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energy

AN EXPERIMENTAL ASSESSMENT OF NATIVE AND NATURALIZED SPECIES OF PLANTS AS RENEWABLE SOURCES OF ENERGY IN GREAT-BRITAIN

Report

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ABSTRACT

Natural vegetation could be used as a renewable source of energy where it is particularly extensive or productive. Experiments have been established to investigate the effects of weather, time of harvesting, frequency of harvesting and addition of fertilisers on the yields of natural vegetation.

If methanol could be produced from Pteridium yielding 8 t $ha^{-1} yr^{-1}$ with an efficiency of 50%, the equivalent of the energy in 25% of all the petrol and petroleum product deliveries in Scotland would be contained in Scotland's Pteridium resource. Farms in northern Britain could be self sufficient for energy by using natural biofuels and could market surplus requirements to generate a new source of income.

Further research is required to develop optimum crop management practices and to demonstrate and cost the suitable agricultural and conversion equipment required to produce biofuels.

The scheme developed to obtain solid biofuels from autumn biomass can be applied to many perennial species which naturally cover large areas of the EEC.

CONTENTS | Page

PART I : Bracken - *Pteridium aquilinum*

C O N T E N T S

SUMMARY

1. Bracken occupies an estimated 3 200 km^2 in Great Britain, approximately 1.5% of the land area, and its extent will probably increase. The species tends to occur on rough unutilized ground where it is often totally dominant and would provide a uniform crop.

2. Peak above ground standing crop is in late July, and in several sites there was a high mean value of 10 dry t ha^{-1}. In autumn, the dead biomass had a mean yield of 7 t ha^{-1}.

3. Our results have shown significant yearly variation which must be attributed to differences in weather. Fertilizer applications did not increase yields, and nutrients therefore, do not appear to be limiting.

4. Bracken fronds have an energy content of 20 kJ g^{-1}, significantly higher than typical values for many other plant species, and there is negligible seasonal variation in the energy value of dry material.

5. The mineral nutrient content of fronds in summer is much greater than that in the autumn. Consequently, autumn biomass can be harvested with lower loss of nutrients to the site, the product being utilized for combustion. Addition of artificial fertilizer may be necessary with autumn harvesting, but anaerobic digestor slurry can be returned to the site if summer crops are used to produce methane.

6. Yields of 6.5-7.2 ha^{-1} yr^{-1} were maintained over 3 years in plots cut in autumn each year, although yields decreased by 30% over this period. There was a greater reduction in yield (85%) in plots where the harvest was carried out in July, though the generally poor growth in 1982 severely affected regrowth. Yields in the 4th year of harvesting (1983) recovered significantly.

7. If harvested each autumn, bracken could be maintained as an energy crop for more than 3 years but a rotation system with a rest year may be required in the long term. If harvested annually in summer, an energy crop could be obtained for about 4 years, after which the poor growth of bracken would enable seeding with grass to generate hill pasture.

8. Bracken harvested in summer readily produces biogas in an anaerobic digestor with an efficiency of conversion of 40%, but the process is uncompetitive in cost with alternative gas supplies.

9. Bracken harvested in autumn can be pelletized to densities of 760 kg m^{-3}, when it forms a versatile fuel which can be easily stored, transported and hopper fed to furnaces.

10. Solid fuel from bracken has been used successfully to run a domestic central heating system. Pellets burned directly costing £3.79 per GJ, are competitive in price with coal, whereas if they were gasified with methanol as an end product, the cost would be between that of pre- and post-tax motor spirit.

11. The environmental impacts of removing dead bracken from the land should be small, certainly when compared with the alternatives of planting grass or trees. Also, the emission of pollutants from burning bracken is likely to be considerably less than from coal.

12. The harvesting and sale of bracken by upland farmers would represent a new source of income to an highly subsidized industry, while providing an additional renewable energy resource which could be particularly important in rural and isolated areas.

RECOMMENDATIONS

1. While it has been shown that bracken can be harvested and converted to a usable fuel, the yield, distribution and harvestability of the total resource have not been assessed. Factors such as aspect, slope and geology should be related to the practicality of harvesting and extended to give a national estimate of present, and potentially harvestable, bracken land.

2. Although bracken is already harvested with conventional equipment, there are technical limits to the performance of such equipment on slopes. A systematic review is required of the range of machines available worldwide for harvesting and collection of biomass from hillsides. This review would also consider the removal of surface rocks and the provision of access routes to cropping sites.

3. Current estimates of harvesting costs are derived from contractor rates and small scale bracken control experiments, conducted 30 years ago. Extensive field trials are necessary to provide a firmer basis for estimates of farm gate prices for bracken fuel, using both standard farm machines and available specialized equipment.

4. Transport, combustion and marketability of unprocessed fuel will be aided by compaction. Further analysis and trials are required to assess the economics of transport of biofuels at different densities, and the handling characteristics and combustability of materials processed by a range of compacting equipment.

5. A multi-fuel stove has successfully run on bracken pellets, and it is predicted that small pellets would be suitable for anthracite boilers. An assessment of the market for bracken fuels is needed to discover which existing fuels bracken would compete with or supplement.

6. The systems of harvesting, storage and distribution will depend on mode of use of the product and the economic radius of operation. The different scenarios require examination in relation to technical feasibility, economics and environmental impact.

7. Yields of bracken are affected by the weather and by repeated cutting. An extended period is required in which the fluctuations of production due to climate and the effects of long term removal of biomass and nutrients can be adequately assessed. Rotation practices to allow rest periods should also be developed and tested.

8. Digestor residues from biogas production are rich in nutrients. The value of by-products of fuel production should be further investigated: savings in weed control costs may indicate positive benefits from processes which appear only marginally economic by themselves.

9. The satisfactory outcome of these recommendations would be a demonstration project, funded through official agencies, with the object of showing the economic viability of bracken-based fuel.

1 INTRODUCTION

Natural vegetation in Great Britain could be an important source of biofuels, either because it is very extensive or because it is highly productive when compared with traditional crops from agriculture and forestry (Callaghan et al. 1978 and Lawson et al. 1980). Bracken combines both features, and is both widespread and productive.

