7.5 t $ha^{-1}$ for the intensive site at Chisworth in 1978, and monthly sampling during 1979 resulted in a maximum total above-ground yield of 9.73 t $ha^{-1}$, with stinging nettle contributing 8.79 t $ha^{-1}$ (Figure 10.2).

Below-ground standing crop amounted to 7.8 t $ha^{-1}$ at the Chisworth site during the summer of 1978, and 5.07 ± 1.54 and 6.16 ± 0.43 when measured on 25 May 1979 and 14 December 1979 respectively.

The water content of the shoots of stinging nettle decreased over the growing season from 85% in young shoots to 77% in senescent shoots. Fresh weight/dry weight ratios were 6.61 ± 0.16, 5.21 ± 0.17 and 4.39 ± 0.10 on 25 May, 26 June and 22 November respectively. The water contents at the end of the season appear high and, as in the case of all water contents presented so far, are likely to be unreliable as they are strongly affected by humidity, etc, at the time of harvesting.

## 10.3 Nutrient content of stinging nettle

### 10.3.1 Inorganic nutrients

Concentrations of the inorganic nutrients at peak standing crop are high (Table 10.1) when compared with other species, eg great hairy willow-herb from a neighbouring site although concentrations of ash are in the centre of the range shown by other species. The concentration of P in stinging nettle is particularly high and compares with concentrations found in policeman's helmet (Figure 5.3) and butterbur (Figure 2.4). Concentrations of K in stinging nettle also tend to be high. However, the pools of inorganic nutrients which would be removed from site by harvesting the maximum above-ground standing crop of stinging nettle (Table 10.1) are in the same order as the traditional applications of N, P and K to agricultural crops (Church 1974).

End of season concentrations of all the inorganic nutrients are lower than mid-season values, and only small amounts of these elements would be removed from site if above-ground biomass were harvested when senescent in November. This late harvest would yield about 4.0 t $ha^{-1}$ of dry matter (Figure 10.2), containing only 272 kg of ash (Table 10.1).

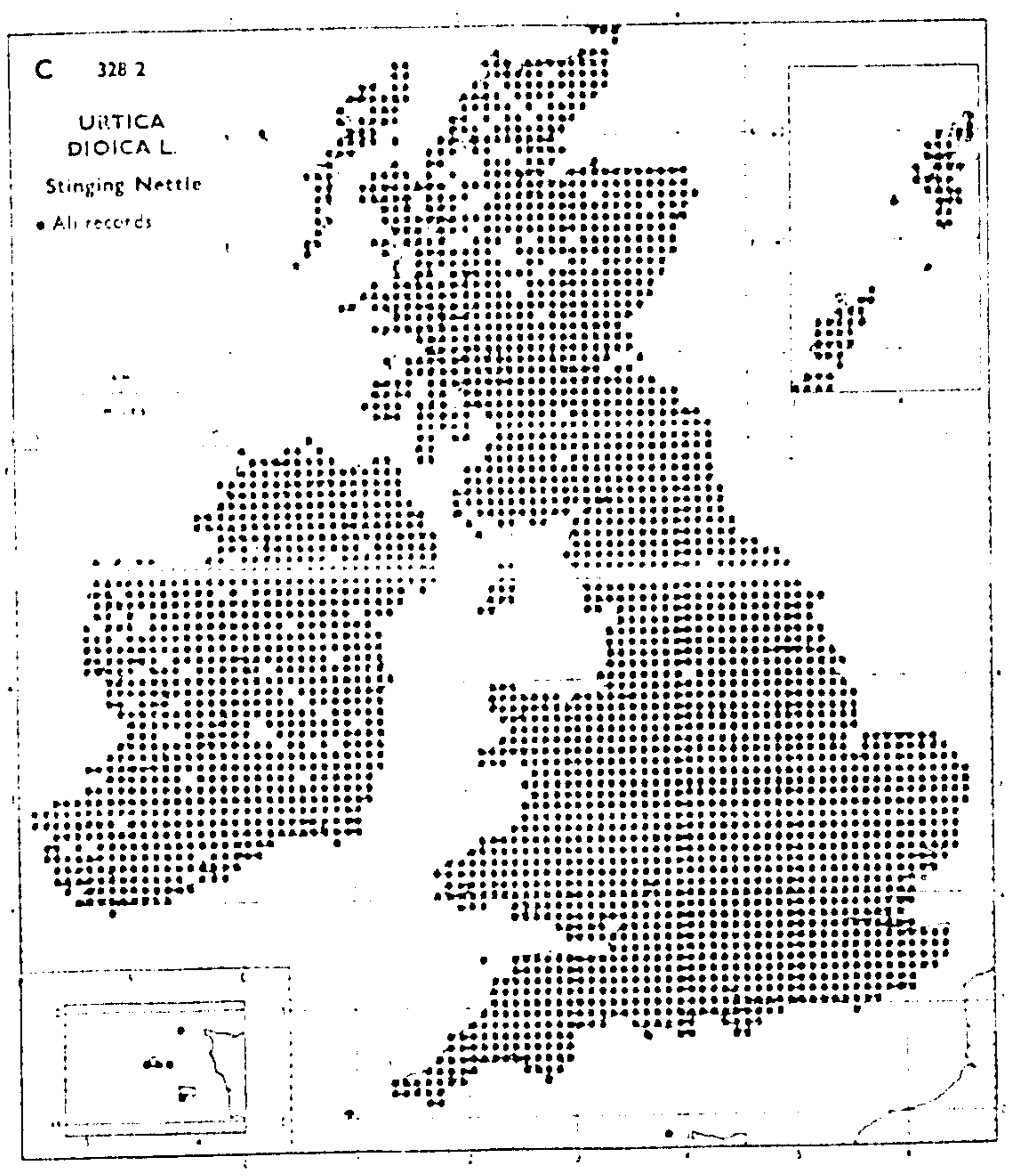


Figure 10.1 The distribution of stinging nettle in Great Britain and Ireland; from Perring & Walters (1962).

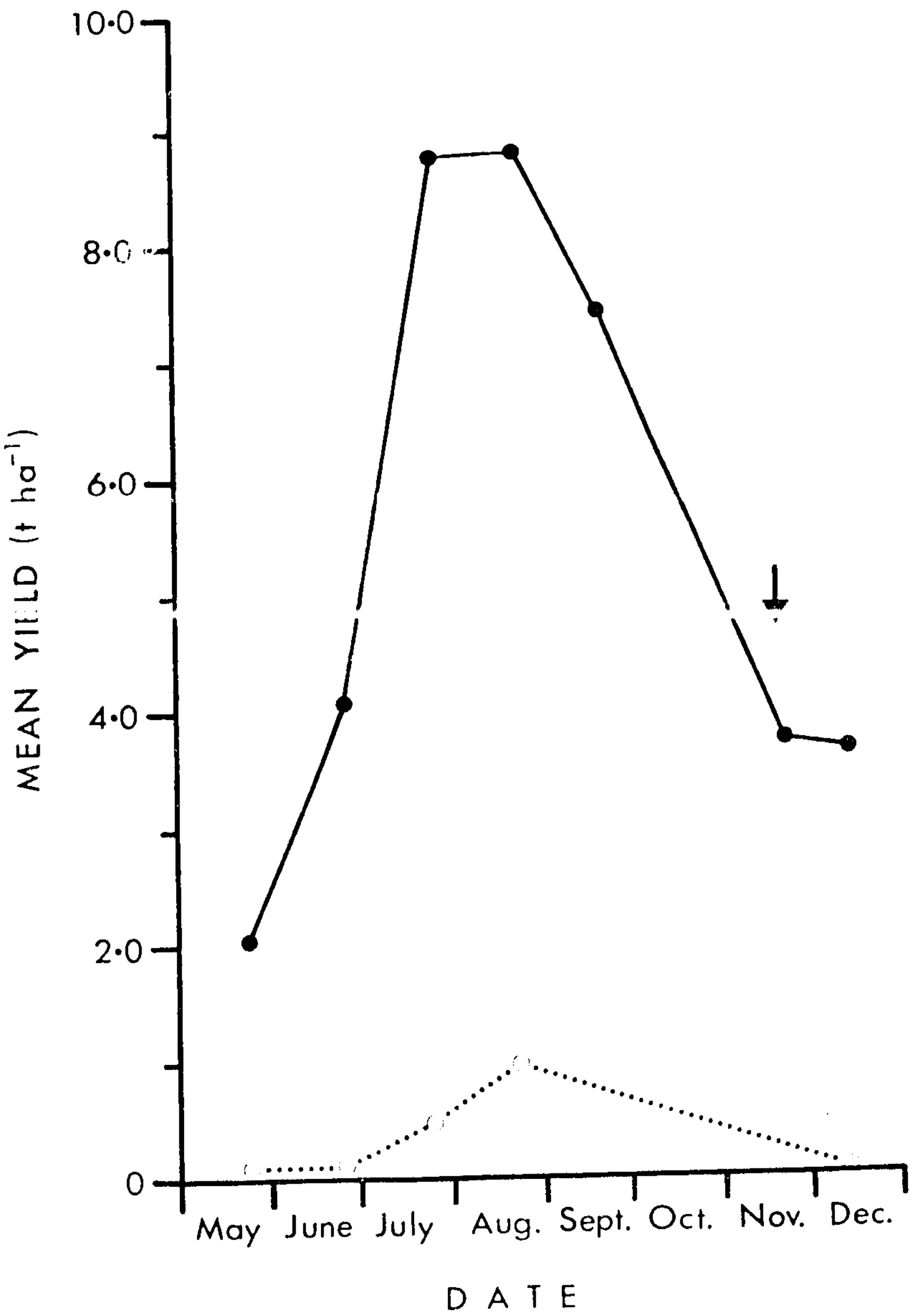


Figure 10.2 The seasonal growth of shoots of stinging nettle (circles and solid line) and its associated species (squares and dotted line) at the Chisworth site. The 2 yield components are not plotted cumulatively. The arrow denotes the date by which all of the shoots of stinging nettle had turned brown.

TABLE 10.1 Inorganic nutrient concentrations and contents (concentration x dry weight) of above-ground tissues of stinging nettle collected from the Chisworth site

| | N | P | K | Ca | Mg | Ash |
|---|---|---|---|---|---|---|
| Concentration (% dry weight) | | | | | | |
| 23 August 1979 | 1.63 | 0.30 | 2.1 | 1.93 | 0.17 | 9.6 |
| 22 November 1979 | 1.09 | 0.20 | 2.0 | 1.02 | 0.14 | 7.3 |
| Content (kg ha$^{-1}$) | | | | | | |
| 23 August 1979 | 143.8 | 26.4 | 184.6 | 169.7 | 14.9 | 844 |
| 22 November 1979 | 40.6 | 7.4 | 74.4 | 37.9 | 5.3 | 272 |

### 10.3.2 Organic plant fractions

During the period of maximum standing crop, the shoots of stinging nettle contain moderate amounts of soluble carbohydrates and, surprisingly, high concentrations of starch, while concentrations of lignin are low (Table 10.2). These shoots should, therefore, break down readily in an anaerobic digestor but if the shoots are harvested at the end of season, when they become more fibrous and lose their energy-storing compounds (Table 10.2), a thermal conversion process would be required to produce fuel.

The mean energy content of the shoots of stinging nettle over the growing season is 19.9 KJ $g^{-1}$ dry weight (Table 10.2), and this would result in energy yields of about 173 x $10^9$ J $ha^{-1}$ and 73 x $10^9$ J $ha^{-1}$, if the shoots were harvested at peak standing crop and when senescent, respectively.

## 10.4 A summary of the potential of stinging nettle as an energy crop

10.4.1 Stinging nettle could be managed as an opportunity energy crop as it grows throughout Great Britain covering an estimated 331 $km^2$, often occurring in waste places and unmanaged field corners.

10.4.2 Yields of shoots of stinging nettle could reach 8.8 t $ha^{-1}$ (173 x $10^9$ J $ha^{-1}$), if harvested at peak standing crop, and species associated with stinging nettle would increase this yield to 9.7 t $ha^{-1}$ (ca 191 x $10^9$ J $ha^{-1}$).

10.4.3 Shoots of stinging nettle would probably be easily digested as between 77 and 88% of their fresh weight is water, concentrations of N, P, K, soluble carbohydrates and starch are high (1.6, 0.3, 2.1, 8.5 and 4.3% of the dry weight respectively), and concentrations of holocellulose and lignin (63 and 5.9% of the dry weight) are not excessive. The shoots contain only 9.6% dry weight of ash.

10.4.4 The harvesting of shoots of stinging nettle at peak standing crop is likely to significantly reduce yields in subsequent years, and stinging nettle is often mown on agricultural land as a control measure. Also, the great decrease in the concentrations of energy-storing compounds (soluble carbohydrates and starch) between summer and autumn independently suggests that cutting at peak standing crop would prevent significant quantities of energy-storing compounds from being translocated to the rhizomes, thereby reducing subsequent re-growth.

10.4.5 If it were desired to maintain areas of stinging nettle, replacement applications of N, P and K (144, 26 and 185 kg $ha^{-1}$ respectively) would be within the ranges of the amounts of these elements currently applied in agriculture.

10.4.6 Shoots of stinging nettle could be harvested when senescent (22 November in 1979), if the species were to be maintained as an energy crop. Yields would be low (3.7 t $ha^{-1}$ = 74 x $10^9$ J $ha^{-1}$), but replacement applications of N, P and K would be reduced by factors of 3.5, 3.6 and 2.5, respectively.

TABLE 10.2 Concentrations (% dry weight) of the organic plant fractions of the shoots of stinging nettle collected from the Chisworth site

| Date | Soluble carbohydrate | Starch | Crude fat | Lignin | Holocellulose | Energy content ($KJ\ g^{-1}$) |
|---|---|---|---|---|---|---|
| 23 August 1979 | 8.47 | 4.27 | 0.40 | 5.91 | 62.7 | 19.7 |
| 22 November 1979 | 1.87 | 0.40 | 1.00 | 9.9 | 73.0 | 20.0 |

10.4.7 If it were possible to harvest the rhizomes of stinging nettle, for example in a programme of eradication, additional yields of 5.6 t $ha^{-1}$ (ca 110 x $10^9$ J $ha^{-1}$) could be obtained.

10.4.8 The mechanical cutting and harvesting of stinging nettle is quite feasible and present hay crops often contain this species.

## 10.5 Conclusion

Stinging nettle shows potential as a short-term opportunity crop in that it would provide high yields if harvested when green. The species is a weed of agricultural land and is often sprayed with herbicides or mown and left to decompose *in situ*. However, it shoots were harvested as an energy crop at peak standing crop, the desired control would be effected while the biomass would have a positive value for conversion to fuel.

## 11 THE PRODUCTIVITY OF MISCELLANEOUS SPECIES SAMPLED FROM THE FIELD

The species discussed below were sampled from a variety of locations sometimes without replication, in order to make some tentative estimate of the productivity of various types of vegetation which were not selected for the more intensive studies presented earlier.

*Phragmites australis* (reed) showed the greatest above-ground standing crop (26.7 t $ha^{-1}$), although yield varied considerably between sites (Table 11.1). In general, the data on reed suggest that this species could be an important energy crop, as it is presently in Sweden (Björk & Graneli 1978a and b). *Iris pseudacorus* (yellow flag: Plate 3b) and *Cirsium arvense* (creeping thistle) are also productive, yielding between 10 and 15 t $ha^{-1}$, and even mixed species of the roadside yield between 5 and 8 t $ha^{-1}$, (Table 11.1).

*Cardamine amara*, a species forming dense, but low, stands in wet habitats yielded only 3.7 t $ha^{-1}$ by June, and the yield of the tall, introduced South American perennial herb *Gunnera manicata* (Plate 3c) was disappointing. However, *G. manicata* was growing sparsely under a dense canopy of trees, and it must be established as a monoculture in order to obtain a more accurate assessment of its potential as an energy crop.

TABLE 11.1 The above-ground standing crops of various types of vegetation in Great Britain. Standard errors are given where available.

| Species | Location | Site No. | Sampling date | Above-ground standing crop (t $ha^{-1}$) |
|---|---|---|---|---|
| *Gunnera manicata* | Birmingham | 23 | 30 August 1979 | 2.57 |
| *Cardamine amara* (large bitter-cress) | Chisworth, Derbyshire | 6 | 3 May 1979 | 1.04 ± 0.14 |
| | | | 25 May 1979 | 2.98 ± 0.22 |
| | | | 26 June 1979 | 3.69 ± 0.44 |
| *Phalaris arundinacea* (reed-grass) | Tuiteam Tarbhach, Ross and Cromarty | 11 | 13 September 1979 | 4.42 |
| *Heracleum mantegazzianum* (giant hogweed) | Cambridge | 33 | 29 August 1979 | 5.29 |
| Mixed roadside vegetation | Sparkbridge, Cumbria | 20 | 20 July 1979 | 6.28 |
| *Armoracia rusticana* (horse-radish) | Risedale, Cumbria | 18 | 24 September 1979 | 7.53 |
| *Cirsium arvense* (creeping thistle) | Ledbury, Herefordshire | 22 | 10 September 1979 | 10.8 ± 1.94 |
| *Iris pseudacorus* (yellow flag) | Tuiteam Tarbhach, Ross and Cromarty. | 11 | 13 September 1979 | 6.3 |
| | Dornie, Ross and Cromarty | 7 | 14 September 1979 | 13.91 ± 1.13 |
| | Plucks Gutter, Kent | 29 | 4 September 1979 | 14.8 ± 4.07 |
| *Phragmites australis* (reed) | Gosberton, Lincolnshire | 27 | 15 August 1979 | 7.7 ± 0.69 |
| | Plucks Gutter, Kent | 29 | 4 September 1979 | 16.6 ± 1.51 |
| | Dornie, Ross and Cromarty | 7 | 14 September 1979 | 26.7 ± 2.94 |

## 12 THE ESTABLISHMENT OF POTENTIAL ENERGY CROPS AT EXPERIMENTAL GARDEN SITES

It was necessary to plant some species of plants at garden sites for one of two reasons:

(a) the plants occurred as small stands, or were scattered, and standing crop could not be assessed in the field, being meaningful only on large pure stands;

(b) the species showed considerable potential as a dedicated energy crop, and it was important to tentatively assess methods of propagation and establishment.