A previous report (Callaghan et al. 1978) quoted earlier estimates (Pearsall & Gorham 1956) which gave a maximum standing crop for bracken between 9.8 and 14.1 t ha^{-1}. On the basis of general review, the species showed considerable potential as a fuel resource; bracken achieves high yields on land which would otherwise only support vegetation of very low productivity. Using the ITE land classification method, national and regional estimates of extent were calculated and mapped. Detailed analysis of catchment areas for each type of conversion process were also possible. Awareness of the extent of bracken (3 200 km^2), and evidence that it was increasingly taking over grazing land, made it a clear subject for assessment as an energy crop, especially as good data on production were scarce.

In Lawson et al. (1980), the biological characteristics of species comprising natural vegetation were considered in relation to the limits to production including climate, soil type, nutrients and site management. Estimates made of costs of fuels derived from the most abundant species, bracken and heather, and the availability of equipment for harvesting indicated that the operations could be practical, economically viable and have positive energy ratios of up to 1400:1.

Consequently, bracken was one of a range of species whose standing crop was measured monthly during 1979 to provide more accurate data on yield and basic biology. Fronds and rhizomes were harvested, dried and analyzed for inorganic nutrients and organic components. The results (Callaghan et al. 1982) were the basis of predictions about the ability of bracken to withstand annual cropping.

However, nothing was known about the long term stability of areas of bracken subjected to annual harvesting and it was important to test the predictions based upon earlier work. Consequently, a 3-year experimental programme was developed to examine practices for the management of bracken for biofuel production. Large amounts of nutrients would be removed from sites by harvests at peak biomass in late summer while nutrient concentrations are high. In senescent fronds the internal concentrations are much lower so late season harvesting would remove minimal amounts of N, P and K from the site. Only if bracken control was an aim of cropping would harvesting at peak biomass be an advantage. In that case, it would be possible to allow cycles of grazing followed by energy cropping after recovery of the bracken. It was predicted that, accepting a perhaps 30% lower total dry matter yield, it should be possible to harvest dead bracken fronds during autumn without affecting yield in subsequent years.

2 BIOLOGY OF BRACKEN

2.1 Description

Bracken is a rhizomatous perennial fern with annually produced photosynthetic fronds, usually in the height range 0.3-1.8 m but occasionally 3-4 m. Establishment is by proliferation of rhizomes but sexual reproduction also occurs (Oinonen 1969). Details of the species growth and ecology are in Braid (1959) while rhizome structure has been described by Daniels (1981) and Conway and Stevens (1954).

2.2 Distribution and extent

Bracken occurs in a range of habitats throughout GB and Ireland, though it prefers well drained acid soils. Its upper altitudinal limit is 600 m, despite having a generally upland distribution. Bracken frequently dominates plant communities, forming almost pure stands. There are probably around 3 000 km^2 of bracken in Great Britain, which is equivalent to 1.5% of the land area (Callaghan et al. 1981). However, authorities differ widely over the extent of bracken (eg 6 339 km^2 - Taylor 1978, 2 300 km^2 - Taylor 1983), and satellite photography is being investigated as a means of quantifying the bracken problem in Scotland (Birnie et al. 1983).

2.3 Growth patterns

Emergence in spring is late compared with other plants, the fronds appearing in May and developing to maximum height in July. Densities of up to 60 fronds m^{-2} have been observed and fronds tend to be taller in dense stands. Sensescence is rapid in the first autumn frosts, usually in late September or early October, and the fronds remain standing until compacted by snow or rain. The presence of a loose bed of undecomposed litter has important effects on surface microclimate (Lowday 1983) and helps maintain the dominance of bracken over other species.

2.4 Yield

A range of 4.6 to 8.9 t ha^{-1} was reported by Callaghan et al. (1982) for fronds from various areas, while 12.5 t ha^{-1} was recorded for rhizomes. Fronds have a water content of 75% in summer and even higher levels during spring growth, but water content declines to 50% in dead fronds. Water content of bracken litter varies according to weather conditions in autumn as rain water is absorbed at a time when evaporation is slow.

2.5 Nutrients

From initially low levels of inorganic nutrients in spring, the peak concentration, coincides with maximum growth in June. In our previous study the maximm N, P and K content of bracken at peak biomass greatly exceeded that of the dead fronds (Figure 1). Soluble carbohydrate concentrations are also low at first, but rapidly increase. Later in the season there is a build up in cellulose and lignin concentrations as carbohydrate declines.