### 12.1 *Polygonum cuspidatum* - Japanese knotweed

This species showed considerable potential as a dedicated energy crop (Chapter 5). It was important, therefore, to assess the ease with which it could be propagated and established.

Small fragments of rhizome, which included the base of a stem formed in the previous year and its associated bud, were collected from the Queen's Park Cemetery site in Manchester (site number 4, Appendix II) on 19 March 1979 and planted in the experimental garden at Merlewood Research Station (site number 34, Appendix II) on the following day at a density of 4 $m^{-2}$. Of 77 fragments of rhizome planted on 20 March 1979, 76 were still surviving, and generally vigorous, on 8 July 1980. Thus, the survival rate was 98.7%.

After planting, the development of a sub-sample of 28 plants was followed by measuring the height of the largest stem of each plant throughout the growing season.

Stems appeared above the soil surface during April and, by 25 May 1979, all of the rhizome fragments had produced a stem (Figure 12.1, A). Throughout the first growing season, stem height increased in a sigmoid trend reaching a maximum height of 96 cm (Figure 12.1, B) and the mean number of stems per plant almost doubled (Figure 12.1, A), giving a density of 7.56 stems $m^{-2}$ compared with 80 stems $m^{-2}$ in the field (Figure 5.2, A). During the second year of development, stem height increased earlier and at a faster rate than in the first year, so that, by 24 June 1980, mean stem height was already 148 cm compared with an interpolated value of 70 cm for the same time in the first year (Figure 12.1,B). Also, a mean of more than 2 buds per plant developed at the beginning of the second year (Figure 12.1, A).

Longer term experiments are required to evaluate the whole establishment phase, but these initial investigations over a period of 15 months strongly suggest that Japanese knotweed can be established easily from material collected in the field and will approach maximum development in its second year of establishment.

### 12.2 *Heracleum mantegazzianum* - giant hogweed

Giant hogweed is a species which appears to have a fast rate of growth. Unfortunately, however, the individual plants are widely spaced (Plate 3d) and measurements of yield *in situ* give modest values (5.3 t $ha^{-1}$, Table 11.1). The measurement of the yield *in situ* is further complicated by the

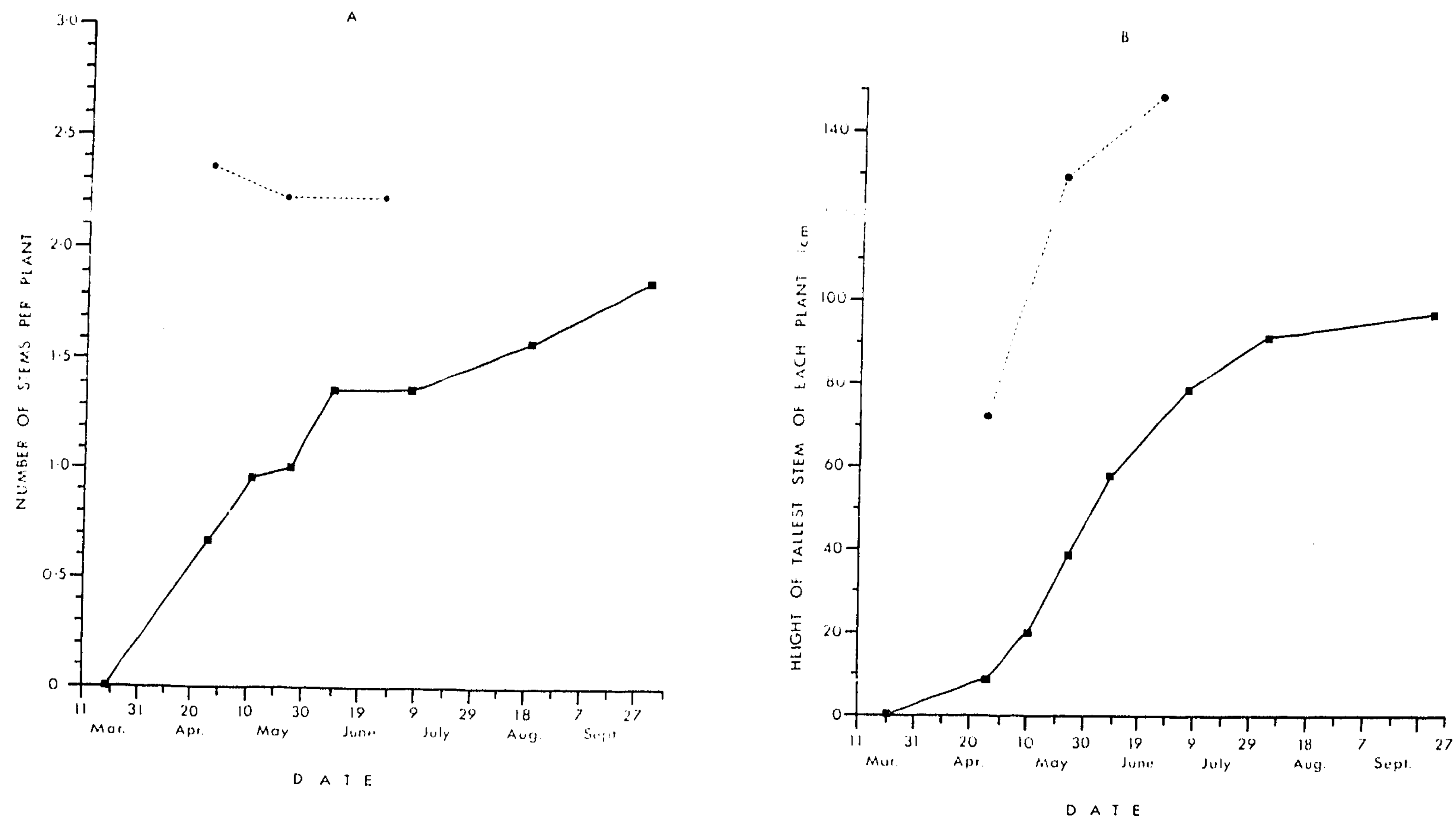


Figure 12.1 The establishment of Japanese knotweed planted at the Merlewood garden site during the first year ie 1979 (solid squares and line) and the following year ( circles and broken line), in terms of density (A) and height growth (B).

biennial nature of the species, in that a rosette of leaves is produced in the first year and the development of the vast flowering stem is restricted to the second or subsequent years. In order to measure yield, small areas were established at the Merlewood site and at the Chisworth site (site 35, Appendix II) from young tap roots.

At the Chisworth site, 150 ramets were planted on 11 May 1979, and the mean fresh weight per ramet was 194.3 ± 12.8 g. On 29 May 1979, the mean height of the plants was 22.5 ± 1.4 cm and increased to 37.7 ± 2.2 cm on 19 June 1979. However, by this latter date, only 85 plants had survived giving a survival rate of 56.7%, which is very low when compared with that of Japanese knotweed. Following these observations, sheep entered the exclosure and preferentially grazed the giant hogweed; the trial was abandoned.

At the Merlewood site, only 30 plants were planted on 11 May 1979, but the survival rate was lower than that at the Chisworth site with only 23% of the plants surviving until the following year (Figure 12.2, A). However, plant survival was stable in the year after planting (Figure 12.2, A), and greater heights (Figure 12.2, B) and numbers of leaves per plants (Figure 12.2, C) were achieved in this year.

It appears, therefore, that giant hogweed could be successfully managed if the high initial mortality rate is anticipated. Although yield quality has not been determined, it appears that the species is digestible by livestock (it is used as fodder in the Soviet Union) and should break down easily in an anaerobic digestor.

### 12.3 *Gunnera manicata*

This species superficially resembles butterbur (Chapter 3) in that it has large rhizomes from the crowns of which arise a number of petioles, each bearing one very large leaf. The leaves form canopies which may reach a height of 4m. In autumn, the petioles collapse and, as in butterbur, the leaves decompose rapidly over winter. *Gunnera manicata* was introduced to this country as a garden plant from South America, but it has become naturalised in damp woodland in a few localities. It possesses blue-green nitrogen-fixing algae in its stems and probably has high nutrient contents in its leaves and petioles. Like butterbur, *Gunnera manicata* would probably be an ideal substrate for an anaerobic digestor.

In order to investigate the possiblities of forming monocultures of *Gunnera manicata*, 16 rhizome fragments with fresh weights of up to 80 kg each were planted at the Chisworth site on 25 April 1979 at a spacing of 1 $m^{-2}$. The survival of plants was monitored and their progress followed by counting the number of leaves per plant and measuring plant height.

Leaves were produced by 69% of the plants one month after they had been planted, but the survival rate was only 62.5% on 25 July (Table 12.1). By the end of the short period of observations, a mean of 2.8 leaves per plant had been produced and the maximum height per plant was 58 cm (Table 12.1).

Although these data are provisional, it is certain that *Gunnera manicata* can easily be established and grows quickly. Longer term experiments are now required to measure the yield of the species as an established monoculture. More data on the sustainable yield of giant hogweed are also essential to assess the value of biennial species as energy crops.

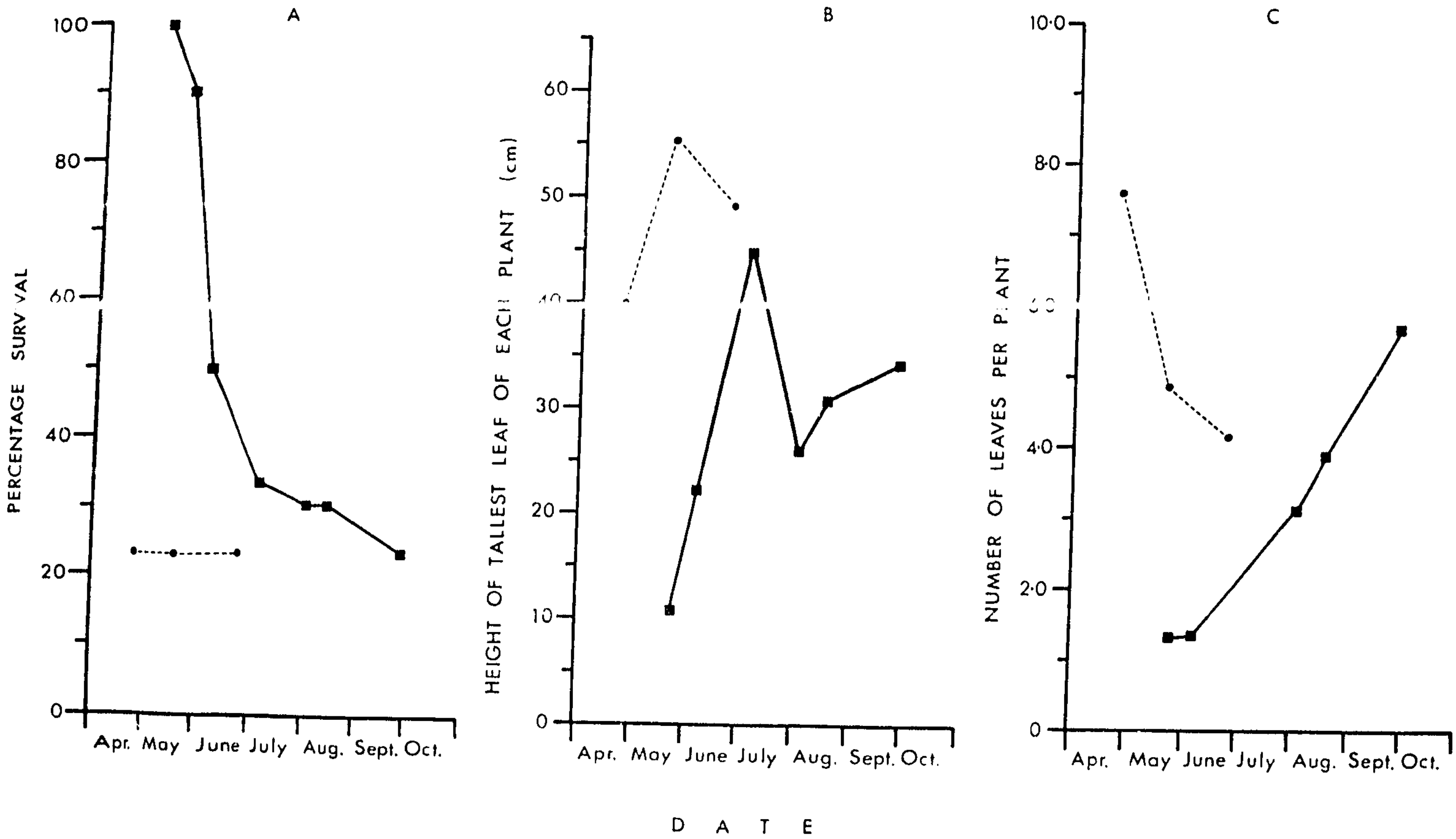


Figure 12.2 The establishment of giant hogweed at the Merlewood garden site during the first year, ie 1979 (solid squares and line) and the following year (circles and broken line) in terms of plant survival (A), height (B) and leaf number (C).

TABLE 12.1 The survival and rate of establishment of *Gunnera manicata* transplanted to the Chisworth site on 11 May 1979. Standard errors are given.

| Date | Number of plants growing | Percentage survival | Number of leaves per plant | Height of largest leaf per plant (cm) |
|---|---|---|---|---|
| 25 April 1979 | 16 | 100 | 0 | 0 |
| 25 May 1979 | 11 | 69 | 1.0 ± 0.0 | 14.5 ± 2.2 |
| 19 June 1979 | 10 | 62.5 | 2.3 ± 0.4 | 40.3 ± 5.9 |
| 25 July 1979 | 10 | 62.5 | 2.8 ± 0.4 | 57.7 ± 8.1 |

# 13 DISCUSSION

## 13.1 Yield

Yields of above-ground plant parts were relatively high at the intensively studied sites (Table 13.1), varying from 6.5 t $ha^{-1}$ to 12.9 t $ha^{-1}$, while at the scattered sites, which were sampled on only one occasion, yields reached 37.5 t $ha^{-1}$, a yield even higher than the 25.3 t $ha^{-1}$ recorded for Japanese knotweed in 1978 (Callaghan *et al.* 1978). The accuracy of the yield data for the intensive sites is good as the variation in yield was only high at the Kents Bank site, all other seasonal trends of yield being highly significant. Also, the samples were taken from extensive, and more or less homogenous stands. Consequently, these data indicate the yields which could be expected from the various species in similar habitats at other locations. The data from the remaining sites are, however, somewhat less reliable as replication was often impossible because of: limited extent of the vegetation; maximum yield may not have been sampled because the seasonal course of dry matter production could not be followed; and the very high yields recorded for small stands may not be typical of yields from extensive areas of these species.

The high yields of small patches of some species are of some significance. High yields of some roadside vegetation have been recorded, eg 22.6 and 25.3 t $ha^{-1}$ for Japanese knotweed (*Polygonum cuspidatum*) at 2 localities, and 37.5 t $ha^{-1}$ for *P. sachalinense*, whereas the yields of Japanese knotweed from extensive stands are much lower, between 9.8 and 11.4 t $ha^{-1}$. Although site differences, eg soil type, microclimate, etc, may contribute to these differences, the high yields probably result from a hedge effect whereby thin strips of vegetation on roadsides, etc, develop an extensive leaf canopy which stretches vertically from the ground to the top of the canopy to produce a wall of photosynthetic tissue. This canopy development would lead to extremely high leaf area indices (LAI) and efficient interception of solar radiation to give high yields. In contrast, extensive stands of the same species show little lateral canopy development, and efficient interception of solar radiation is restricted to the upper layers of the canopy.

Two inferences can be made from the "hedge effect":

a. In the development of monocultures of tall herbs, a spacing system giving rise to "hedges" may be more productive than one with equidistant spacing of plants.

b. Thin strips of land such as railway embankments, roadside verges and hedgerows, although only representing small areas, may be disproportionately productive when compared with large uniform areas of land such as adjoining fields.

It is suggested, therefore, that thin strips of land should receive special attention as sites with high potential for the growth of energy crops. These energy crops could be either opportunity energy crops, in which case the vegetation would remain unchanged, with the associated benefits for amenity and conservation, or dedicated energy crops which would involve the introduction of species more productive than those currently occurring at the sites. Land in this category is often found along lines of transport where transport costs should be cheapest. Also, considerable costs are currently involved in controlling the productive vegetation of these areas, but the resulting biomass is wasted.

E 13.1 A summary of the potential of species from the intensive study sites as energy crops. > is greater than, < is less than and = is within the range of current agricultural applications of fertilizers. Yields in brackets are values from the literature in contrast to those determined in the present study. ? denotes lack of data.

| ...n | Yield of shoots (t ha$^{-1}$) when standing crop is greatest | Yield of shoots (t ha$^{-1}$) during senescence | Extent (km$^2$) | Predicted re-growth after harvesting: when standing crop is greatest | Predicted re-growth after harvesting: during senescence | Replacement fertilizer inputs, compared with current agricultural dressings after harvesting: when standing crop is greatest N | P | K | during senescence N | P | K | Predicted digestibility (after harvesting when standing crop is greatest) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ...en | (2.4) 8 - 9 (31.6) | 4.6 - 8.0 | 3,224 [illegible] | poor | very good | > | > | > | < | < | < | good |
| ...rbur | (6.0) 8.2 | - | 33.5 | moderate | - | = | = | > | —— | | | very good |
| ...rass | 6.1 - 16.8 | 4.0 - 11.4 | 120 | good | very good | < | < | < | < | < | < | moderate |
| ...ese knotweed ...achalinense | (7.5) 9.8-11.4 (37.5) | 5.0 - ? | 3.1 | good | very good | = | = | > | < | < | < | moderate |
| ...oman's helmet | 11.4 | - | 0.6 | annual establishment from seed | | > | = | > | —— | | | very good |
| ...ow-sweet | (4.0) 6.5 (7.1) | 4.7 | 110 | good | very good | = | = | = | < | < | < | moderate |
| ...bay ...illow-herb | (4.4) 10.6 | ? | 138 | moderate | very good | = | = | = | < | < | < | good |
| ...t hairy ...illow-herb | (7.8) 12.9 | 7.0 | 6.0 | moderate | very good | ? | ? | ? | < | < | < | ? |
| ...ging nettle | (6.5) 9.7 | 3.7 | 331 | poor | very good | = | = | = | < | < | < | good |

The lower yields of extensive stands of vegetation (6.5 to 12.9 t $ha^{-1}$) should not be under-rated. Reliable data for the yield of cord-grass at Southport suggest that some salt marshes could produce 16.8 t $ha^{-1}$, and fertilizer applications may not be necessary in this particular environment. Similarly, bracken yields 9 t $ha^{-1}$ on a soil with a pH of 3.9 and only 0.17 mg of phosphorus per 100 g of dry soil. These yields could be immediately obtained from many different habitats throughout Great Britain without changing the current land use. Although the species considered in this report have been sampled from unfavourable natural habitats, eg waterlogged land, acid heath land, salt marshes, etc, the yields compare favourably with those predicted for agricultural crops and trees on neighbouring land. For example, yield at the Chisworth site varied between 6.5 and 12.9 t $ha^{-1}$. This site is classified as land class 17 in the ITE land classification (Bunce 1980), and yields of 11.2 t $ha^{-1}$ and 10.1 t $ha^{-1}$ have been predicted for potential energy crops from agriculture (Spedding *et al.* 1980) and forestry (Mitchell & Matthews 1978) respectively. However, predictions for yields of agricultural and tree crops include the effects due to careful selection of genotype, cultivation and the application of fertilizers. It must be concluded, therefore, that opportunity energy crops of natural vegetation are currently very competitive with dedicated energy crops from agriculture and forestry.

Dedicated energy crops derived from natural vegetation could be even more competitive with traditional crops if selected, managed and fertilized in better habitats. The highest yields predicted in Great Britain for (i) agricultural energy crops (fodder beet) is 18.9 t $ha^{-1}$ (Spedding *et al.* 1979), (ii) coppice energy crops is 20 t $ha^{-1}$ (Pearce *et al.* 1979), and (iii) single stem tree energy crops is 15 t $ha^{-1}$ (Mitchell & Matthews 1978). Thus, the suggested dedicated energy crops of Japanese knotweed, *P. sachalinense* and policeman's helmet which currently yield 11.4, 37.5 (as a "hedge") and 11.4 t $ha^{-1}$ respectively in poor habitats should be very productive when managed as monocultures in cultivated conditions.

## 13.2 Re-growth

This research has concentrated on a one-year cycle of vegetation development, but it is essential to estimate the long-term stability of yield in order to assess the potential of a perennial species as an energy crop. In the traditional crops of agriculture and forestry, re-growth is unimportant as new crops are planted after the former crop has been harvested. Opportunity energy crops of natural vegetation would be managed like coppice, however, in that the shoots would be removed each year and the under-ground organs would remain *in situ* to produce new shoots in following years. Thus, the yield in the second year will be closely related to the history of management in the first year.

Two methods have been used to predict the success of re-growth. First, the re-growth of some species has been measured within the growing season by cutting on 2 occasions. Second, the seasonal cycle of inorganic nutrients and organic plant fractions within the plant has been used to make inferences on the relative impoverishment of rhizomes caused by removing shoots.

In all the perennial species studied, re-growth was disappointing, in that 2 harvests rarely gave a higher yield than a single harvest. As 2 harvests within one season will double the input of energy in harvesting, while little, if any, extra biomass will be obtained, this harvesting strategy should only be considered if it is desired to rapidly eradicate a species. However, re-growth of 4.9 t $ha^{-1}$ was recorded for Japanese knotweed after an initial harvest in June, which implies that this species is resilient to harvesting and that re-growth in the year following harvesting should be good.

The amount of re-growth in years following harvesting will depend strongly on the amount of nutrients and energy-storing compounds removed in harvested biomass, although the former may be artificially replaced.

Some species, particularly bracken, appear to move energy sources, such as soluble carbohydrates, from the shoots into rhizomes before the shoots die, and up to about 90% of the inorganic nutrients are also re-cycled naturally, mainly through translocation and leaching during autumn. Consequently, if the shoots of these species were harvested during summer, when they were still alive, considerable quantities of inorganic nutrients and energy substrates for re-growth would be removed from the site and subsequent growth would be retarded.

Bracken, Japanese knotweed, cord-grass, the willow-herbs and stinging nettle show, to a greater or lesser degree, the translocation strategy described above (Table 13.1). Butterbur, however, shows a different strategy in that shoots suddenly collapse at the end of season, and the inorganic elements appear to be returned to the soil. Decomposition is very fast and is probably accelerated by the high concentration of soluble carbohydrates in the dead shoot material. The re-growth of butterbur should not, therefore, be greatly affected by harvesting maximum shoot standing crop. The roots of this species and the very small roots of policeman's helmet should be efficient in taking nutrients up from the soil, and the yield of these species should respond readily to fertilizer application.

## 13.3 Harvesting strategies

The patterns of re-growth discussed above allow 2 basic harvesting strategies to be developed. In the case of butterbur and policeman's helmet, living shoots could be harvested when yield is greatest. The remaining species, however, should be harvested at this time only if their ultimate eradication is desired (eg stinging nettle, bracken and cord-grass), and they are regarded as short-term opportunity energy crops. Bracken and stinging nettle would be probably quickly controlled by cutting living shoots during the summer and this method is, in fact, used as a control measure. On the other hand, Japanese knotweed may withstand this harvesting regime for many years. This strategy of harvesting to give maximum yields would initially result in the yields discussed above.

The second harvesting strategy is one of harvesting senescent tissues. This strategy should maximise re-growth and allow either dedicated or opportunity energy crops to be maintained almost indefinitely. However, yields would be lower by up to 50% of the maximum yield (Table 13.1).

Some of the yields of senescent shoots, eg those of cord-grass and great hairy willow-herb, are still competitive with yields of traditional crops, and a yield of 4.6 t $ha^{-1}$ of dry bracken fronds is still probably higher than the yields of adjacent upland pastures. Also, because this harvesting strategy allows most of the inorganic nutrient elements to be re-cycled naturally, fertilizer applications required to replace nutrients removed in harvested biomass would be very low, and generally far lower than those currently applied to agricultural crops (Table 13.1). Contents of N, P and K in senescent bracken fronds, for example, are only 20%, 12% and 30% respectively of the 169, 16 and 240 kg $ha^{-1}$ of these elements in living shoots, and 18.4, 1.7 and 3 kg $ha^{-1}$ of N, P and K may be added annually to upland vegetation in rainfall (Perkins, 1978).

Because replacement levels of inorganic nutrients are low (perhaps even zero in the case of cord-grass), it should be possible to increase the yields of the native and naturalised plant species discussed in this report by adding extra amounts of fertilizer. Great hairy willow-herb and its associated species, for example, yield 12.9 t $ha^{-1}$ at peak standing crop, and 7.0 t $ha^{-1}$ when senescent, on poor soil which has only 0.73 mg P per 100 g dry soil.

It is interesting that the amount of K which would be removed in harvested biomass is generally far greater than the amounts of N and P and, if living shoots were harvested, replacement applications of K would often be far higher than levels currently applied to agricultural crops. For example, if shoots of policeman's helmet were harvested at peak standing crop, 408 kg $ha^{-1}$ K would be removed from the site and yet the maximum traditional application of K in agriculture, which is generally only 2/3 of that removed, is only 183 kg $ha^{-1}$ to maincrop potatoes (Church 1975 cited in Appendix V). The need for replacement fertilizer application may vary considerably between soils, however.

## 13.4 The quality of biomass in relation to chemical conversion to usable fuels

The 2 basic harvesting strategies outlined above will determine the chemical conversion process required to produce a usable fuel from the plant matter.

It species are harvested in summer, water contents will be high (over 75% of the fresh weight) and anaerobic digestion would probably be the process used to generate a fuel, in this case methane. On the other hand, shoots harvested in autumn, during senescence, would be much drier, and a thermal process would be more suitable, generating either direct heat, soil charcoals, liquid hydrocarbons or biogas.

The digestibility of fresh plant material will be increased by high water contents, high protein contents (represented by concentrations of N and P), high concentrations of soluble carbohydrates and starch, and low concentrations of the cell wall materials - holocellulose and lignin. Holocellulose will also make a good substrate for digestion, but its decomposition will be slower than the energy storing compounds and protein. Tissues of policeman's helmet would be particularly easily digested as the water contents are up to 85% of the fresh weight, concentrations of N, P, and soluble carbohydrates are 1.8 to 1.9%, 0.24 to 0.30% and 10 to 35% of the dry weight, whereas concentrations of lignin and holocellulose are only 3 to 10% and 37 to 51% of the dry weight, respectively. In contrast, cord-grass may digest at a slower rate, as the water content is only 60% of the fresh weight and concentrations of N, P and soluble carbohydrates are only 1.2, 0.17 and 7.4% of the dry weight, respectively.

The chemical composition of biomass is less important in determining the efficiency of thermal chemical conversion processes, as these processes usually subject plant material to very high temperatures at which all plant matter is burned. However, the water content of the feedstock is of great importance as the artificial drying of biomass would probably be energy intensive and costly, and high water contents would also add to transport costs.

The energy content of plant material is of fundamental importance to any chemical conversion process. Callaghan *et al.* (1978) reviewed the literature on the energy contents of approximately 200 species represented by about 500 values, and found very little variation between species, the overall mean being $18.27 \pm 0.11$ KJ $g^{-1}$ dry weight. They suggested, however, that the energy content of plants might vary more throughout the growing season within one species than between different plant species, genera and families. This report has shown that there is little variation in the energy content of plant matter over the growing season, and a significant seasonal trend was found in only 2 species, cord-grass and Japanese knotweed. The lowest energy content recorded was 17.0 KJ $g^{-1}$ dry weight, whereas the highest was 23.0 KJ $g^{-1}$ dry weight. Rhizomes generally showed lower energy contents than shoots ($19.5 \pm 0.21$ KJ $g^{-1}$ and $20.2 \pm 0.16$ KJ $g^{-1}$ respectively). Because of the great variation in yield between species, between harvesting times and between habitats, the energy content of plant matter may be regarded as a constant in the fuels from biomass scenarios.

The ash content of plant matter is also important in the chemical conversion processes, as this represents the minimum residue which will remain to be removed after conversion.

In general, ash contents are low (2.2 to 13.9% of the dry weight) and should not cause problems in the conversion of most species. However, the ash concentrations in shoots of cord-grass (31% of the dry weight) are exceptionally high and must be taken into consideration in the conversion technology.

## 13.5 Suggestions for the management of natural energy crops

Two primary factors will determine the management of opportunity energy crops of natural vegetation: the requirement for the eradication of vegetation resulting from a desired changed in land use and the nature of the fuel required, ie the choice between a biogas generated from anaerobic digestion and solid, liquid and biogas fuels generated by thermal methods.

If eradication of the vegetation and a biogas are required, the vegetation would be harvested when standing crop is highest. This would apply to bracken, stinging nettle and rosebay willow-herb, for example. In some of these cases, it may be possible to extract rhizomes, which would accelerate the speed of eradication while initially giving high yields of, for example, 11 to 17 t $ha^{-1}$ in the case of bracken.

If the vegetation were to be maintained as a long-term energy crop, it would be harvested when senescent, and a thermal conversion process would be required to generate usable fuels. This generalisation applies to most of the perennial opportunity energy crops except butterbur and similar soft, fleshy, herbaceous species, which could only be harvested at peak standing crop. It is doubtful if thermal conversion processes could ever be applied to such species.

The harvesting of senescent material increases the period during which harvesting can be carried out (a period of several months), whereas the harvesting of living shoots at peak standing crop must be carried out within relatively short time limits during the growing season. This is particularly true of the species which collapse at the end of the season (eg butterbur and policeman's helmet). The prolonged harvesting period for senescent material would ensure a more stable supply of feedstock to chemical conversion units. Plants with strong persistent shoots, eg reed, would be particularly valuable in this respect.

Dedicated energy crops of indigenous and naturalised British plant species can easily be established, as the preliminary trials have shown. Because these species are particularly resilient, eg Japanese knotweed, it is probable that a single harvest could be taken at any time of the year without greatly affecting subsequent re-growth. It may also be possible to harvest rhizomes. Standing crops of rhizomes of Japanese knotweed are very high (12 to 30 t $ha^{-1}$), although their annual productivity is not known. The removal of large numbers of rhizomes from one extensive stand was followed by profuse re-growth. As the rhizomes of this species spread and extend over considerable distances each year, it may be possible to remove them from alternate strips of land, thus allowing the remaining unharvested rhizomes to provide an inoculum to recolonise the harvested strips. Each strip of vegetation could provide a yield of shoots each year, and a yield of rhizomes on a rotational basis.

The suggestion of harvesting rhizomes presupposes that this would be technologically feasible. In general, the species investigated in this report could be harvested using conventional agricultural and forestry equipment, and only the species of wet habitats (eg butterbur and cord-grass) would present particular problems. However, these have been overcome in Sweden where equipment has been developed to excavate rhizomes and harvest shoots of reed from lakes.

## 13.6 Conclusion

The indigenous and naturalised plant species of Great Britain include some species with a high potential as energy crops. Some of these species, like bracken, cord-grass, and the willow-herbs, cover large areas and could be harvested to give high yields without significantly disturbing traditional land use, whereas other species, like Japanese knotweed, *P. sachalinense* and policeman's helmet, are extremely prolific and could be planted on good land to give yields which may be higher than those of conventional agricultural crops and trees. The stability of yield of these species under repeated harvesting at various times in the annual cycle of growth is not known.

ACKNOWLEDGMENTS

This study was funded by the Department of Energy, through the Energy Technology Support Unit, and we are also grateful to the Institute of Terrestrial Ecology (NERC) for the facilities made available to us.

We are pleased to acknowledge the technical assistance of Carine Jeanrenaud whose time was in part funded by the Short Term Employment Programme of Cumbria County Council. A. Millar kindly assisted with the fieldwork. The extent of the various species in Great Britain was calculated and made available by Dr. R. G. H. Bunce and C. J. Barr.

We are particularly grateful to the staff of the subdivision of chemistry and instrumentation at Merlewood Research Station who were responsible for all chemical analyses.

The following kindly gave access to sites under their control:-

C. Burrow; Kents Bank, R. W. Hind; Lowick Common, D. Radley; Winterbourne, A. J. Truscott; Sefton Metropolitan Borough, S. M. Walters; Cambridge Botanic Garden, D. M. Wood; Manchester Recreation Services Department.

We gratefully acknowledge the use of the plant distribution maps published by Thomas Nelson and Sons Ltd for the Botanical Society of the British Isles.

Many helpful discussions have been held with colleagues in ITE and in the ETSU group of projects and we would like to thank J. N. R. Jeffers, Prof. F. T. Last, Dr. S. W. Greene and G. J. Lawson of ITE for commenting on the draft manuscript.

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1(a) [illegible]

([illegible])

1(b) [illegible]

(butterbur)

1(c) [illegible]

(cordgrass)

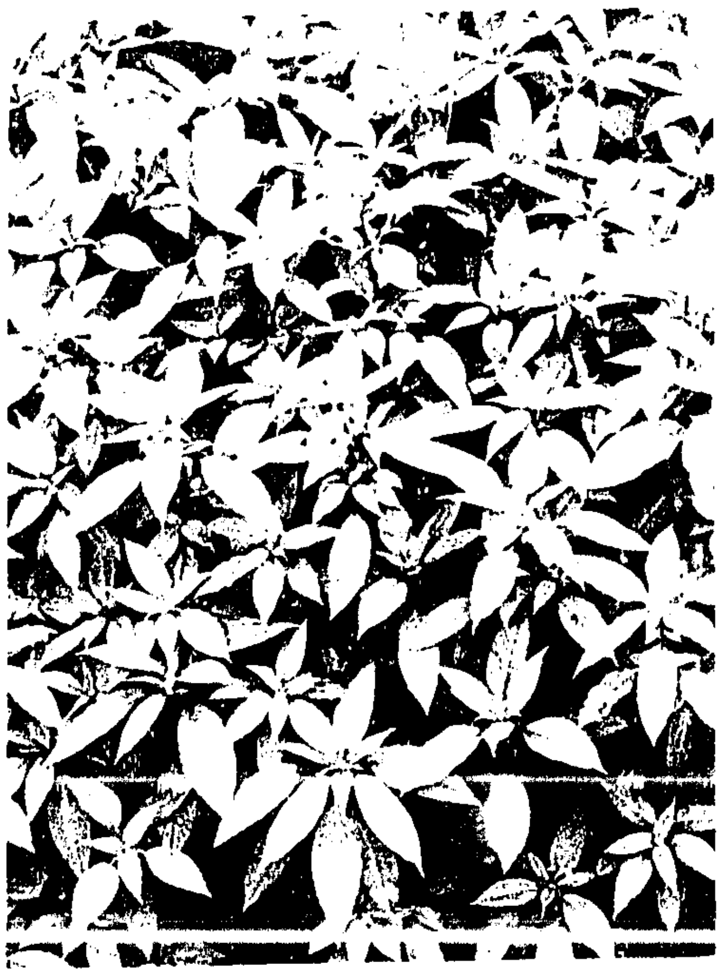
1(d) [illegible]

(Japanese knotweed)

1(e) [illegible]

(giant knotweed)

Plate 1. Native and introduced plant species investigated for fuel production



2(a) [illegible]
(policeman's helmet)

2(b) [illegible]
(meadow sweet)

2(c) [illegible]
(rosebay willow-herb)

2(d) [illegible]
(great hairy willow-herb)

Fig. 2 Native and introduced plant species investigated for fuel production

3(a) [illegible]
(stinging nettle)

3(b) [illegible]
(yellow flag)

3(c) [illegible]

3(d) [illegible]
(giant hogweed)

Plate 3. Native and introduced plant species investigated for fuel production

# APPENDIX I - METHODS

## Biomass sampling

Above ground standing crop samples were taken monthly from the early part of the growing season until after the death of the plant tops. 5 replicate 1 x 1 m squares were selected randomly from a permanently marked grid (see Fig I.1) for bracken, butterbur and cord-grass, but in the more patchy stands of the other species a regular grid was impractical so samples were taken progressively through each stand. Also, because of the limited extent of some of the species and because of practical difficulties with below ground samples some of the quadrat sizes were reduced. Table I.1 gives a summary of quadrat sizes for the different species.