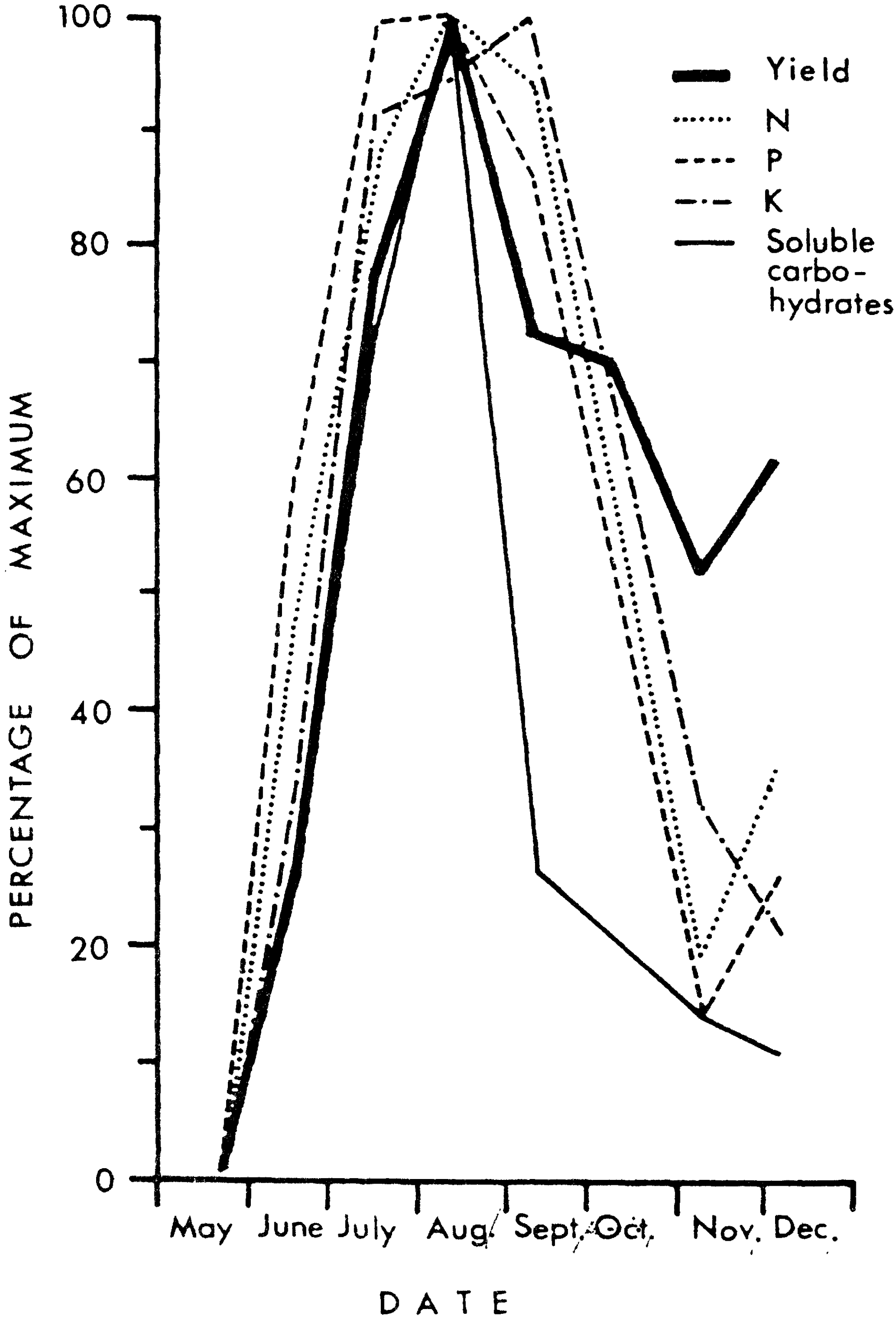


Figure 1. Seasonal pattern of yield and internal components of bracken fronds.

2.6 Energy value

Proportions of organic fractions change during frond development as noted above, but energy content varies little from 20 KJ g^{-1} during the growing season (Figure 2). Total energy content of the crop is, therefore, primarily a function of biomass. The energy content per g dry weight is, however, quite high when compared with other species which show a mean of 18.3 KJ g^{-1} dry weight (Callaghan et al. 1978).

2.7 Uses of bracken

In the past, the species was widely exploited (Rymer 1976) and its growth was valued and even encouraged. "Potash", potassium carbonate, was produced from boiled-down bracken ash and was used in glass and soap making, in dyes and for washing wool and line. Four ha of bracken could yield 1 t of ash with a K_2O content of 40%. As late as 1917, a price of £25 t^{-1} was quoted (Berry 1917) for bracken ash.

Bracken was used as fuel for brick making, baking and brewing, as well as in domestic fires. Fuel cropping was in the autumn, in contrast to potash cropping which took place during the summer and aimed at maximizing the potash content. Roofing thatch was also gathered in autumn, and bracken was rated second only to heather for its durability. It is still used as a bedding and flooring material, but now only for animals. Bracken litter mixed with animal dung is richer than manure containing straw, and composted bracken is highly recommended for potatoes.

Human consumption of bracken rhizomes is recorded from Europe, New Zealand, the Canaries and North America. The Japanese regard young shoots as a delicacy. However, eating bracken may be hazardous. This is well documented in cattle, and is associated with cancers of the digestive tract or effects of the breakdown of the vitamin thiamine (Evans et al., 1982).

2.8 Control of bracken

On grazing land, bracken is regarded as a weed and its present extent is a result of woodland clearance and a preponderance of sheep. The traditional method of control was scything, most effective during June or July, with repeat cuts to eliminate regrowth. Chemical methods have taken over, but to achieve eradication there must be follow up with fertilizer, reseeding and a high stocking rate on the reclaimed land. Farmers will not risk valuable animals on partially cleared pasture, or land which is regressing, so, in the absence of intensive management, which necessitates high labour inputs, there will be further encroachment by bracken.

The average cost of bracken control in Scotland is around £160 ha^{-1} (Appendix VI), yet, despite the existence of government schemes to pay up to 50% of control costs, it has been estimated that bracken may be spreading in the UK by up to 10 000 ha yr^{-1} (Taylor 1983).

In the absence of any major use for bracken its continued spread is unwelcome, though it is regarded as beneficial in terms of visual amenity terms because of the colour it adds to the winter landscape. In a nature conservation context it reduces diversity and dominates plant communities. Where there is a high level of trampling or passage by vehicles, the damage to rhizomes also suppresses above-ground growth. Disturbance is an important aspect of bracken control, and it may be anticipated, that in a regime of management designed to conserve and crop the species, it will be necessary to minimize damage to the underground parts of the plant.

That energy cropping of bracken may be the most productive land-use for many upland areas is shown by Table 1. Even after ploughing, fertilizing and re-seeding, the annual production of improved grassland is signficantly lower than the bracken yield reported here.

Table 1. Typical production from indigenous hill vegetation types and sown pasture (HFRO 1979)

	Indigenous pasture		Sown pasture
Sward type	Little grazing control	Moderate grazing control	Good grazing control
	Yield (t ha^{-1})	Yield (t ha^{-1})	Yield (t ha^{-1})
Acid grassland (_Agrostis-Festuca_) spp. poor	2.5	2.8	6.0
Dry shrub heath	2.0	2.0	5.0
Wet grass heath	1.5	1.6	4.5
Bog	1.4	1.4	4.0