Standing material was cut as close as possible to ground level. Fresh weight was determined in the field using a spring balance. In some species it was possible to separate belowground biomass in the field (bracken and butterbur) but others, notably cord-grass had to be returned to the laboratory to wash off the encasing soil. This imposed a limitation on the number of samples which could be handled.

As well as monthly samples, another cut was performed at the time of peak biomass, of all the previously cut quadrats to assess the amount of re-growth.

## Laboratory Analyses

A period of storage at ca 4°c was sometimes necessary before the samples could be further processed. Cropped material not already sorted in the field was paritioned into live and dead stems of the study species, other associated species also being separated for drying.

For Japanese knotweed and butterbur, samples comprising individual whole shoots were divided into leaf and stem fractions for leaf area measurement and separate weighing. Leaf area of the 1 m sample quadrats was estimated from the values derived from the sub-samples. Outlines of the leaves were traced onto paper and the area measured by use of a digitising image analyser.

Samples were dried in a large oven at 80°c. Most reached constant dry wt. overnight but some of the more substantial stems and rhizomes needed up to 48h in the oven.

Subsamples of the dried material were ground in a 2 mm mesh hammer mill and the following analyses were carried out

K )<br>
Ca ) extractable in 2.5 v/v. acetic acid<br>
Mg )<br>
P )

CHISWORTH BRACKEN SITE

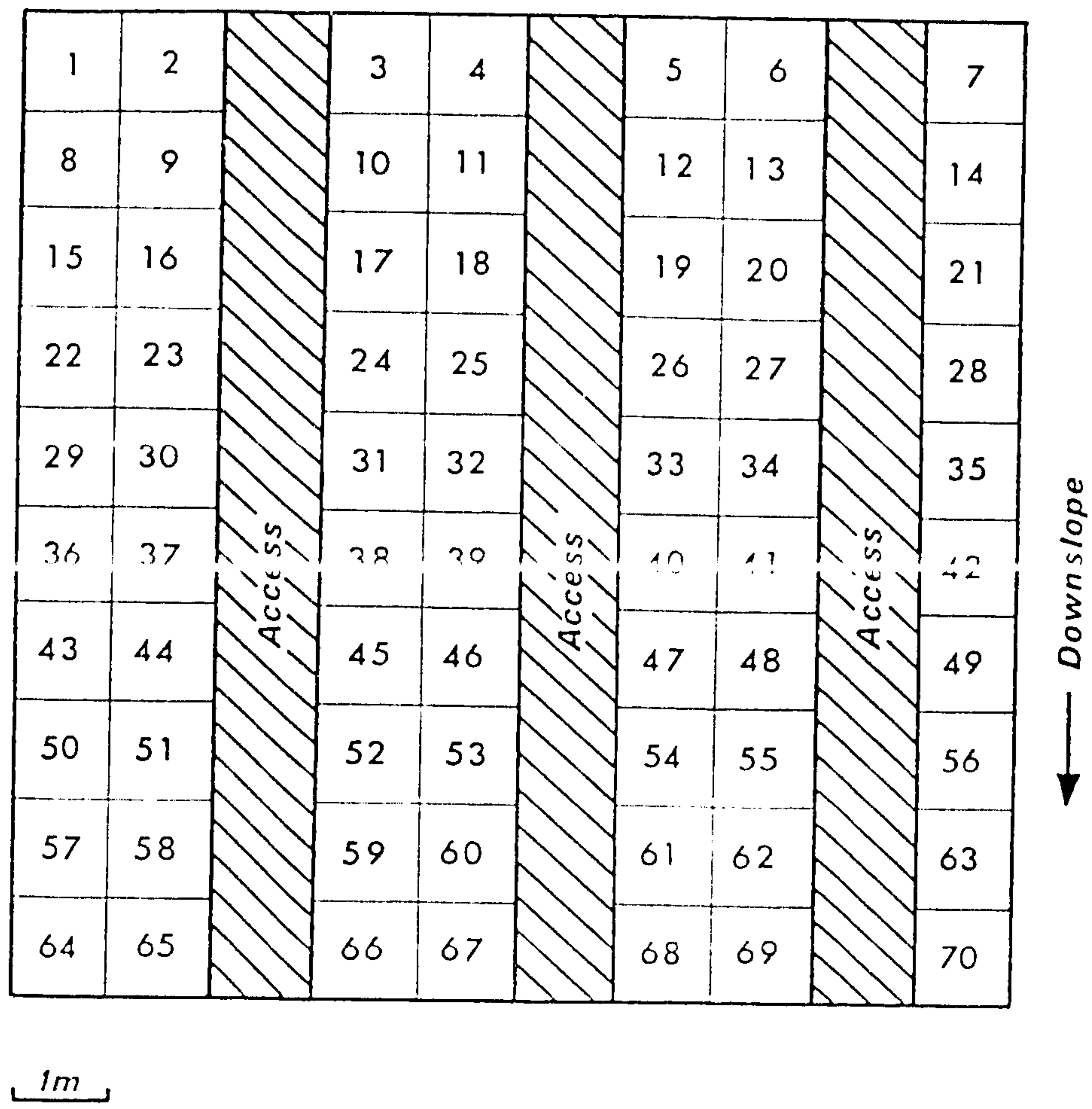



Figure I.1 The design of intensive field sites.

TABLE I.1

Biomass sample quadrat sizes

| Species | Above ground | Below ground | Associated species |
|---|---|---|---|
| *Polygonum cuspidatum* (Japanese knotweed) | 1 | 0.25 | 1 |
| *Pteridium aquilinum* (bracken) | 1 | 0.25 | - |
| *Spartina anglica* (cord-grass) | 1 | 0.25 | 1 |
| *Impatiens glandulifera* (policeman's helmet) | 1 | 0.25 | 1 |
| *Petasites hybridus* (butterbur) | 1 | 0.25 | 0.25 |
| *Cardamine amara* (large bitter-cress) | 0.25 | 0.0625 | 0.25 |
| *Chamaenerion angustifolium* (rosebay willow-herb) | 0.25 | 0.0625 | 0.25 |
| *Epilobium hirsutum* (great hairy willow-herb) | 0.25 | 0.0625 | 0.25 |
| *Filipendula ulmaria* (meadow sweet) | 0.25 | 0.0625 | 0.25 |
| *Urtica dioica* (stinging nettle) | 0.25 | 0.0625 | 0.25 |

| | |
|---|---|
| Nitrogen | - Total, determined by Kjeldahl digestion method. |
| Soluble Carbohydrate | - by anthrone colorimetry after solution in hot water. |
| Starch | - potassium iodide colorimetry after extraction in perchloric acid. |
| Crude Fat | - ether extraction and weighing of residue after evaporation. |
| Holocellulose | - delignified with weak acetic acid and sodium chlorite. Dried extract corrected for ash, and nitrogen expressed as crude protein (N x 6.25). |

Details of methods are presented in Allen *et al.* (1974).

Soil sampling and analyses

Sections of soil 5 cm deep were taken using a stainless steel corer. Surface litter was removed along with live plant matter and stones found in the core. The samples were dried at 40°C in an air circulation oven and after drying ground through a 2 mm mesh in a roller mill. The following analyses were carried out:

| | |
|---|---|
| pH | - water slurry allowed to stand for 15 mins, electrometric analysis. |
| L.O.I. | - weighing residue after 4 hrs ignition at 450°C. % loss calculated. |
| K, Ca, Mg, P, N. | - as above. Methods as presented in Allen *et al.* (1974). |

## APPENDIX II - SITE DESCRIPTIONS

Site selection was made in order to assess the potential of selected indigenous or naturalised British plant species as opportunity energy crops or dedicated energy crops. The variation of yield of species belonging to both categories was assessed by sampling species from sites located throughout Great Britain.

### II.1 Opportunity energy crops

These are species which are currently extensive in this country and could be harvested immediately without greatly affecting traditional amenity or conservation uses of the land. Because of the limited duration of the project (one field season), sites were selected where productivity appeared to be typical or high, where logistics were uncomplicated, and where permission to disturb the vegetation could easily be obtained. Occasionally, more than one site per species was selected to investigate the between-site variation in yield. The following sites, details of which are contained in Table II.1 and Figure II.1, were established:

| | | | |
|---|---|---|---|
| *Pteridium aquilinum* | - | bracken | Lowick Common & Chisworth |
| *Petasites hybridus* | - | butterbur | Chisworth |
| *Spartina anglica* | - | cord-grass | Rampside |
| *Filipendula ulmaria* | - | meadow-sweet | Chisworth |
| *Chamaenerion angustifolium* | - | rosebay willow-herb | Chisworth |
| *Epilobium hirsutum* | - | great hairy willow-herb | Chisworth |
| *Urtica dioica* | - | stinging nettle | Chisworth |

### II.2 Dedicated energy crops

Dedicated energy crops are high yielding species which are not usually very extensive and often occur as isolated stands of vegetation on derelict land. Consequently, they would not be harvested for energy purposes *in situ* but would be transplanted to areas of land designated for energy crop production. The field sites at which yield was determined were selected for their apparent high productivity and had to be sufficiently extensive to allow sampling. The sites, details of which are presented in Table II.1 and Figure II.1, were:

| | | | |
|---|---|---|---|
| *Polygonum cuspidatum* | - | Japanese knotweed | Kents Bank and Queen's Park Cemetery |
| *Impatiens glandulifera* | - | policeman's helmet | Chorlton Brook |

In addition to measuring yield *in situ*, some preliminary transplant trials were initiated to investigate methods of propagation and the subsequent success of plant establishment. The following sites were used:

| | | | |
|---|---|---|---|
| *Polygonum cuspidatum* | - | Japanese knotweed | Merlewood Research Station |
| *Heracleum mantegazzianum* | - | giant hogweed | Merlewood Research Station & Chisworth |
| *Gunnera manicata* | | | Chisworth |

## 11.3 Extensive sites

Whereas the sites described above were studied intensively, the range of variation in the yield of tall herbs in Great Britain was assessed by sampling widespread sites on only one occasion. Sites were selected using a statistically-based framework. 25,one inch Ordnance Survey maps were selected at random from all of the map sheets covering Great Britain. The 10 x 10 km square in the south-west corner of each sheet was then surveyed. Details and the locations of the sites are presented in Table 11.1 and Figure 11.1, respectively. The sites were:

| | | |
|---|---|---|
| *Polygonum cuspidatum* | - Japanese knotweed | Dornie, Coldstream and Southport |
| *P. sachalinense* | | Loch Locky and Lynton |
| *Pteridium aquilinum* | - bracken | Strathoykel, Lowick Common, Eggerslack Wood, Loughrigg, Gaufron, Romsey and Ashhurst Wood |
| *Phragmites australis* | - reed | Dornie, Gosberton and Plucks Gutter |
| *Iris pseudacorus* | - yellow flag | Dornie, Tulteam Tarbhach, and Plucks Gutter |
| *Chamaenerion angustifolium* | - rosebay willow-herb | Stralton, Bellmuir, Dollarbeg, Pontefract, Risedale and Holsworthy |
| *Epilobium hirsutum* | - great hairy willow-herb | Kettleburgh, Sheepy Magna and Plucks Gutter |
| *Phalaris arundinacea* | - reed grass | Tulteam Tarbhach |
| *Spartina anglica* | - cord-grass | Southport |
| *Cirsium arvense* | - creeping thistle | Ledbury |
| *Petasites hybridus* | - butterbur | Winterbourne Botanical Gardens |
| *Gunnera manicata* | | Winterbourne Botanical Gardens |
| *Heracleum mantegazzianum* | - giant hogweed | Cambridge Botanical Gardens |

Table II.1

Description of experimental sites
(nomenclature follows Clapham *et al.* 1962)

| Site | Location | Study species | General site description | Vegetation | Sampling dates |
|---|---|---|---|---|---|
| a) Intensive sites | | | | | |
| 1 Lowick common | Near Ulverston Cumbria SD 286 854 | *Pteridium aquilinum* | c 5° slope to NW at 80 m. Fairly well drained pod-solic brown earth soil. | Open moorland dominated by *Pteridium aquilinum* and *Ulex europeaus*. Other species include: [illegible] *Narthecium ossifragum*, *Endymion non-scriptus*, *Dactylis glomerata*. | Monthly from May to November 1979. |
| 2 Rampside | Near Barrow-in-Furness Cumbria SD 235 657 | *Spartina anglica* | coastal mud flat subject to tidal flooding ie substratum is marine silt. Elevation c 3 m. | Fore-shore dominated by *Spartina anglica*. Other species include: *Puccinellia maritima*, *Suaeda maritima*, *Salicornia europaea*. | Monthly from June to December 1979. |
| 3 Kents Bank | Grange-over-Sands Cumbria SD 403 769 | *Polygonum cuspidatum* | 5° slope to SW at 15 m. The disturbed soil is predominantly brown earth which is well-drained. | Derelict land dominated by *Polygonum cuspidatum*. Other species include: *Heracleum sphondylium*, *Ranunculus ficaria*, *Narcissus pseudo-narcissus*, *Galanthus rivalis*, *Urtica dioica*, *Aegopodium podagraria*, *Rubus fruticosus*, *Ornithogalum umbellatum*, *Rumex obtusifolius*, *Chamaenerion angustifolium*, *Cirsium arvense*. | Monthly from June to November 1979. |
| 4 Queen's Park Cemetery | Rochdale Road, Manchester SD 855 011 | *Polygonum cuspidatum* | level ground at 76 m in a disturbed urban area. The substratum is a brown earth on top of clay with much refuse (eg bricks and cement) present. The soil is well drained. | Derelict land and old cemetery over-run by *Polygonum cuspidatum*. Other species include: *Agrostis stolonifera*, *A. canina*, *Poa annua*, *P. pratensis*. | Monthly from May to December 1979. |
| 5 Chorlton Brook | Chorlton-cum-Hardy Manchester SU 806 934 | *Impatiens glandulifera* | 50° slope to S at 20 m on the bank of a large polluted drainage dyke, the riverine sediment is periodically flooded. | Periodically disturbed area dominated by *Impatiens glandulifera*. Other species include: *Urtica dioica*, *Festuca rubra*, *Phalaris arundinacea*. | Monthly from July to November 1979. |

| Site | Location | Study species | General site description | Vegetation | Sampling dates |
|---|---|---|---|---|---|
| **a) Intensive sites** | | | | | |
| 6 Chisworth | near Glossop, Derbyshire SJ 985 927 | *Pteridium aquilinum* | $15^{\circ}$ slope to W at 122 m along a wooded stream valley. The soil is a well drained brown earth on top of clay. | Heath, in woodland clearing dominated by *Pteridium aquilinum*. Other species include: *Poa trivialis*, *Galium saxatile*. | Monthly from May to December 1979. |
| | | *Petasites hybridus* | almost level water-logged area near stream at 100 m. The soil is a gley. | Wet flush, in woodland clearing dominated by *Petasites hybridus*. Other species include: *Heracleum sphondylium*, *Urtica dioica*, *Galium aparine*, *Poa trivialis*, *Cardamine hirsuta*. | Monthly from March to December 1979. |
| | | *Filipendula ulmaria* | $10^{\circ}$ slope to W at 122 m along a stream valley on derelict agricultural land where the drinage system has broken down. The waterlogged soil is a gley. | Wet flush, in woodland clearing dominated by *Filipendula ulmaria* associated with *Angelica sylvestris*, *Equisetum arvense*, *Cardamine flexuosa*, *Cirsium palustre*, *Juncus inflexus*, *Lathyrus pratensis*. | Monthly from May to November 1979. |
| | | *Epilobium hirsutum* | $10^{\circ}$ slope to W at 122 m along a stream valley on derelict agricultural land where the drainage system has broken down. The waterlogged soil is a gley. | Wet flush, in woodland clearing dominated by *Epilobium hirsutum* in association with: *Filipendula ulmaria*, *Heracleum sphondylium*, *Cardamine pratensis*, *Cirsium palustre*, *C. arvense*. | Monthly from May to November 1979. |
| | | *Chamaenerion angustifolium* | $10^{\circ}$ slope to W at 122 m along a stream valley on well drained derelict agricultural land. The soil is a brown earth. | Old pasture, invaded by ruderals, dominated by *Chamaenerion angustifolium* in association with *Heracleum sphondylium*, *Holcus lanatus*, *H. mollis*, *Dactylis glomerata*, *Alopecurus pratensis*, *Urtica dioica*. | Monthly from May to September 1979. |
| | | *Urtica dioica* | $10^{\circ}$ slope to W at 122 m along a stream valley on damp derelict agricultural land. The soil is a brown earth. | Old pasture, invaded by weed species, dominated by *Urtica dioica* in association with *Impatiens glandulifera*, *Chamaenerion angustifolium*, *Holcus mollis*. | Monthly from May to November 1979. |
| | | *Cardamine amara* | Wet flush resulting from broken drains on derelict agricultural land at 122 m. | Wet flush dominated by *Cardamine amara* associated with *Ranunculus repens* and *Veronica beccabunga*. | May and June 1979. |

| Site | Location | Study species | General site description | Vegetation | Sampling dates |
|---|---|---|---|---|---|
| b) **Extensive sites** | | | | | |
| 7 Dornie | Ross and Cromarty NG 828 281 | *Polygonum cuspidatum* | roadside situation along disturbed edge of former road at 250 m; good drainage. | Disturbed area dominated by *Polygonum cuspidatum*. Associated species include: *Juncus effusus*, *Urtica dioica*, *Rubus fruticosus*, *Rubus idaeus*. | 14 September 1979. |
| | NG 826 270 | *Phragmites australis* | roadside situation in drainage ditch and surrounding banks at 250 m - receiving water. | wet flush area dominated by *Phragmites australis*. Associated species: *Filipendula ulmaria*, *Juncus inflexus*, *Rubus idaeus*. | 14 September 1979 |
| | NG 826 270 | *Iris pseudacorus* | roadside situation at 250 m on a wet verge receiving water. | wet flush of *Iris pseudacorus* with associated species: *Filipendula ulmaria*, *Urtica dioica*, *Juncus inflexus*, [illegible] *sphondylium*. | 14 September 1979. |
| 8 Loch Locky | Nr. Fort William NN 238 894 | *Polygonum sachalinense* | roadside situation at 107 m on steep 45° slope on banks of Loch Locky - good drainage. brown earth soil which has been disturbed by roadside dumping. | On edge of ash/alder woodland area entirely dominated by *Polygonum sachalinense*. | 14 September 1979. |
| 9 Straiton | Ayrshire NS 377 063 | *Chamaenerion angustifolium* | roadside situation at 107 m growing on brown earth soil which is very well drained. Surrounding area is cattle-grazed pasture and forestry land. | *Chamaenerion angustifolium* growing among newly-planted spruce. Associated species: *Dactylis glomerata*, *Arrhenatherum elatius*, *Festuca ovina*, *Agrostis stolonifera*, *Poa trivialis*, *Urtica dioica*, *Aegopodium podagraria*, *Rosa canina*, *Rubus fruticosus*. | 1 October 1979. |
| 10 Strathoykel | Lairg NC 416 013 | *Pteridium aquilinum* | roadside situation on steep bank at c 45°, facing south at 30 m altitude among loose rocks. | *Pteridium aquilinum* growing at the edge of *Betula* scrub. Associated species: *Festuca ovina*, *Potentilla erecta*, *Polytrichum commune*. | 13 September 1979. |
| 11 Tuiteam Tarbhach | Ross and Cromarty NC 445 014 | *Phalaris arundinacea* | wet flush area at base of small stream entering main river, facing south at 6 m altitude. | pasture edge dominated by *Phalaris arundinacea* with associated species. *Iris pseudacorus*, *Deschampsia flexuosa*, *Poa trivialis*, *Juncus effusus*. | 13 September 1979. |
| | | *Iris pseudacorus* | Drainage ditch for field adjacent to river at 6 m altitude. | Pasture edge dominated by *Phalaris arundinacea* with associated species *Deschampsia flexuosa*, *Poa trivialis*, *Juncus effusus*. | 13 September 1979. |

| | Site | Location | Study species | General site description | Vegetation | Sampling dates |
|---|---|---|---|---|---|---|
| 12 | Bellmuir | SE Methlick NJ 871 361 | *Chamaenerion angustifolium* | Wooded terrace between road and river bank at 26 m. Well-drained. A woodland brown earth soil. | *Chamaenerion angustifolium* growing on edge of *Acer pseudoplatanus*. Associated species: *Digitalis purpurea, Silene dioica, Cirsium arvense.* | 13 September 1979. |
| 13 | Dollarbeg | Nr. Alloa NS 961 966 | *Chamaenerion angustifolium* | Well-drained edge of grazing meadow at 76 m facing north; soil is a brown earth - disturbed, with some refuse. | *Chamaenerion angustifolium* growing at the edge of *Fraxinus* trees. Associated species: *Urtica dioica, Rubus idaeus, R. fruticosus, Agrostis stolonifera, Heracleum sphondylium, Dryopteris filix-mas, Geum urbanum.* | 14 September 1979. |
| 14 | Coldstream | Berwickshire NT 845 399 | *Polygonum cuspidatum* | North bank of the River Tweed at 15 m; well drained alluvial gravel soil. | Dense stand of *Polygonum cuspidatum* along river bank. Associated species: *Petasites* [illegible] *Urtica dioica, Arrhenatherum elatius, Agropyron repens, Dactylis glomerata.* | 14 September 1979. |
| 15 | Pontefract | Yorkshire SE 442 236 | *Chamaenerion angustifoium* | Wayside area between M62, roundabout, A639 and railway embankment. A disturbed site with good drainage at 27 m altitude. | *Dactylis/Arrhenatherum* grassland with spreading patches of *Chamaenerion angustifolium, Urtica dioica, Cirsium arvense, Foeniculum vulgaris.* | 4 September 1979. |
| 16 | Lowick common | Cumbria SD 290 852 | *Pteridium aquilinum* | A 10° slope to the N at 122 m - well drained podsolic brown earth soil. | Hillside area dominated by *Pteridium aquilinum* with few associated species: *Galium saxatile, Sieglingia decumbens, Festuca rubra, Poa pratensis.* | 5 October 1979 |
| 17 | Eggerslack Wood | nr. Grange-over-Sands Cumbria SD 405 794 | *Pteridium aquilinum* | Well drained clearing in trees at 153 m, on 5° slope facing SSE. Brown earth soil. | *Pteridium aquilinum* growing in a clearing with *Larix* and *Quercus* saplings. Associated species: *Hedera helix, Lonicera periclymenum.* | 8 October 1979. |
| 18 | Risedale | Grange-over-Sands Cumbria SD 395 766 | *Chamaenerion angustifolium* | Well drained former tip area at 70 m. Disturbed soil. | *Chamaenerion angustifolium* growing on unstable bank. Associated species: *Urtica dioica, Rubus fruticosus, Senecio jacobaea, Heracleum sphondylium, Arrhenatherum elatius.* | 24 September 1979. |
| 19 | Loughrigg | Cumbria NY 336 053 | *Pteridium aquilinum* | Well drained podsolic/brown earth at 180 m on a 25° slope facing SW. | *Pteridium aquilinum* - dominated hillside with limited occurrence of *Galium saxatile, Poa pratensis, Holcus mollis.* | 20 July 1979. |

| Site | Location | Study species | General site description | Vegetation | Sampling dates |
|---|---|---|---|---|---|
| 20 Sparkbridge | Cumbria SD 307 837 | Mixed roadside vegetation. | Well drained roadside verge at 45 m on slope of 30° to E.N.E. Brown earth soil. | Mixed vegetation - dominant species *Holcus mollis*, *H. lanatus*, *Heracleum sphondylium*, *Festuca rubra*, *Agropyron repens*, *Poa pratensis*. | 20 July 1979. |
| 21 Southport | Merseyside SD 348 198 | *Polygonum cuspidatum* | Well drained tip earth on landward side of causeway along the coast at 7 m: sand overblown on refuse base. | Area dominated by *Polygonum cuspidatum*. Associated species: *Elymus arenarius*, *Urtica dioica*, *Cakile maritima*, *Senecio jacobaea*, *Tripleurospermum maritimum*. | 10 October 1979. |
| | SD 354 206 | *Spartina anglica* | Coastal mud flat at 3 m subject to tidal flooding and deposition of silt. | Fore-shore dominated by *Spartina anglica*. Infrequent occurrence of *Puccinellia maritima*. | 10 October 1979 and 20 December |
| 22 Ledbury | Nr. Wellington Heath SD 711 406 | *Cirsium arvense* | 10° slope to NW at 137 m. A well-drained site on edge of field with brown earth soil. | *Cirsium arvense* growing on edge of former pasture - Associated species: *Urtica dioica*, *Holcus mollis*, *Poa trivialis*, *Rubus fruticosus*. | 10 September 1979. |
| 23 Winterbourne Botanical Gardens | Birmingham SP 055 844 | *Gunnera manicata* | A very wet site with peaty gley soil at 130 m, close to drainage ditch and lake. | *Gunnera manicata* growing in shade conditions under tree canopy - other exotic spp. (eg *Lysichitum camschatschense*) present. | 30 August 1979. |
| | SP 054 845 | *Petasites hybridus* | A level wet site at 130 m with gley soil, close to lake. | *Petasites hybridus* growing in shade conditions under trees, bare ground beneath. | 30 August 1979. |
| 24 Gaufron | Powys SN 998 681 | *Pteridium aquilinum* | Hillside; 30° slope facing NNE at 244 m. Well drained podsol soil with abundant stones. | *Pteridium aquilinum* - dominated hillside above *Quercus* woodland. Associated species: *Endymion non-scriptus*, *Polytrichum* sp., *Agrostis stolonifera*, *Luzula multiflora*. | 16 August 1979. |
| 25 Kettleburgh | Suffolk TM 274 602 | *Epilobium hirsutum* | Hedge/ditch position at edge of road facing south at 43 m. Base of ditch wet and receiving water. | *Epilobium hirsutum* with associated species *Rubus fruticosus*, *Cirsium arvense*, *Urtica dioica*, *Centaurea nigra*, *Bromus mollis*, *Arrhenatherum elatius*, *Heracleum sphondylium*, *Sambucus nigra*. | 3 September 1979. |

| Site | | Location | Study species | General site description | Vegetation | Sampling dates |
|---|---|---|---|---|---|---|
| 26 | Holsworthy | Devon<br>SS 442 043 | *Chamaenerion angustifolium* | Young plantation with podsol soils which have been ploughed to give free drainage - almost level position at 103.7 m. | *Chamaenerion angustifolium* in a young mixed conifer and deciduous plantation. Associated species: *Filipendula ulmaria*, *Poa trivialis*, *Rubus fruticosus*, *Urtica dioica*, *Heracleum sphondylium*. | 9 September 1979. |
| 27 | Gosberton | Lincolnshire<br>TF 2[illegible] 305 | *Phragmites australis* | Roadside verge/ditch area receiving water - gley soil - 3.0 m. | Ditch area dominated by *Phragmites australis*, *Torilis japonica*, *Urtica dioica*, *Plantago major*, *Convolvulus arvensis*, *Dactylis glomerata*, *Arrhenatherum elatius*, *Lolium perenne*, *Poa pratensis*, *Rubus fruticosus*. | 15 August 1979. |
| 28 | Sheepy Magna | Leicestershire<br>SK 342 027 | *Epilobium hirsutum* | Roadside site at 82 m, almost level ditch with gley soil; area receiving water. | Predominantly *Epilobium hirsutum* with associated species: *Urtica dioica*, *Arrhenatherum elatius*, *Dactylis* [illegible] *pratensis*, *Agropyron repens*, *Rubus fruticosus*. | 16 August 1979. |
| 29 | Plucks Gutter | nr. Canterbury<br>TR 269 634 | *Epilobium hirsutum* | A level site which is poorly drained at 3.0 m; gley/ brown earth soil. | *Epilobium hirsutum* growing at the edge of agricultural land together wtih associated species: *Filipendula ulmaria*, *Urtica dioica*, *Rubus fruticosus*, *Dactylis glomerata*, *Juncus inflexus*. | 4 September 1979. |
| | | | *Iris pseudacorus* | Drainage ditch/stream edge with waterlogged soil and poor drainage. | Predominantly *Iris pseudacorus* with *Juncus effusus*. | 4 September 1979. |
| | | | *Phragmites australis* | Drainage ditch at edge of field-area receiving water and has a gley soil. | Edge of ditch predominantly *Phragmites australis* with limited occurrence of *Epilobium hirsutum*, *Juncus effusus* and *Urtica dioica*. | 4 September 1979. |
| 30 | Romsey | Hampshire<br>SU 303 193 | *Pteridium aquilinum* | Well-drained woodland brown-earth soil under *Betula* and *Quercus* trees, slight slope $5^{o}$ at 3 m. | Ground flora of *Pteridium aquilinum* growing in shade with some *Rubus fruticosus*, *Poa trivialis* and *Aegopodium podagraria*. | 8 September 1979. |

| Site | Location | Study species | General site description | Vegetation | Sampling dates |
|---|---|---|---|---|---|
| 31 Ashurst wood | nr. East Grinstead TQ 425 391 | *Pteridium aquilinum* | Well-drained humus rich woodland brown-earth soil at 122 m. Almost level, shade conditions. | *Pteridium aquilinum* growing under dense canopy of predominantly *Quercus* woodland with some *Fagus* and *Betula*. | 5 September 1979. |
| 32 Lynton | Devon SS 657 438 | *Polygonum sachalinense* | Roadside bank at 274 m well-drained brown-earth soil; disturbed at edge of road facing NW. | *Polygonum* sp. growing at edge of road with limited other species: *Rubus fruticosus*, *Urtica dioica*, *Poa trivialis*. | 9 September 1979. |
| 33 Cambridge Botanic Garden | Cambridge TL 455 571 | *Heracleum mantegazzianum* | A flat, well-drained site at 10 m close to buildings. | *Heracleum mantegazzianum* dominated area - dead leaves and basal rosettes covering ground. | 29 August 1979. |
| c) Transplant sites | | | | | |
| 34 Merlewood Garden | Grange-over-Sands Cumbria SD 408 796 | *Polygonum cuspidatum* | A gently sloping fertile garden site at 91 m facing south-east. Cultivated brown earth soil with good drainage. | *Polygonum cuspidatum* rhizomes planted April 1979. | Monthly April to November 1979. |
| | | *Heracleum mantegazzianum* | A gently sloping fertile garden site at 91 m facing south-east. Cultivated brown earth woil which has good drainage. | *Heracleum mantegazzium* planted 11th May 1979. | Monthly May to November 1979. |
| | | *Symphytum officinale* | A rich garden soil having grown *Symphytum* for a number of years, at 91 m facing south east; good drainage. | A range of cutting regimes carried out on an existing stand of *Symphytum officinale*. | Monthly May to November 1979. |
| 35 Chisworth | Derbyshire SJ 985 927 | *Heracleum mantegazzianum* | A 5° slope to the NW at 80 m - well-drained brown earth soil. | *Heracleum mantegazzianum* planted 29 May 1979 in a former pasture. Associated species in the area include: *Heracleum sphondylium*, *Urtica dioica*, *Holcus lanatus*, *Dactylis glomerata*. | Monthly May to November 1979. |
| | | *Gunnera manicata* | A 5° slope to the W at 122 m along a wet drainage line giving a heavy peaty gley soil. | Wet flush in woodland clearing planted with *Gunnera manicata* rhizomes on 29th May 1979. | Monthly May to November 1979. |

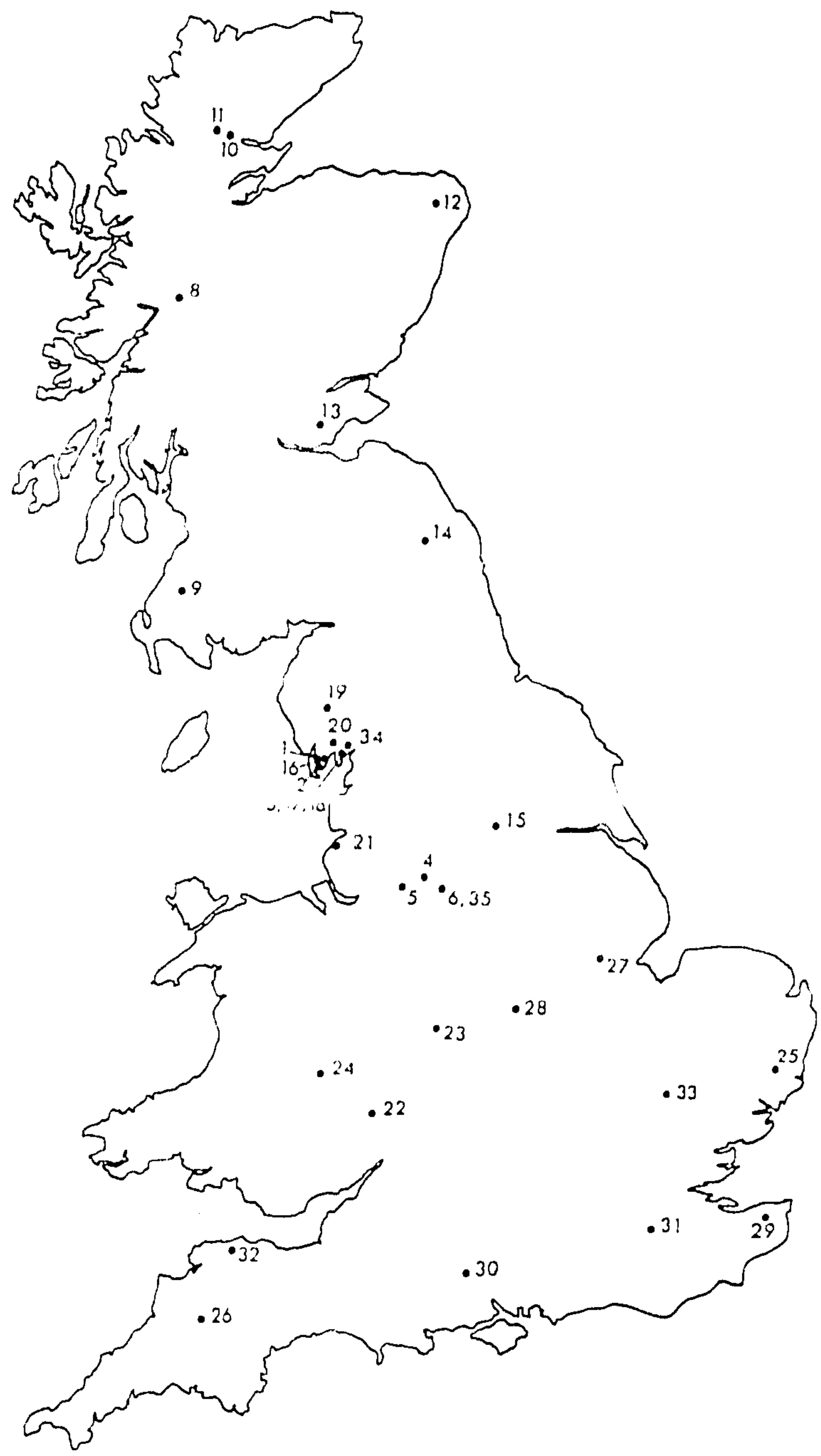



Figure II.1 The location of study sites in Great Britain.