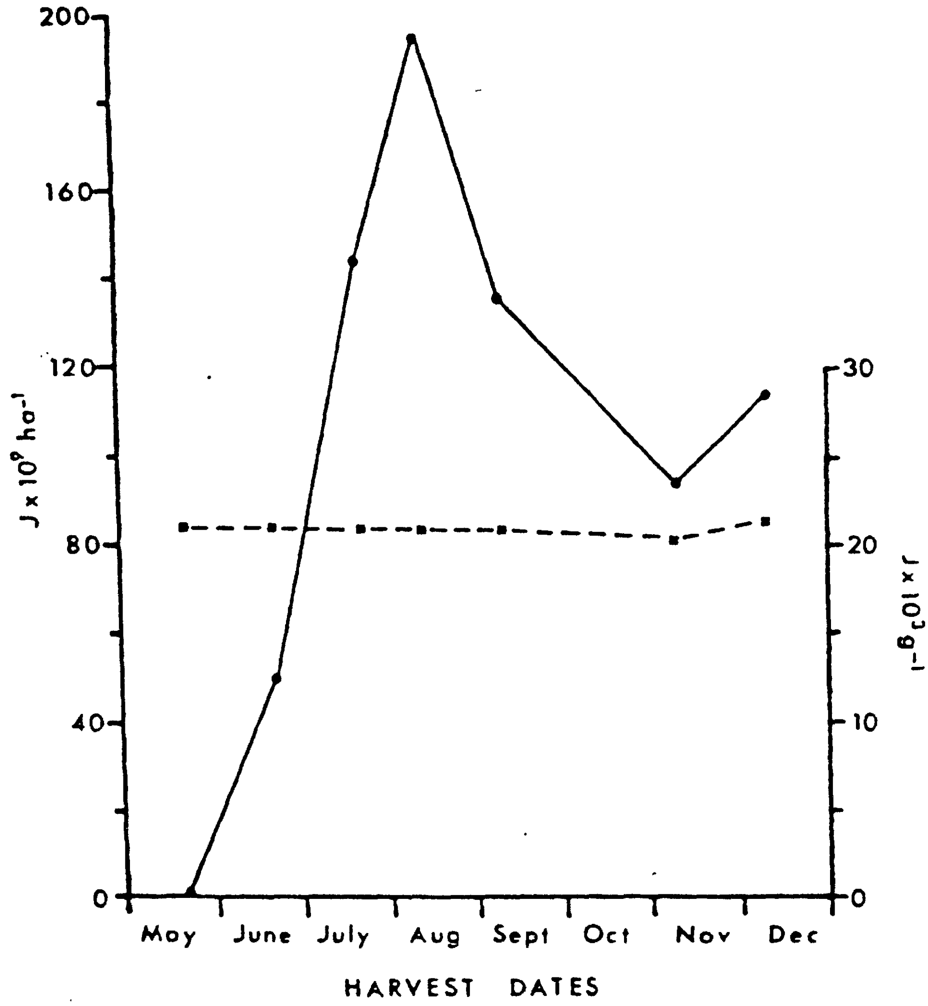


Figure 2. **Energy values of bracken**

(●——●) content of fronds unit area^{-1}

(■---■) content of frond g^{-1}

3 EXPERIMENTAL ASSESSMENT

3.1 Objectives and methods

The main objectives in the assessment of bracken as an energy crop were:

1. to establish an experimental site,
2. to measure yield in relation to applications of conventional fertilizer,
3. to assess the effects of time and frequency of harvesting on yield and regrowth,
4. to monitor the effects of climatic variables on yield,
5. to assess the digestibility of fresh bracken in an experimental anaerobic digestor.
6. to develop strategies for harvesting bracken integrated with conventional farming,
7. to extend these results to a national level

In order to measure yield in relation to fertilizer applications, time and frequency of harvesting and weather (objectives 2-4), an experimental site of 0.17 ha was established in 1980 at Lindale, Cumbria (SD 418813), in an extensive area of bracken covering an east-facing 13° slope. A randomized split plot design was developed (see Appendix I) in which the following factors were assessed:

a. the effect of weather

Bracken was cut from previously undisturbed quadrats in 1980, 1981 and 1982. Differences between years, therefore, are entirely the result of weather conditions.

b. the effect of fertilizer

Each treatment was subdivided into 4 fertilizer regimes applied annually in April.

c. the effect of cutting.

The regrowth of bracken in relation to frequency of harvesting was assessed after cutting once before (assessment in 1981 after cutting in 1980 and assessment in 1982 after cutting in 1981). The effect of 2 previous cuts was assessed in 1982 (after cutting in 1980 and 1981). Each of the above treatments was repeated for 4 harvest dates to allow an assessment of regrowth in relation to time of harvesting.

The results of the experiment were subjected to a split-split plot analysis of variance (Appendix II) and more detailed comparisons were made using 2-way analyses of variance. Analysis showed that there were no significant effects of fertilizer inputs on yields (Appendix II). Consequently, fertilizer treatments were combined in the remaining comparisons.

Biomass collected from the above experiment on 28 July (ie summer biomass) was processeed by Dr D Stafford in an anaerobic digestor at Cardiff to determine the efficiency of digestion, and material collected on 21 October (ie senescent autumn biomass) was pelletized by Dankaert to explore the possibilities of converting bracken to a solid fuel. Results from the field and conversion trials were formulated in suggested management options for the use of bracken on a farm scale. Local, regional and national impacts were also assessed (objectives 6-7) but are mainly discussed in Volume V of this series.

3.2 The effect of weather on the performance of bracken

The seasonal development of bracken is represented by the emergence of fronds in May or June, the achievement of peak yield in late July, and subsequent loss of yield during senescence (Figure 3). The highest summer yields were obtained in 1981 when a mean yield of 11.2 t ha^{-1} was recorded on 28 July, and the early season yield was 55% and 77% greater than those in 1982 and 1980 respectively. Senescence during autumn, in 1981 and 1980 was slow and yields were in the region of 8.25 t ha^{-1}, whereas yield rapidly decreased to 4.6 t ha^{-1} in 1982 (Figure 3A). Thus, differences in yield between years in relation to weather may vary by 29% in summer but almost 100% in autumn. The average yields for the Lindale site over the years 1980, 1981 and 1982 are surprisingly similar to yields recorded by Callaghan et al. at other very different sites (Figure 3B). Although the data are somewhat limited, the indications are, first, that bracken yields are fairly stable, particularly in summer, in relation to climatic conditions, and second, average summer and autumn yields of 9.8 and 7.0 t ha^{-1} respectively can be expected.

The main climatic variables which influence yield are likely to be summer temperature, late frosts and drought. Differences between years in temperature (Figure 4), and occurrence of frost and/or snow (Figure 5B) appear too small to account for the low yield of 1980, but there was a noticeable spring drought in this year (Figure 5A). Significant differences in frond densities and height also occurred. The slightly lower summer yields during 1980 were associated with low densities and shorter fronds (Figures 6A and B). In contrast leaf area indices measured in 1980 were very high, reaching 15 m^2 m^{-2} (Figure 6C), even when compared with agricultural crops (6.5 m^2 m^{-2} Callaghan et al. 1978). However, the high values were associated with a lower yield than that attained in 1981 with lower leaf area indices (Figure 6C). This suggests that the optimum leaf area index at the site is around 8 m^2 m^{-2}, and above this level, the increased respiration of shaded leaves reduces production.