<u>Sites 1- 6</u> intensive field sites

<u>Sites 7-33</u> extensive field sites

<u>Sites 34 & 35</u> garden transplant sites

## APPENDIX III STATISTICAL RESULTS

Results of statistical analyses on data presented in figures, tables and in the text

| Data Source | Comparison | Statistical Test | Results |
|---|---|---|---|
| | *Pteridium* | | |
| Figure 2.1, B page 7 | (a) between means of frond height at the Chisworth site | one way anovar | $P \leq 0.001$ ($F = 1071.71$ with 3 and 1072 degrees of freedom) |
| | (b) between means of frond height at the Lowick Common site | one way anovar | $P \leq 0.001$ ($F = 967.12$ with 2 and 1058 degrees of freedom) |
| | (c) between means of frond density at the Chisworth site | one way anovar | $P \leq 0.05$ ($F = 5.47$ with 2 and 22 degrees of freedom) |
| | (d) between means of frond density at the Lowick Common site | one way anovar | $P \leq 0.01$ ($F = 5.77$ with 2 and 22 degrees of freedom) |
| Page 9 | Between means of fresh wt/dry wt ratios in summer at the Chisworth and Lowick sites | t-test | $P \leq 0.001$ ($t = 9.2$ with 18 degrees of freedom |
| | Between means of fresh wt/dry wt ratios at 2 dates at the Lowick site | t-test | $P \leq 0.001$ ($t = 17.74$ with 13 degrees of freedom) |
| | (a) between means of rhizome standing crop at the Chisworth site | one way anovar | $P > 0.05$ ($F = 1.72$ with 2 and 17 degrees of freedom) |
| | (b) between means of rhizome standing crop at the Lowick Common site | one way anovar | $P > 0.05$ ($F = 0.19$ with 2 and 17 degrees of freedom) |

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|---|---|---|---|
| Figure 2.2 page 10 | (a) between means of standing crop of fronds at the Chisworth site | one way anovar | $P \leq 0.001$ ($F = 18.7$ with 7 and 47 degrees of freedom) |
| | (b) between means of standing crop of fronds at the Lowick Common site | one way anovar | $P \leq 0.001$ ($F = 21.6$ with 6 and 38 degrees of freedom) |
| Table 2.2 page 11 | (a) between means of re-growth at the Chisworth site | one way anovar | $P > 0.05$ ($F = 0.94$ with 2 and 12 degrees of freedom) |
| | (b) between means of re-growth at the Lowick Common site | one way anovar | $P \leq 0.001$ ($F = 15.33$ with 3 and 16 degrees of freedom |
| Table 2.3 page 13 | (a) between means of rhizome standing crop at the Chisworth site | one way anovar | $P > 0.05$ ($F = 0.64$ with 3 and 16 degrees of freedom) |
| | (b) between means of rhizome standing crop at the Lowick Common site | one way anovar | $P > 0.05$ ($F = 1.74$ with 4 and 20 degrees of freedom) |
| Figure 2.3 page 14 | (a) between means of N concentration | one way anovar | $P \leq 0.001$ ($F = 16.2$ with 6 and 11 degrees of freedom) |
| | (b) between means of P concentration | one way anovar | $P \leq 0.001$ ($F = 57.5$ with 6 and 11 degrees of freedom) |
| | (c) between means of K concentration | one way anovar | $P \leq 0.001$ ($F = 39.7$ with 6 and 11 degrees of freedom) |
| | (d) between means of Ca concentration | one way anovar | $P \leq 0.001$ ($F = 16.6$ with 6 and 11 degrees of freedom) |
| | (e) between means of Mg concentration | one way anovar | $P \leq 0.001$ ($F = 12.3$ with 6 and 11 degrees of freedom) |
| | (f) between means of ash concentration | one way anovar | $P \leq 0.001$ ($F = 41.92$ with 6 and 11 degrees of freedom) |

Table 2.4 page 15

| | | | |
|---|---|---|---|
| (a) | between means of N concentration | one way anovar | $P>0.05$ ($F = 0.36$ with 2 and 4 degrees of freedom) |
| (b) | between means of P concentration | one way anovar | $P>0.05$ ($F = 2.53$ with 2 and 4 degrees of freedom) |
| (c) | between means of K concentration | one way anovar | $P>0.05$ ($F = 0.15$ with 2 and 4 degrees of freedom) |
| (d) | between means of Ca concentration | one way anovar | $P>0.05$ ($F = 0.28$ with 2 and 4 degrees of freedom) |
| (e) | between means of Mg concentration | one way anovar | $P>0.05$ ($F = 1.66$ with 2 and 4 degrees of freedom) |
| (f) | between means of ash concentration | one way anovar | $P\leq0.05$ ($F = 7.32$ with 2 and 4 degrees of freedom) |
| (g) | between means of N total content | one way anovar | $P>0.05$ ($F = 4.71$ with 2 and 4 degrees of freedom) |
| (h) | between means of P total content | one way anovar | $P>0.05$ ($F = 0.85$ with 2 and 4 degrees of freedom) |
| (i) | between means of K total content | one way anovar | $P>0.05$ ($F = 0.67$ with 2 and 4 degrees of freedom) |
| (j) | between means of Ca total content | one way anovar | $P>0.05$ ($F = 1.92$ with 2 and 4 degrees of freedom) |
| (k) | between means of Mg total content | one way anovar | $P>0.05$ ($F = 1.10$ with 2 and 4 degrees of freedom) |
| (l) | between means of ash total content | one way anovar | $P>0.05$ ($F = 3.23$ with 2 and 4 degrees of freedom) |

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|---|---|---|---|
| Table 2.5 page 17 | (a) between means of N total content | one way anovar | $P\leq0.05$ ($F = 3.3$ with 6 and 10 degrees of freedom) |
| | (b) between means of P total content | one way anovar | $P\leq0.05$ ($F = 4.6$ with 6 and 10 degrees of freedom) |
| | (c) between means of K total content | one way anovar | $P\leq0.01$ ($F = 6.2$ with 6 and 10 degrees of freedom) |
| | (d) between means of Ca total content | one way anovar | $P\leq0.05$ ($F = 3.92$ with 6 and 10 degrees of freedom) |
| | (e) between means of Mg total content | one way anovar | $P\leq0.05$ ($F = 3.46$ with 6 and 10 degrees of freedom) |
| | (f) between means of ash total content | one way anovar | $P\leq0.01$ ($F = 7.56$ with 6 and 11 degrees of freedom) |
| Page 19 | Between means of energy content per g dry wt. of shoots and per g. dry wt. of rhizomes | t-test | $P\leq0.001$ ($t = 7.12$ with 23 degrees of freedom) |
| Figure 2.5 page 20 | (a) between means of soluble carbohydrate concentration | one way anovar | $P\leq0.001$ ($F = 28.87$ with 6 and 11 degrees of freedom) |
| | (b) between means of starch concentration | one way anovar | $P>0.05$ ($F = 0.39$ with 6 and 11 degrees of freedom) |
| | (c) between means of crude fat concentration | one way anovar | $P\leq0.001$ ($F = 26.49$ with 6 and 11 degrees of freedom) |
| | (d) between means of holo-cellulose concentration | one way anovar | $P\leq0.001$ ($F = 20.35$ with 6 and 11 degrees of freedom) |
| | (e) between means of lignin concentration | one way anovar | $P\leq0.001$ ($F = 40.48$ with 6 and 11 degrees of freedom) |
| Table 2.6 page 21 | (a) between means of soluble carbohydrate concentration | one way anovar | $P>0.05$ ($F = 0.19$ with 2 and 4 degrees of freedom) |
| | (b) between means of starch concentration | one way anovar | $P>0.05$ ($F = 2.29$ with 2 and 4 degrees of freedom) |

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| | (c) between means of crude fat concentration | one way anovar | P>0.05 ($F = 4.0$ with 2 and 4 degrees of freedom) |
| | (d) between means of holo-cellulose concentration | one way anovar | P>0.05 ($F = 1.84$ with 2 and 4 degrees of freedom) |
| | (e) between means of lignin concentration | one way anovar | P≤0.01 ($F = 31.02$ with 2 and 4 degrees of freedom) |
| Figure 2.6 page 22 | Between means of energy content per g dry wt. of shoots | one way anovar | P>0.05 ($F = 1.14$ with 6 and 11 degrees of freedom) |
| | *Petasites* | | |
| Figure 3.2, A page 27 | (a) between means of no. of leaves $m^{-2}$ | one way anovar | P≤0.01 ($F = 4.96$ with 4 and 20 degrees of freedom) |
| | (b) between means of petiole height | one way anovar | P≤0.001 ($F = 161.41$ with 4 and 215 degrees of freedom) |
| Figure 3.2, B page 27 | (a) between means of area per leaf | one way anovar | P≤0.001 ($F = 28.18$ with 4 and 196 degrees of freedom) |
| | (b) between means of leaf area index | one way anovar | P>0.05 ($F = 2.13$ with 4 and 20 degrees of freedom) |
| Page 28 | (a) between means of fresh wt./ dry wt. ratios | one way anovar | P>0.05 ($F = 3.42$ with 2 and 12 degrees of freedom) |
| | (b) between means of dry wts. of rhizomes | one way anovar | P>0.05 ($F = 0.18$ with 2 and 12 degrees of freedom) |
| Figure 3.3 page 29 | (a) between means of *Petasites* standing crop | one way anovar | P≤0.001 ($F = 17.61$ with 9 and 40 degrees of freedom) |
| | (b) between means of the standing crop of associated species | one way anovar | P≤0.05 ($F = 2.29$ with 8 and 36 degrees of freedom) |

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| Table 3.1 page 30 | Between means of re-growth of *Petasites* | one way anovar | $P>0.05$ ($F = 2.66$ with 2 and 12 degrees of freedom) |
| | Between means of re-growth of associated species | one way anovar | $P>0.05$ ($F = 1.24$ with 2 and 12 degrees of freedom) |
| Table 3.2 page 31 | Between means of rhizome standing crop | one way anovar | $P>0.05$ ($F = 1.46$ with 3 and 16 degrees of freedom) |
| Figure 3.4 page 33 | (a) between means of N concentration | one way anovar | $P \geq 0.001$ ($F = 14.13$ with 5 and 11 degrees of freedom) |
| | (b) between means of P concentration | one way anovar | $P \geq 0.001$ ($F = 21.34$ with 5 and 11 degrees of freedom) |
| | (c) between means of K concentration | one way anovar | $P \leq 0.05$ ($F = 4.25$ with 5 and 11 degrees of freedom) |
| | (d) between means of Ca concentration | one way anovar | $P>0.05$ ($F = 0.75$ with 5 and 11 degrees of freedom) |
| | (e) between means of Mg concentration | one way anovar | $P>0.05$ ($F = 2.46$ with 5 and 11 degrees of freedom) |
| | (f) between means of ash concentration | one way anovar | $P>0.05$ ($F = 2.3$ with 5 and 11 degrees of freedom) |
| Table 3.3 page 34 | (a) between means of N concentration | one way anovar | $P \leq 0.05$ ($F = 8.24$ with 2 and 6 degrees of freedom) |
| | (b) between means of P concentration | one way anovar | $P>0.05$ ($F = 5.7$ with 2 and 6 degrees of freedom) |
| | (c) between means of K concentration | one way anovar | $P \leq 0.05$ ($F = 9.62$ with 2 and 6 degrees of freedom) |

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| | (d) between means of Ca concentration | one way anovar | P>0.05 (F = 0.26 with 2 and 6 degrees of freedom) |
| | (e) between means of Mg concentration | one way anovar | P>0.05 (F = 0.12 with 2 and 6 degrees of freedom) |
| | (f) between means of ash concentration | one way anovar | P>0.05 (F = 2.17 with 2 and 6 degrees of freedom) |
| | (g) between means of N total content | one way anovar | P>0.05 (F = 2.63 with 2 and 6 degrees of freedom) |
| | (h) between means of P total content | one way anovar | P>0.05 (F = 0.35 with 2 and 6 degrees of freedom) |
| | (i) between means of K total content | one way anovar | P>0.05 (F = 1.26 with 2 and 6 degrees of freedom) |
| | (j) between means of Ca total content | one way anovar | P>0.05 (F = 0.55 with 2 and 6 degrees of freedom) |
| | (k) between means of Mg total content | one way anovar | P>0.05 (F = 0.32 with 2 and 6 degrees of freedom) |
| | (l) between means of ash total content | one way anovar | P>0.05 (F = 0.51 with 2 and 6 degreees of freedom) |
| Table 3.4 page 36 | (a) between means of N total content | one way anovar | P⩽0.01 (F = 5.57 with 5 and 11 degrees of freedom) |
| | (b) between means of P total content | one way anovar | P⩽0.05 (F = 4.79 with 5 and 11 degrees of freedom) |
| | (c) between means of K total content | one way anovar | P⩽0.01 (F = 7.42 with 5 and 11 degrees of freedom) |
| | (d) between means of Ca total content | one way anovar | P⩽0.05 (F = 4.14 with 5 and 11 degrees of freedom) |
| | (e) between means of Mg total content | one way anovar | P⩽0.01 (F = 6.04 with 5 and 11 degrees of freedom) |
| | (f) between means of ash total content | ome way anovar | P⩽0.01 (F = 7.91 with 5 and 11 degrees of freedom) |

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| Figure 3.6 page 38 | (a) between means of soluble carbohydrate concentration | one way anovar | P≤0.001 (F = 13.97 with 5 and 11 degrees of freedom) |
| | (b) between means of starch concentration | one way anovar | P>0.05 (F = 0.35 with 5 and 11 degress of freedom) |
| | (c) between means of crude fat concentration | one way anovar | P≤0.01 (F = 6.1 with 5 and 11 degrees of freedom) |
| | (d) between means of holocellulose concentration | one way anovar | P≤0.001 (F = 21.96 with 5 and 11 degrees of freedom) |
| | (e) between means of lignin concentration | one way anovar | P≤0.05 (F = 3.68 with 5 and 11 degrees of freedom) |
| Page 39 | Between means of energy content per g dry wt. of shoot and per g dry wt. of rhizome | t-test | P≤0.01 (t = 2.88 with 24 degrees of freedom) |
| Table 3.5 page [illegible] | (a) between means of soluble carbohydrate concentration | one way anovar | P≤0.05 (F = 4.42 with 2 and 6 degrees of freedom) |
| | (b) between means of starch concentration | one way anovar | P>0.05 (F = 0.33 with 2 and 6 degrees of freedom) |
| | (c) between means of crude fat concentration | one way anovar | P>0.05 (F = 0.28 with 2 and 6 degrees of freedom) |
| | (d) between means of holocellulose concentration | one way anovar | P≤0.05 (F = 5.38 with 2 and 6 degrees of freedom) |
| | (e) between means of lignin concentration | one way anovar | P>0.05 (F = 0.0 with 2 and 6 degrees of freedom) |
| Figure 3.7 page 41 | Between means of energy content per g dry wt. of shoots | one way anovar | P>0.05 (F = 0.2 with 5 and 11 degrees of freedom) |

*Spartina*

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|---|---|---|---|
| Figure 4.2 page 45 | (a) between means of *Spartina* standing crop | one way anovar | $P \leq 0.001$ ($F = 19.1$ with 10 and 44 degrees of freedom) |
| | (b) between means of standing crop of associated species | one way anovar | $P > 0.05$ ($F = 0.95$ with 5 and 24 degrees of freedom) |
| Page 46 | Between means of fresh wt./dry wt. ratios | one way anovar | $P \leq 0.001$ ($F = 196.29$ with 3 and 16 degrees of freedom) |
| Table 4.1 page 47 | Between means of re-growth | one way anovar | $P \leq 0.001$ ($F = 16.26$ with 4 and 20 degrees of freedom) |
| Figure 4.3 page 48 | (a) between means of N concentration | one way anovar | $P \leq 0.001$ ($F = 149.86$ with 5 and 12 degrees of freedom) |
| | (b) between means of P concentration | one way anovar | $P \leq 0.001$ (F = [illegible] with 5 and 12 degrees of freedom) |
| | (c) between means of K concentration | one way anovar | $P \leq 0.001$ ($F = 48.23$ with 5 and 12 degrees of freedom) |
| | (d) between means of Ca concentration | one way anovar | $P \leq 0.01$ ($F = 5.66$ with 5 and 12 degrees of freedom) |
| | (e) between means of Mg concentration | one way anovar | $P \leq 0.001$ ($F = 10.28$ with 5 and 12 degrees of freedom) |
| | (f) between means of ash concentration | one way anovar | $P \leq 0.01$ ($F = 7.78$ with 5 and 12 degrees of freedom) |
| Table 4.2 page 49 | (a) between means of N concentration | one way anovar | $P \leq 0.01$ ($F = 19.32$ with 2 and 4 degrees of freedom) |
| | (b) between means of P concentration | one way anovar | $P \leq 0.05$ ($F = 11.43$ with 2 and 4 degrees of freedom) |
| | (c) between means of K concentration | one way anovar | $P > 0.05$ ($F = 1.59$ with 2 and 4 degrees of freedom |