The effects of weather are compounded by harvesting, as a more extreme micro-climate is created when the surface layer of dead fronds is removed during harvesting. Lowday (1983), measuring surface temperatures in harvested and unharvested bracken areas, has found that partial removal and compaction of this litter layer can reduce minimum temperatures by 1°C, whilst increasing maxima by 4°C. In years with late frosts, like 1982 (Figure 5B), soil temperatures below zero will damage the first frond buds to appear and thereby reduce total yields. Conversely, in mild springs, eg 1981, the higher soil temperatures on previously harvested areas will stimulate early growth.

3.3 The effect of fertilizer applications

Fertilizers were applied to bracken for 2 reasons: (a) fertilizers were expected to increase the overall yield of bracken, and (b) the management of bracken as an energy crop would involve the removal of biomass containing mineral nutrients which would eventually reduce yield unless replaced. Surprisingly, the overall analysis of variance showed no significant effect of fertilizers on the yield of bracken fronds, frond density or height (Appendix II). Indeed, a more detailed analysis of plots which had been cut each year for 3 years (Figure 7) indicated that far from increasing yields, high levels of fertilizer application appeared to depress yield and frond density.

These trends are difficult to interpret. However, the indication that high fertilizer application rates decrease yield probably results from the direct contact of granules of fertilizer with sensitive emerging fronds. The general lack of positive response of yield to fertilizer application could result from:

a. the surface application of fertilizer not allowing uptake by the deep roots of bracken (studies of Rubus chamaemorus showed a significant effect of fertilizers only when they were supplied at depths of 30-40 cm (Dahl et al. 1973) in the soil);

b. bracken growth not being limited by NPK on this site but by other factors including other nutrients;

c. bracken having attained its maximum yield, as increased frond area led to decreases in yield.

Although the present experiment failed to demonstrate any effect of fertilizers on yield, it is important to re-examine this, particularly in relation to applying fertilizers at a time to avoid frond damage and at a depth where they will be available to the roots. It is also important to accurately determine the trade-off between fertilizer cost and any increased - or sustained - yield. This is emphasized by Table 2 which shows that the costs of replacing nutrients removed in senescent biomass are low compared with agricultural rates. Volume IV examines the changes in chemical content of soils and plant tissues associated with this experiment.

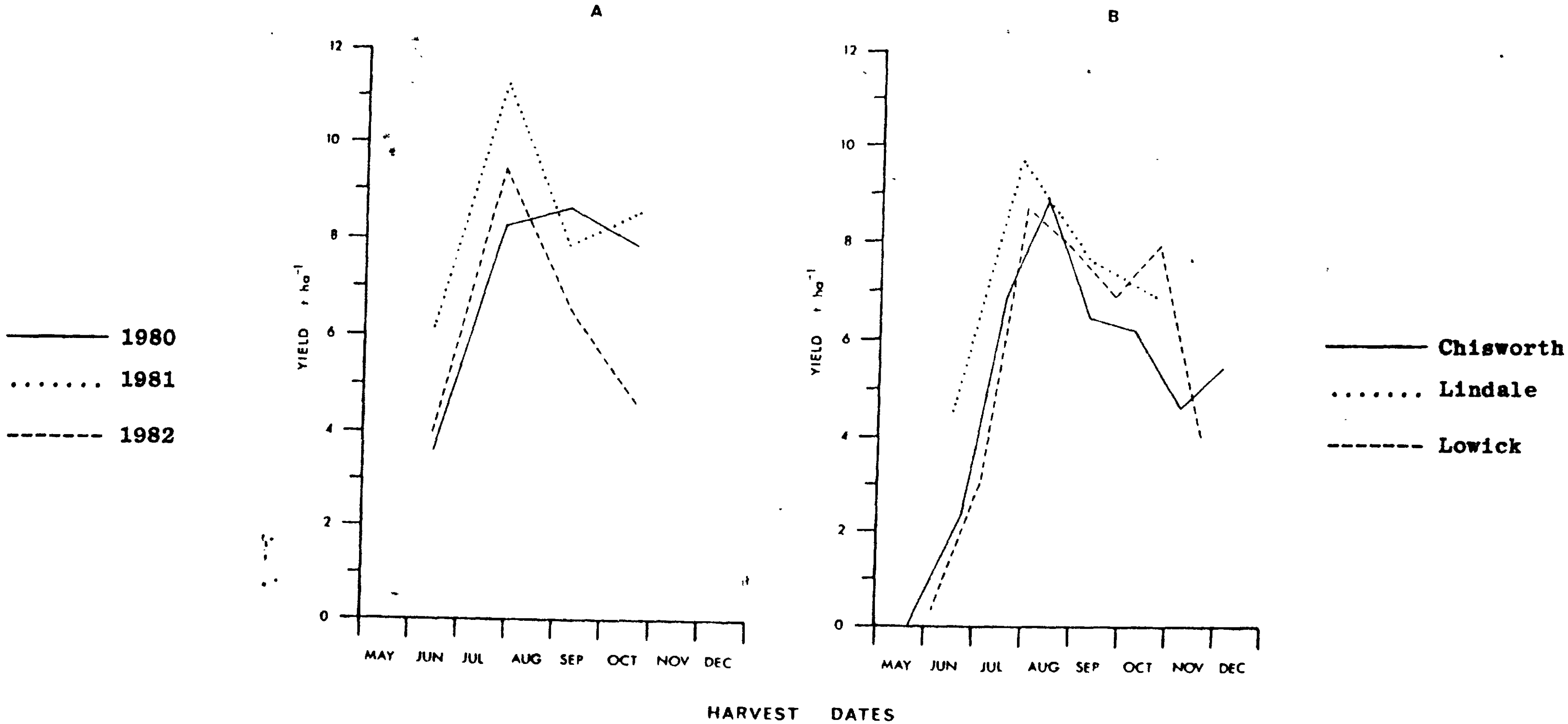


Figure 3. Seasonal development of bracken: A. yields in 3 years at the Lindale site, B. mean yields from Lindale in 1980-82, compared with yields from other field sites sampled in 1979.