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| | (d) between means of Ca concentration | one way anovar | P>0.05 (F = 4.45 with 2 and 4 degrees of freedom) |
| | (e) between means of Mg concentration | one way anovar | P≤0.05 (F = 15.82 with 2 and 4 degrees of freedom) |
| | (f) between means of ash concentration | one way anovar | P>0.05 (F = 2.0 with 2 and 4 degrees of freedom) |
| | (g) between means of N total content | one way anovar | P≤0.01 (F = 28.82 with 2 and 4 degrees of freedom) |
| | (h) between means of P total content | one way anovar | P≤0.01 (F = 46.05 with 2 and 4 degrees of freedom) |
| | (i) between means of K total content | one way anovar | P≤0.01 (F = 39.03 with 2 and 4 degrees of freedom) |
| | (j) between means of Ca total content | one way anovar | P>0.05 (F = 8.55 with 2 and 4 degrees of freedom) |
| | (k) between means of Mg total content | one way anovar | P≤0.01 (F = 33.77 with 2 and 4 degrees of freedom) |
| | (l) between means of ash total content | one way anovar | P≤0.05 (F = 8.62 with 2 and 4 degrees of freedom) |
| Table 4.3 page 51 | (a) between means of N total content | one way anovar | P≤0.001 (F = 16.3 with 6 and 14 degrees of freedom) |
| | (b) between means of P total content | one way anovar | P≤0.001 (F = 14.68 with 6 and 14 degrees of freedom) |
| | (c) between means of K total content | one way anovar | P≤0.001 (F = 18.3 with 6 and 14 degrees of freedom) |
| | (d) between means of Ca total content | one way anovar | P≤0.001 (F = 15.31 with 6 and 14 degrees of freedom) |
| | (e) between means of Mg total content | one way anovar | P≤0.001 (F = 19.13 with 6 and 14 degrees of freedom) |
| | (f) between means of ash total content | one way anovar | P≤0.001 (F = 17.03 with 5 and 12 degrees of freedom) |

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|---|---|---|---|
| **Figure 4.5 page 53** | (a) between means of soluble carbohydrate concentration | one way anovar | P≤0.05 (F = 5.0 with 5 and 12 degrees of freedom) |
| | (b) between means of starch concentration | one way anovar | P>0.05 (F = 2.18 with 5 and 12 degrees of freedom) |
| | (c) between means of crude fat concentration | one way anovar | P≤0.001 (F = 22.45 with 5 and 12 degrees of freedom) |
| | (d) between means of holocellulose concentration | one way anovar | P≤0.01 (F = 6.85 with 5 and 12 degrees of freedom) |
| | (e) between means of lignin concentration | one way anovar | P≤0.05 (F = 3.48 with 5 and 12 degrees of freedom) |
| **Page 54** | Between means of energy content per g dry wt. of shoot and per g dry wt. of rhizome | t-test | P>0.05 (t = 0.29 with 23 degrees of freedom) |
| **Table 4.4 page 55** | (a) between means of soluble carbohydrate concentration | one way anovar | P>0.05 (F = 4.77 with 2 and 4 degrees of freedom) |
| | (b) between means of starch concentration | one way anovar | P>0.05 (F = 0.13 with 2 and 4 degrees of freedom) |
| | (c) between means of crude fat concentration | one way anovar | P≤0.001 (F = 69.54 with 2 and 4 degrees of freedom) |
| | (d) between means of holocellulose concentration | one way anovar | P>0.05 (F = 2.25 with 2 and 4 degrees of freedom) |
| | (e) between means of lignin concentration | one way anovar | P≤0.05 (F = 12.56 with 2 and 4 degrees of freedom) |
| **Figure 4.6 page 56** | Between means of energy content per g dry wt. of shoot material over season | one way anovar | P≤0.001 (F = 15.92 with 5 and 12 degrees of freedom) |

*Polygonum*

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|---|---|---|---|---|
| Figure 5.2 page 60 | (a) | between means of no. of stems $m^{-2}$ at Queen's Park Cemetery site | one way anovar | $P \leq 0.01$ ($F = 5.16$ with 6 and 24 degrees of freedom) |
| | (b) | between means of no. of stems $m^{-2}$ at Kents Bank site | one way anovar | $P \leq 0.01$ ($F = 4.2$ with 5 and 24 degrees of freedom) |
| | (c) | between means of no. of leaves per stem at Queen's Park Cemetery site | one way anovar | $P \leq 0.001$ ($F = 54.43$ with 3 and 177 degrees of freedom) |
| | (d) | between means of no. of leaves per stem at Kents Bank site | one way anovar | $P > 0.05$ ($F = 0.47$ with 2 and 26 degrees of freedom) |
| | (e) | between means of area per leaf at Queen's Park Cemetery site | one way anovar | $P \leq 0.001$ ($F = 355.9$ with 6 and 965 degrees of freedom) |
| | (f) | between means of area per leaf at Kents Bank site | one way anovar | $P \leq 0.001$ ($F = 67.65$ with 5 and 507 degrees of freedom) |
| Page 61 | (a) | between means of rhizome standing crop at Queen's Park Cemetery site | t-test | $P > 0.05$ ($t = 1.94$ with 13 degrees of freedom) |
| | (b) | between means of rhizome standing crop at Kents Bank site | one way anovar | $P > 0.05$ ($F = 0.39$ with 2 and 12 degrees of freedom) |
| Figure 5.3 page 63 | (a) | between means of standing crop of *Polygonum* at Queen's Park Cemetery site | one way anovar | $P \leq 0.001$ ($F = 23.11$ with 8 and 46 degrees of freedom) |
| | (b) | between means of standing crop of *Polygonum* at Kents Bank site | one way anovar | $P > 0.05$ ($F = 0.88$ with 6 and 28 degrees of freedom) |
| | (c) | between means of standing crop of species associated at Kents Bank site | one way anovar | $P > 0.05$ ($F = 1.89$ with 6 and 28 degrees of freedom) |

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|---|---|---|---|
| Table 5.2 page 64 | (a) between means of fresh wt./ dry wt. ratios at Kents Bank site | one way anovar | $P>0.05$ ($F = 0.8$ with 3 and 11 degrees of freedom) |
| | (b) between means of fresh wt./ dry wt. ratios at Queen's Park Cemetery site | t-test | $P>0.05$ ($t = 0.87$ with 5 degrees of freedom) |
| Table 5.3 page 66 | (a) between means of re-growth at Queen's Park Cemetery site | one way anovar | $P\leq 0.001$ ($F = 10.23$ with 4 and 20 degrees of freedom) |
| | (b) between means of re-growth at Kents Bank site | one way anovar | $P\leq 0.01$ ($F = 6.39$ with 3 and 16 degrees of freedom) |
| Table 5.4 page 67 | Between means of rhizome standing crop at Kents Bank site | one way anovar | $P>0.05$ ($F = 2.55$ with 4 and 20 degrees of freedom) |
| Figure 5.4 page 68 | (a) between means of N concentration | one way anovar | $P\leq 0.001$ ($F = 263.79$ with 4 and 10 degrees of freedom) |
| | (b) between means of P concentration | one way anovar | $P\leq 0.001$ ($F = 169.9$ with 4 and 10 degrees of freedom) |
| | (c) between means of K concentration | one way anovar | $P\leq 0.001$ ($F = 48.6$ with 4 and 10 degrees of freedom) |
| | (d) between means of Ca concentration | one way anovar | $P\leq 0.001$ ($F = 27.58$ with 4 and 10 degrees of freedom) |
| | (e) between means of Mg concentration | one way anovar | $P\leq 0.001$ ($F = 23.72$ with 4 and 10 degrees of freedom) |
| | (f) between means of ash concentration | one way anovar | $P\leq 0.001$ ($F = 17.79$ with 4 and degrees of freedom |

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| Table 5.5 page 69 | (a) | between means of N concentration | one way anovar | P>0.05 (F = 0.93 with 4 and 10 degrees of freedom) |
| | (b) | between means of P concentration | one way anovar | P>0.05 (F = 1.07 with 4 and 10 degrees of freedom) |
| | (c) | between means of K concentration | one way anovar | P>0.05 (F = 3.4 with 4 and 10 degrees of freedom) |
| | (d) | between means of Ca concentration | one way anovar | P≤0.01 (F = 21.24 with 4 and 10 degrees of freedom) |
| | (e) | between means of Mg concentration | one way anovar | P>0.05 (F = 1.13 with 4 and 10 degrees of freedom) |
| | (f) | between means of ash concentration | one way anovar | P>0.05 (F = [illegible] with 4 and 10 degrees of freedom) |
| | (g) | between means of N total content | one way anovar | P>0.05 (F = 1.38 with 4 and 10 degrees of freedom) |
| | (h) | between means of P total content | one way anovar | P>0.05 (F = 1.16 with 4 and 10 degrees of freedom) |
| | (i) | between means of K total content | one way anovar | P>0.05 (F = 1.28 with 4 and 10 degrees of freedom) |
| | (j) | between means of Ca total content | one way anovar | P>0.05 (F = 0.92 with 4 and 10 degrees of freedom) |
| | (k) | between means of Mg total content | one way anovar | P>0.05 (F = 1.12 with 4 and 10 degrees of freedom) |
| | (l) | between means of ash total content | one way anovar | P>0.05 (F = 2.04 with 4 and 10 degrees of freedom) |
| Table 5.6 page 70 | (a) | between means of N total content | one way anovar | P>0.05 (F = 2.69 with 4 and 10 degrees of freedom) |
| | (b) | between means of P total content | one way anovar | P>0.05 (F = 2.37 with 4 and 10 degrees of freedom) |
| | (c) | between means of K total content | one way anovar | P>0.05 (F = 3.3 with 4 and 10 degrees of freedom) |

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|---|---|---|---|
| | (d) between means of Ca total content | one way anovar | P≤0.05 (F = 4.14 with 4 and 10 degrees of freedom) |
| | (e) between means of Mg total content | one way anovar | P≤0.05 (F = 3.53 with 4 and 10 degrees of freedom) |
| | (f) between means of ash total content | one way anovar | P>0.05 (F = 1.92 with 4 and 10 degrees of freedom) |
| Figure 5.6 page 73 | (a) between means of soluble carbohydrate concentration | one way anovar | P≤0.001 (F = 33.73 with 4 and 10 degrees of freedom) |
| | (b) between means of starch concentration | one way anovar | P≤0.01 (F = 8.46 with 4 and 10 degrees of freedom) |
| | (c) between means of crude fat concentration | one way anovar | P≤0.001 (F = 88.21 with 4 and 10 degrees of freedom) |
| | (d) between means of holocellulose concentration | one way anovar | P≤0.001 (F = 310.98 with 4 and 10 degrees of freedom) |
| | (e) between means of lignin concentration | one way anovar | P≤0.01 (F = 6.16 with 4 and 10 degrees of freedom) |
| Table 5.7 page 74 | (a) between means of soluble carbohydrate concentration | one way anovar | P≤0.05 (F = 3.49 with 4 and 10 degrees of freedom) |
| | (b) between means of starch concentration | one way anovar | P>0.05 (F = 1.87 with 4 and 10 degrees of freedom) |
| | (c) between means of crude fat concentration | one way anovar | P>0.05 (F = 2.97 with 4 and 10 degrees of freedom) |
| | (d) between means of holocellulose concentration | one way anovar | P>0.05 (F = 0.58 with 4 and 10 degrees of freedom) |
| | (e) between means of lignin concentration | one way anovar | P>0.05 (F = 0.72 with 4 and 10 degrees of freedom) |
| Page 75 | Between means of energy content per g dry wt. of shoot and per g dry wt. of rhizome | t-test | P≤0.01 (t = 3.34 with 28 degrees of freedom) |

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|---|---|---|---|
| Figure 5.7 page 76 | Between means of energy content per g of shoot material over season | one way anovar | P≤0.01 (F = 7.44 with 4 and 10 degrees of freedom) |
| | *Impatiens* | | |
| Figure 6.2 page 80 | Between means of standing crop | one way anovar | P≤0.05 (F = 3.43 with 4 and 20 degrees of freedom) |
| Figure 6.3 page 82 | (a) between means of N concentration | one way anovar | P≤0.01 (F = 8.13 with 3 and 8 degrees of freedom) |
| | (b) between means of P concentration | one way anovar | P≤0.001 (F = 19.91 with 3 and 8 degrees of freedom) |
| | (c) between means of K concentration | one way anovar | P>0.05 (F = 3.05 with 3 and 8 degrees of freedom) |
| | (d) between means of Ca concentration | one way anovar | P≤0.05 (F = 5.9 with 3 and 8 degrees of freedom) |
| | (e) between means of Mg concentration | one way anovar | P≤0.01 (F = 11.95 with 3 and 8 degrees of freedom) |
| | (f) between means of ash concentration | one way anovar | P>0.05 (F = 3.91 with 3 and 8 degrees of freedom) |
| Table 6.2 page 84 | (a) between means of N total content | one way anovar | P≤0.01 (F = 12.56 with 3 and 8 degrees of freedom) |
| | (b) between means of P total content | one way anovar | P≤0.01 (F = 15.19 with 3 and 8 degrees of freedom) |
| | (c) between means of K total content | one way anovar | P≤0.01 (F = 8.23 with 3 and 8 degrees of freedom) |
| | (d) between means of Ca total content | one way anovar | P≤0.05 (F = 7.3 with 3 and 8 degrees of freedom) |
| | (e) between means of Mg total content | one way anovar | P≤0.05 (F = 6.48 with 3 and 8 degrees of freedom) |
| | (f) between means of ash total content | one way anovar | P>0.05 (F = 1.72 with 3 and 8 degrees of freedom) |

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|---|---|---|---|
| Page 86 | Between means of energy content per g dry wt. of shoots and per g dry wt. of rhizome | t-test | $P>0.05$ ($t = 0.59$ with 13 degrees of freedom) |
| Figure 6.5 page 87 | (a) between means of soluble carbohydrate concentration | one way anovar | $P \leq 0.05$ ($F = 4.87$ with 3 and 8 degrees of freedom) |
| | (b) between means of starch concentration | one way anovar | $P \leq 0.05$ ($F = 7.39$ with 3 and 8 degrees of freedom) |
| | (c) between means of crude fat concentration | one way anovar | $P \leq 0.001$ ($F = 17.04$ with 3 and 8 degrees of freedom) |
| | (d) between means of holocellulose concentration | one way anovar | $P \leq 0.01$ ($F = 11.62$ with 3 and 8 degrees of freedom) |
| | (e) between means of lignin concentration | one way anovar | $P>0.05$ ($F = 3.59$ with 3 and 8 degrees of freedom) |
| Figure 6.6 page 89 | Between means of energy content per g dry wt. of shoot | one way anovar | $P>0.05$ ($F = 3.55$ with 3 and 8 degrees of freedom) |

*Filipendula*

| | | | |
|---|---|---|---|
| Page 91 | Between means of standing crop of rhizomes | t-test | $P>0.05$ ($t = 0.53$ with 8 degrees of freedom) |
| Page 91 | Between means of fresh wt./dry wt. ratios | one way anovar | $P \leq 0.001$ ($F = 16.34$ with 2 and 11 degrees of freedom) |
| Figure 7.2 page 93 | Between means of standing crop of *Filipendula* | one way anovar | $P \leq 0.001$ ($F = 8.19$ with 7 and 32 degrees of freedom) |
| | Between means of standing crop of other species | one way anovar | $P \leq 0.001$ ($F = 5.32$ with 7 and 32 degrees of freedom) |