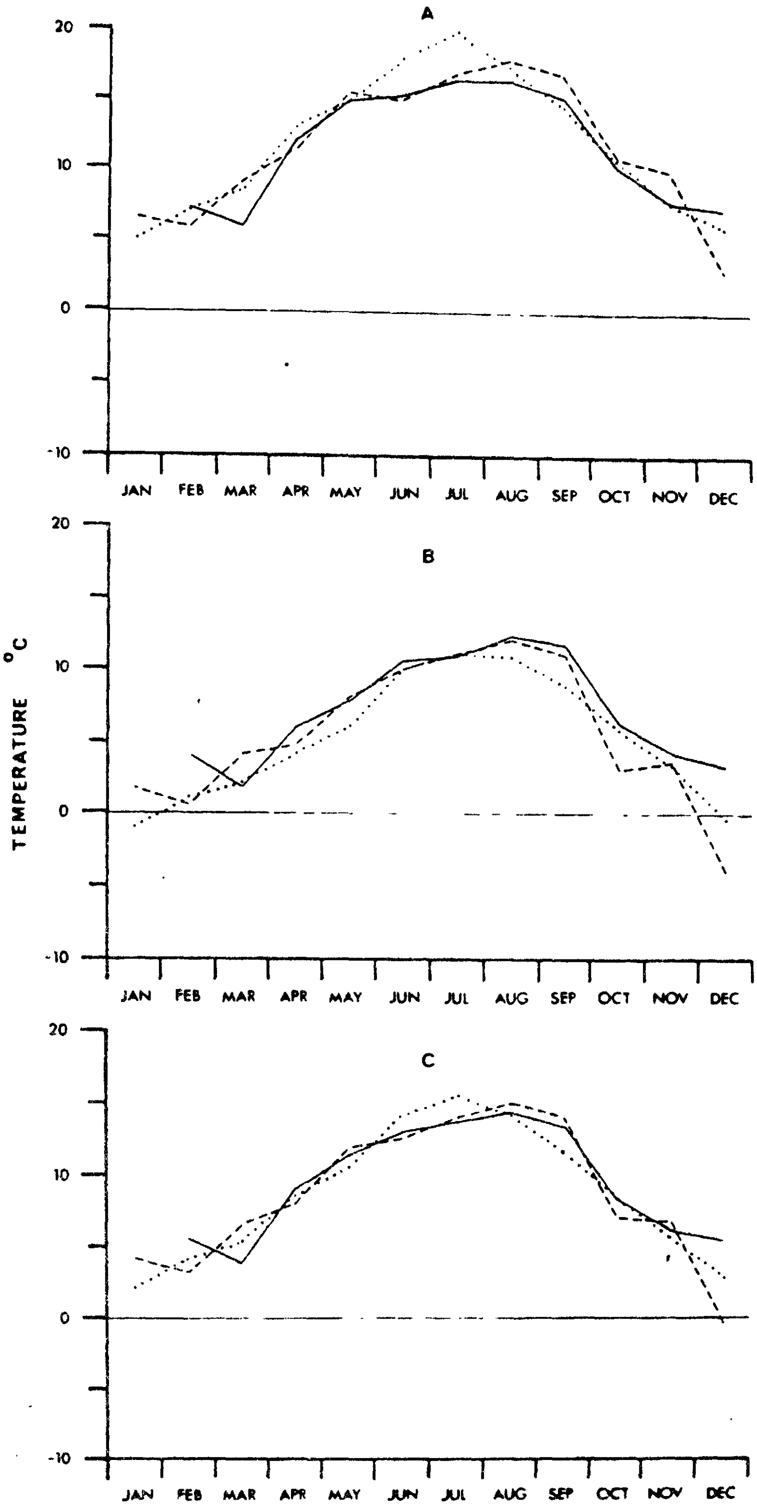


Figure 4. Monthly maximum (A), minimum (B) and mean (C) temperatures recorded at Grange-over-Sands in 1980 (——), 1981 (----) and 1982 (····).

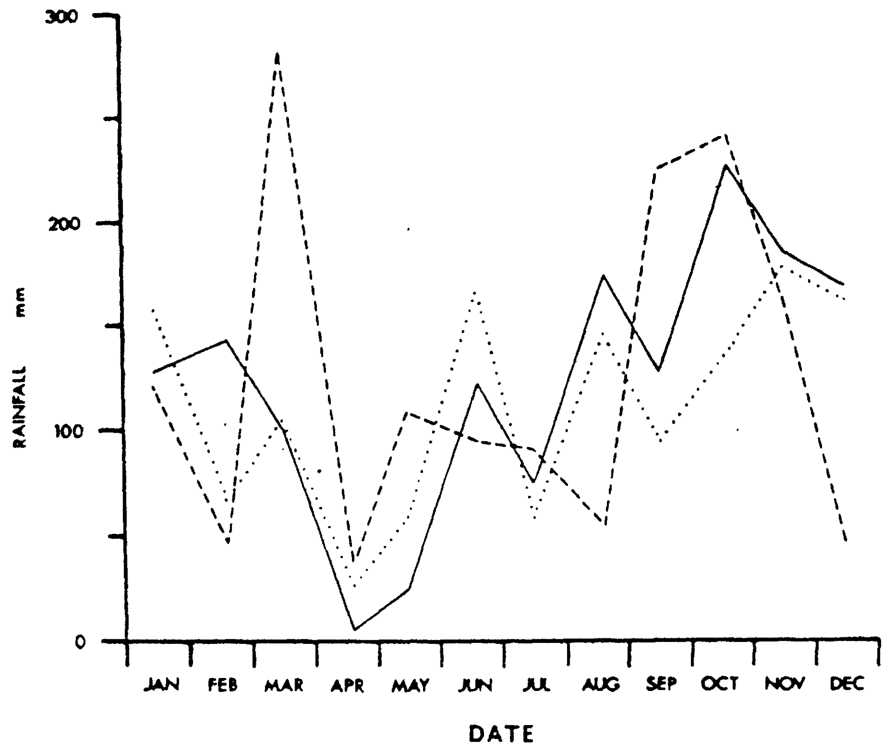


Figure 5A. Rainfall monthly totals at Grange-over-Sands recorded in 1980 (——), 1981 (----) and 1982 (····).

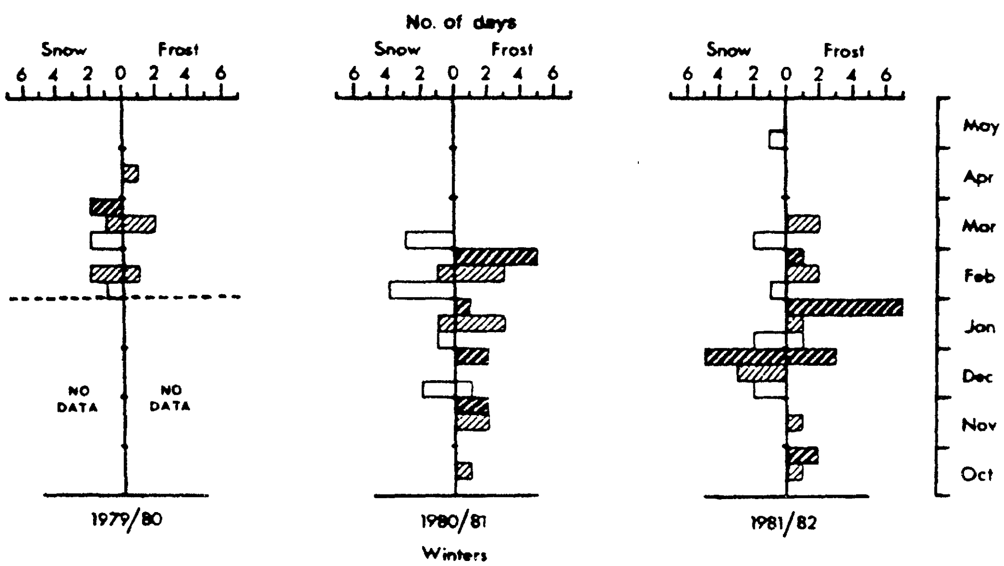


Figure 5B. The occurrence of frost and snow in the winter months of years 1980-1982.

Heavy Moderate Light

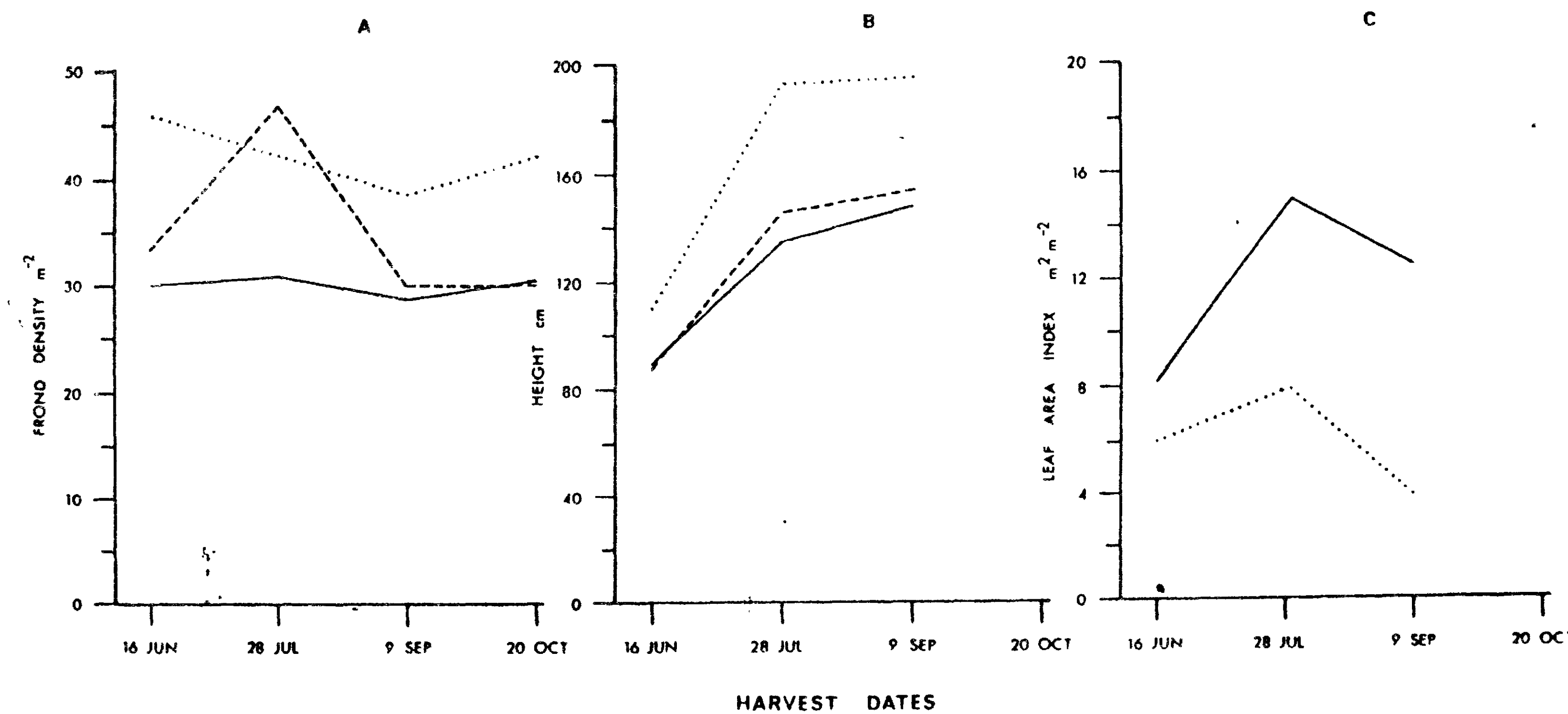


Figure 6. Effect of weather on frond density (A), height (B), and leaf area index (C) in 1980 (——), 1981 (····), and 1982 (----)