Table 7.1 page 95

| | | | |
|---|---|---|---|
| (a) | between means of N concentration in above ground b. | t-test | $P \leq 0.001$ ($t = 13.39$ with 3 degrees of freedom) |
| (b) | between means of P concentration in above ground b. | t-test | $P \leq 0.01$ ($t = 7.99$ with 3 degrees of freedom) |
| (c) | between means of K concentration in above ground b. | t-test | $P \leq 0.001$ ($t = 14.98$ with 3 degrees of freedom) |
| (d) | between means of Ca concentration in above ground b. | t-test | $P \leq 0.05$ ($t = 3.81$ with 3 degrees of freedom) |
| (e) | between means of Mg concentration in above ground b. | t-test | $P \leq 0.01$ ($t = 12.58$ with 3 degrees of freedom) |
| (f) | between means of ash concentration in above ground b. | t-test | $P \leq 0.01$ ($t = 5.84$ with 3 degrees of freedom) |
| (g) | between means of N content in above ground biomass | t-test | $P \leq 0.001$ ($t = 25.63$ with 3 degrees of freedom) |
| (h) | between means of P content in above ground biomass | t-test | $P \leq 0.001$ ($t = 35.61$ with 3 degrees of freedom) |
| (i) | between means of K content in above ground biomass | t-test | $P \leq 0.001$ ($t = 93.22$ with 3 degrees of freedom) |
| (j) | between means of Ca content in above ground biomass | t-test | $P \leq 0.01$ ($t = 6.34$ with 3 degrees of freedom) |
| (k) | between means of Mg content in above ground biomass | t-test | $P \leq 0.001$ ($t = 24.92$ with 3 degrees of freedom) |
| (l) | between means of ash content in above ground biomass | t-test | $P \leq 0.001$ ($t = 24.35$ with 3 degrees of freedom) |
| (m) | between means of N concentration in below ground b. | t-test | $P > 0.05$ ($t = 1.67$ with 4 degrees of freedom) |
| (n) | between means of P concentration in below ground b. | t-test | $P > 0.05$ ($t = 0.92$ with 4 degrees of freedom) |
| (o) | between means of K concentration in below ground b. | t-test | $P > 0.05$ ($t = 1.53$ with 4 degrees of freedom) |

| | | | |
|---|---|---|---|
| | (p) between means of Ca concentration in below ground b. | t-test | P>0.05 (t = 0.79 with 4 degrees of freedom) |
| | (q) between means of Mg concentration in below ground b. | t-test | P>0.05 (t = 0.0 with 4 degrees of freedom) |
| | (r) between means of ash concentration in below ground b. | t-test | P>0.05 (t = 0.17 with 4 degrees of freedom) |
| | (s) between means of N content in below ground biomass | t-test | P>0.05 (t = 0.51 with 4 degrees of freedom) |
| | (t) between means of P content in below ground biomass | t-test | P>0.05 (t = 0.06 with 4 degrees of freedom) |
| | (u) between means of K content in below ground biomass | t-test | P>0.05 (t = 1.14 with 4 degrees of freedom) |
| | (v) between means of Ca content in below ground biomass | t-test | P>0.05 (t = 0.06 with 4 degrees of freedom) |
| | (w) between means of Mg content in below ground biomass | t-test | P>0.05 (t = 0.27 with 4 degrees of freedom) |
| | (x) between means of ash content in below ground biomass | t-test | P>0.05 (t = 0.21 with 4 degrees of freedom) |
| Table 7.2 page 96 | (a) between means of soluble carbohydrate concentration in above ground biomass | t-test | P≤0.001 (t = 11.66 with 3 degrees of freedom) |
| | (b) between means of starch concentration in above ground b. | t-test | P≤0.001 (t = 10.52 with 3 degrees of freedom) |
| | (c) between means of crude fat concentration in above ground b. | t-test | P≤0.01 (t = 12.17 with 3 degrees of freedom) |
| | (d) between means of lignin concentration in above ground b. | t-test | P>0.05 (t = 3.0 with 3 degrees of freedom) |
| | (e) between means of holocellulose concentration in above ground b. | t-test | P≤0.01 (t = 7.5 with 3 degrees of freedom) |

| | | | |
|---|---|---|---|
| | (f) between means of energy content in above ground b. | t-test | $P>0.05$ ($t = 0$ with 3 degrees of freedom) |
| | (g) between means of soluble carbohydrate concentration in below ground biomass | t-test | $P\leq0.001$ ($t = 8.85$ with 4 degrees of freedom) |
| | (h) between means of starch concentration in below ground b. | t-test | $P\leq0.001$ ($t = 22.14$ with 4 degrees of freedom) |
| | (i) between means of crude fat concentration in below ground b. | t-test | $P>0.05$ ($t = 0.22$ with 4 degrees of freedom) |
| | (j) between means of lignin concentration in below ground b. | t-test | $P>0.05$ ($t = 2.75$ with 4 degrees of freedom) |
| | (k) between means of holocellulose concentrations in below ground b. | t-test | $P>0.05$ ($t = 1.01$ with 4 degrees of freedom) |
| | (l) between means of energy content in below ground biomass | t-test | $P>0.05$ ($t = 2.12$ with 4 degrees of freedom) |
| | *Chamaenerion* | | |
| Figure 8.2 page 100 | Between means of standing crop of *Chamaenerion* | one way anovar | $P\leq0.001$ ($F = 37.22$ with 4 and 20 degrees of freedom) |
| | Between means of standing crop of associated species | one way anovar | $P\leq0.01$ ($F = 8.96$ with 3 and 16 degrees of freedom) |
| Table 8.1 page 101 | Between means of fresh wt./dry wt. ratios | one way anovar | $P\leq0.001$ ($F = 48.13$ with 5 and 24 degrees of freedom) |

| | *Epilobium* | | |
|---|---|---|---|
| Page 105 | Between means of rhizome standing crop | t-test | P>0.05 (t = 1.95 with 8 degrees of freedom) |
| | Between means of fresh wt./dry wt. ratios | t-test | P≤0.001 (t = 15.02 with 8 degrees of freedom) |
| Figure 9.2 page 107 | (a) between means of *Epilobium* standing crop | one way anovar | P≤0.01 (F = 4.98 with 6 and 28 degrees of freedom) |
| | (b) between means of standing crop of associated species | one way anovar | P≤0.01 (F = 16.88 with 6 and 28 degrees of freedom) |
| Table 9.2 page 110 | (a) between means of N concentration in above ground b. | t-test | P>0.05 (t = 0.18 with 4 degrees of freedom) |
| | (b) between means of P concentration in above ground b. | t-test | P>0.05 (t = 1.11 with 4 degrees of freedom) |
| | (c) between means of K concentration in above ground b. | t-test | P≤0.01 (t = 8.33 with 4 degrees of freedom) |
| | (d) between means of Ca concentration in above ground b. | t-test | P>0.05 (t = 1.99 with 4 degrees of freedom) |
| | (e) between means of Mg concentration in above ground b. | t-test | P≤0.05 (t = 3.06 with 4 degrees of freedom) |
| | (f) between means of ash concentration in above ground b. | t-test | P≤0.01 (t = 6.69 with 4 degrees of freedom) |
| | (g) between means of N content in above ground biomass | t-test | P>0.05 (t = 1.3 with 4 degrees of freedom) |
| | (h) between means of P content in above ground biomass | t-test | P>0.05 (t = 1.46 with 4 degrees of freedom) |
| | (i) between means of K content in above ground biomass | t-test | P≤0.05 (t = 2.97 with 4 degrees of freedom) |
| | (j) between means of Ca content in above ground biomass | t-test | P>0.05 (t = 1.74 with 4 degrees of freedom) |
| | (k) between means of Mg content in above ground biomass | t-test | P>0.05 (t = 2.66 with 4 degrees of freedom) |

| | | | |
|---|---|---|---|
| (l) | between means of ash content in above ground biomass | t-test | $P>0.05$ ($t = 0.87$ with 4 degrees of freedom) |
| (m) | between means of N concentration in below ground b. | t-test | $P>0.05$ ($t = 0.59$ with 4 degrees of freedom) |
| (n) | between means of P concentration in below ground b. | t-test | $P\leq0.05$ ($t = 4.16$ with 4 degrees of freedom) |
| (o) | between means of K concentration in below ground b. | t-test | $P\leq0.01$ ($t = 6.13$ with 4 degrees of freedom) |
| (p) | between means of Ca concentration in below ground b. | t-test | $P\leq0.05$ ($t = 4.06$ with 4 degrees of freedom) |
| (q) | between means of Mg concentration in below ground b. | t-test | $P\leq0.05$ ($t = 4.53$ with 4 degrees of freedom) |
| (r) | between means of ash concentration in below ground b. | t-test | $P\leq0.05$ ($t = 3.35$ with 4 degrees of freedom) |
| (s) | between means of N content in below ground biomass | t-test | $P\leq0.05$ ($t = 3.03$ with 4 degrees of freedom) |
| (t) | between means of P content in below ground biomass | t-test | $P>0.05$ ($t = 2.62$ with 4 degrees of freedom) |
| (u) | between means of K content in below ground biomass | t-test | $P>0.05$ ($t = 1.91$ with 4 degrees of freedom) |
| (v) | between means of Ca content in below ground biomass | t-test | $P>0.05$ ($t = 1.37$ with 4 degrees of freedom) |
| (w) | between means of Mg content in below ground biomass | t-test | $P>0.05$ ($t = 1.94$ with 4 degrees of freedom) |
| (x) | between means of ash content in below ground biomass | t-test | $P>0.05$ ($t = 1.31$ with 4 degrees of freedom) |

Table 9.3 page 111

| | | | |
|---|---|---|---|
| (a) | between means of soluble carbohydrate concentration in above ground biomass | t-test | P>0.05 (t = 1.63 with 4 degrees of freedom) |
| (b) | between means of starch concentration in above ground b. | t-test | P>0.05 (t = 1.82 with 4 degrees of freedom) |
| (c) | between means of crude fat concentration in above ground b. | t-test | P>0.05 (t = [illegible] with 4 degrees of freedom) |
| (d) | between means of lignin concentration in above ground b. | t-test | P>0.05 (t = 1.78 with 4 degrees of freedom) |
| (e) | between means of holocellulose concentration in above ground b. | t-test | P≤0.05 (t = 2.8 with 4 degrees of freedom) |
| (f) | between means of energy content in above ground biomass | t-test | P>0.05 (t = 0.91 with 4 degrees of freedom) |
| (g) | between means of soluble carbohydrate concentration in below ground biomass | t-test | P≤0.05 (t = 3.45 with 4 degrees of freedom) |
| (h) | between means of starch concentration in below ground b. | t-test | P≤0.01 (t = 8.03 with 4 degrees of freedom) |
| (i) | between means of crude fat concentration in below ground b. | t-test | P>0.05 (t = 0.68 with 4 degrees of freedom) |
| (j) | between mean of lignin concentration in below ground b. | t-test | P>0.05 (t = 0.94 with 4 degrees of freedom) |
| (k) | between means of holocellulose concentration in below ground b. | t-test | P>0.05 (t = 1.09 with 4 degrees of freedom) |
| (l) | between means of energy content in below ground biomass | t-test | P≤0.05 (t = 3.0 with 4 degrees of freedom) |

*Urtica*

| | | | |
|---|---|---|---|
| Page 113 | Between means of standing crop of rhizomes | t-test | P>0.05 (t = 0.68 with 8 degrees of freedom) |
| | Between means of fresh wt./dry wt. ratios | one way anovar | P≤0.001 (F = 58.61 with 2 and 12 degrees of freedom) |
| Figure 10.2 page 115 | Between means of standing crop of *Urtica* | one way anovar | P≤0.001 (F = 15.2 with 6 and 28 degrees of freedom) |
| | Between means of standing crop of associated species | one way anovar | P>0.05 (F = 2.61 with 4 and 20 degrees of freedom) |
| Table 10.1 page 116 | (a) between means of N concentration | t-test | P≤0.05 (t = 3.89 with 4 degrees of freedom) |
| | (b) between means of P concentration | t-test | P>0.05 (t = 0.6 with 4 degrees of freedom) |
| | (c) between means of K concentration | t-test | P>0.05 (t = 0.46 with 4 degrees of freedom) |
| | (d) between means of Ca concentration | t-test | P≤0.05 (t = 3.1 with 4 degrees of freedom) |
| | (e) between means of Mg concentration | t-test | P>0.05 (t = 0.97 with 4 degrees of freedom) |
| | (f) between means of ash concentration | t-test | P>0.05 (t = 2.16 with 4 degrees of freedom) |
| | (g) between means of N content | t-test | P≤0.01 (t = 6.71 with 4 degrees of freedom) |
| | (h) between means of P content | t-test | P≤0.01 (t = 4.89 with 4 degrees of freedom) |
| | (i) between means of K content | t-test | P≤0.05 (t = 3.71 with 4 degrees of freedom) |

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|---|---|---|---|
| | (j) between means of Ca content | t-test | P≤0.01 (t = 4.87 with 4 degrees of freedom) |
| | (k) between means of Mg content | t-test | P≤0.01 (t = 6.13 with 4 degrees of freedom) |
| | (l) between means of ash content | t-test | P≤0.01 (t = 5.62 with 4 degrees of freedom) |
| Table 10.2 page 118 | (a) between means of soluble carbohydrate concentration | t-test | P≤0.001 (t = 11.65 with 4 degrees of freedom) |
| | (b) between means of starch concentration | t-test | P≤0.05 (t = 4.43 with 4 degrees of freedom) |
| | (c) between means of crude fat concentration | t-test | P≤0.01 (t = 6.97 with 4 degrees of freedom) |
| | (d) between means of lignin concentration | t-test | P≤0.05 (t = 3.02 with 4 degrees of freedom) |
| | (e) between means of holocellulose concentration | t-test | P≤0.05 (t = 4.28 with 4 degrees of freedom) |
| | (f) between means of energy content | t-test | P>0.05 (t = 0.91 with 4 degrees of freedom) |
| Figure 12.1 page 123 | Between means of no. of stems per plant of Japanese knotweed in 1979 | one way anovar | P≤0.001 (F = 13.04 with 6 and 189 degrees of freedom) |
| | Between means of no. of stems per plant of Japanese knotweed in 1980 | one way anovar | P>0.05 (F = 0.26 with 3 and 108 degrees of freedom) |
| | Between means of ht. of tallest stems of Japanese knotweed plants in 1979 | one way anovar | P≤0.001 (F = 31.33 with 7 and 216 degrees of freedom) |
| | Between means of ht. of tallest stems of Japanese knotweed plants in 1980 | one way anovar | P≤ 0.001 (F = 22.1 with 3 and 108 degrees of freedom) |

| | | | |
|---|---|---|---|
| Figure 12.2 page 125 | Between means of ht. of tallest leaf of each plant of giant hogweed in 1979 | one way anovar | P≤0.001 (F = 14.67 with 5 and 71 degrees of freedom) |
| | Between means of ht. of tallest leaf of each plant of giant hogweed in 1980 | one way anovar | P≤0.05 (F = 5.18 with 2 and 18 degrees of freedom) |
| | Between means of no. of leaves per plant of giant hogweed in 1979 | one way anovar | P≤0.001 (F = 36.56 with 4 and 62 degrees of freedom) |
| | Between means of no. of leaves per plant of giant hogweed in 1980 | one way anovar | P≤0.05 (F = 5.8 with 2 and 18 degrees of freedom) |
| Table 12.1 page 126 | Between means of no. of leaves per plant of *Gunnera manicata* | one way anovar | P≤0.01 (F = 8.9 with 2 and 28 degrees of freedom) |
| | Between means of ht. of largest leaves per plant of *Gunnera manicata* | one way anovar | P≤0.001 (F = 14.57 with 2 and 28 degrees of freedom) |

## PPENDIX IV - SOIL ANALYSES

he results of soil analyses on the top 5 cm of soil (core diameter = 11.3 cm) from the study sites. he means of 3 replicates plus and minus one standard error are presented.

| PECIES | SITE | DATE | pH | Loss on ignition (%) | Extractable (mg $100^{-1}$ g) K | Ca | Mg | P | Total (%) N |
|---|---|---|---|---|---|---|---|---|---|
| racken | Lowick Common | 21.1.80 | 4.0 ± 0.06 | 30 ± 2.9 | 28 ± 5.8 | 27 ± 8.7 | 10 ± 2.1 | 0.28 ± 0.55 | 1.3 ± 0.08 |
| .tterbur | Chisworth | 18.1.80 | 6.6 ± 0.19 | 15 ± 4.2 | 21 ± [illegible] | 213 ± 64 | 34 ± 5.9 | 1.7 ± 1.02 | 0.64 ± 0.17 |
| ord-grass | Rampside | 21.1.80 | 8.1 ± 0.09 | 6.[illegible] ± 0.31 | 58 ± [illegible] | 2367 ± 120 | 98 ± 1.7 | 3.4 ± 0.17 | 0.22 ± 0.006 |
| apanese knotweed | Kents Bank | 23.1.80 | 7.5 ± 0.07 | 14 ± 2.3 | 14 ± [illegible] | 6300 ± 1026 | 37 ± 3.5 | 8.7 ± 1.79 | 0.37 ± 0.21 |
| apanese knotweed | Queen's Park Cemetery | 18.1.80 | 5.9 ± 0.35 | 12 ± 0.0 | 13 ± [illegible] | 110 ± 20 | 26 ± 3.1 | 4.8 ± 0.95 | 0.32 ± 0.025 |
| Policeman's helmet | Chorlton Brook | 18.1.80 | 6.4 ± 0.03 | 19 ± 2.0 | 17 ± [illegible] | 207 ± 3.3 | 30 ± 1.5 | 8.9 ± 0.42 | 0.75 ± 0.017 |
| Great hairy willow-herb | Chisworth | 18.1.80 | 6.3 ± 0.10 | 27 ± 0.5 | 33 ± [illegible] | 245 ± 15 | 42 ± 10 | 0.73 ± 0.01 | 1.17 ± 0.15 |
| Stinging nettle | Chisworth | 18.1.80 | 6.6 ± 0.05 | 25 ± 0.0 | 21 ± [illegible] | 145 ± 15 | 17 ± 2.0 | 5.8 ± 1.85 | 0.89 ± 0.03 |

APPENDIX V - Fertilizer use on farm crops in England and Wales

Note: The following values are taken from Church (1975) - Survey of fertilizer practice: fertilizer use on farm crops in England and Wales, 1974; MAFF SS/SAF/14. Throughout the text of the report, amounts of nutrients needed to replace nutrients removed from site in harvested biomass are compared with the current and traditional fertilizer applications listed below.

| Crop | Fertilizer applications | | | | | |
|---|---|---|---|---|---|---|
| | lb $acre^{-1}$ | | | kg $ha^{-1}$ | | |
| | N | $P_2O_5$ | $K_2O$ | N | P | K |
| maincrop potatoes | 141 | 148 | 196 | 158 | 72 | 183 |
| sugar beet | 118 | 78 | 146 | 132 | [illegible] | 136 |
| maize | 99 | 61 | 60 | 111 | 30 | 56 |
| spring wheat | 58 | 35 | 35 | 65 | 17 | 32 |
| brussel sprouts | 184 | 100 | 158 | 206 | 49 | 147 |
| 2 - 7 year leys | 122 | 45 | 38 | 137 | 22 | 36 |
| permanent grass | 86 | 42 | 31 | 96 | 21 | 29 |