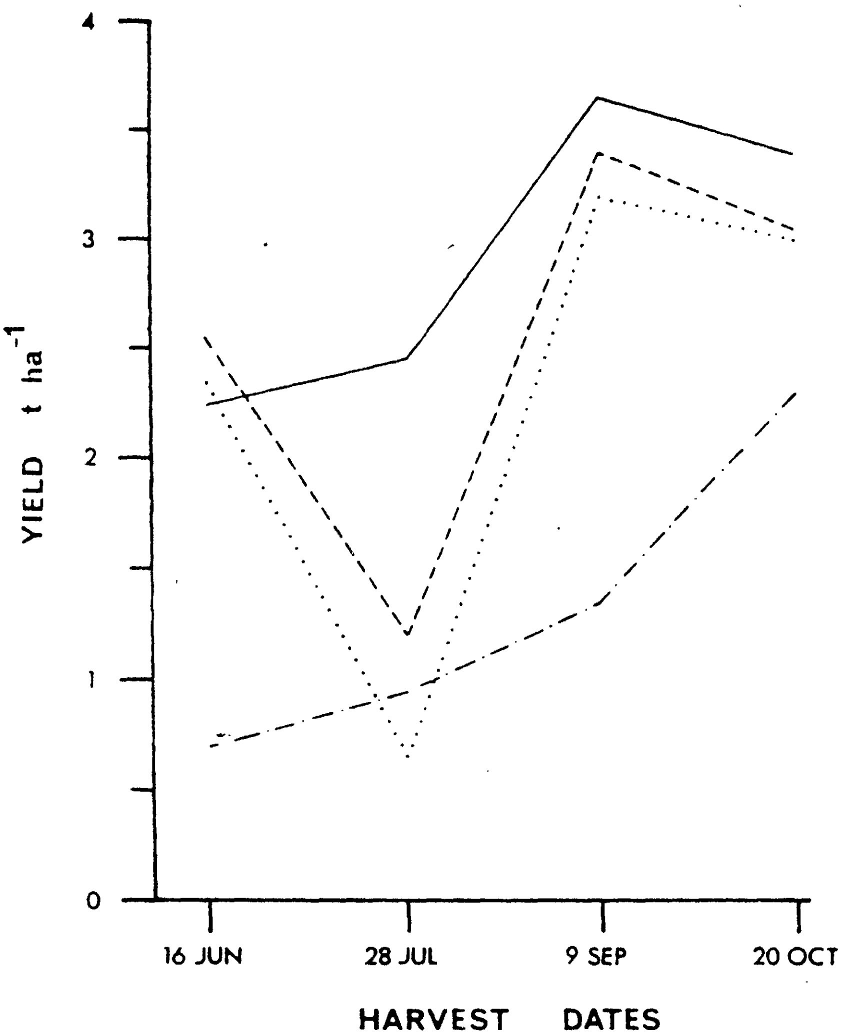


Figure 7. **Effect of the level of fertilizer application on bracken yield after 3 years of harvesting**

———	0 g m^{-2}	
-----	50 g m^{-2}	(100 g m^{-2} = 1 t ha^{-1})
·····	100 g m^{-2}	
-·-·-	200 g m^{-2}	

Table 2. Scenarios for fertilizer applications (kg ha^{-1}) to energy crops of bracken[1]

	Nutrients removed in bracken biomass		Nutrients currently applied
	autumn cut	summer cut	to agriculture[2]
N	96.7	175.9	158
P	8.8	22.2	72
K	91.8	186.1	183
Total cost of replacement	£62	£114	£120[3]

[1]Observed 3-year average summer and autumn yields are 9.26 t ha^{-1} yr^{-1}, 7.01 t ha^{-1} yr^{-1} respectively.
[2]Figures quoted are for maincrop potatoes, selected as an analogue for rhizomatous bracken plants, Church (1975).
[3]From Nix (1982) for fertilizer costs (40p kg^{-1} N, 31p kg^{-1} P, 15p kg^{-1} K) and Farm Contractor magazine (June 1983) for aerial spreading costs (£7.50 ha^{-1}.

3.4 The effect of frequency and date of cutting

The perennial nature of existing stands of bracken can confer a considerable advantage on the use of this species as an energy crop, and no preparation or planting costs are anticipated. However, to be successful as an energy crop, bracken must be shown capable of regrowth under an optimum harvesting regime.

The effect of prior cutting on yield was calculated by subtracting current yields of previously cut plots from current yields of uncut plots. This difference was then expressed as a positive or negative percentage of the expected yield, ie the yield of the previously uncut plots.

There are 2 effects to be distinguished: the effects of spring, summer and autumn cuts on the following year's growth, and the effect of successive annual cuts on annual yields.

Considering the yield on plots which had been cut once previously, the seasonal effect differed somewhat between 1981 and 1982. The single-previous-cut plots harvested in 1981 showed higher yields than controls in spring and autumn, but 10% lower yields in summer (Figure 8A). However, in 1982 yields in single-previous-cut plots were considerably lower than the controls in spring (40%), summer (60%) and autumn (30%).

Thus, from the first 3 year's study it appears that regrowth in the year following a harvest in spring or autumn will be only slightly reduced (12.5% and 10% respectively - Figure 8A), but harvesting in summer reduces yields by an average of 35%. This confirms the supposition of Callaghan et al. (1981) that repeated harvesting will be possible, without rest years, only if cutting has been delayed until the process of senescence causes the bulk of nutrients and soluble carbohydrates in the bracken fronds to be translocated below ground to over-wintering rhizomes.

When bracken was cut for 3 successive years (Figure 9A), yields in the third year (1982) showed a similar seasonal pattern to yields after one previous cut: the maximum yield reduction taking place in summer and the minimum effect (35%) being in autumn. However these conclusions are influenced by the low yields recorded in 1982 for all treatments, and it may be that weather conditions affected the weakened bracken plants in repeatedly harvested plots more than the controls. Certainly, when results for 1983 are included in calculating the average yields which can be sustained over 2, 3 and 4 years, it can be seen that autumn yields in this year have recovered very strongly (Figure 10).

This trial was funded and designed for a 3-year period, and results in 1983 could only be collected on a more limited basis, which does not permit direct inclusion in Figures 6-9. Nevertheless, strong growth in 1983, and suggestions of the same in 1984, indicate that autumn yields in excess of 7 t ha^{-1} yr^{-1} may be sustained at this site for at least 5-years of continuous cropping. Such a yield is high considering the environmental adversity of bracken covered areas and their present lack of utilization.

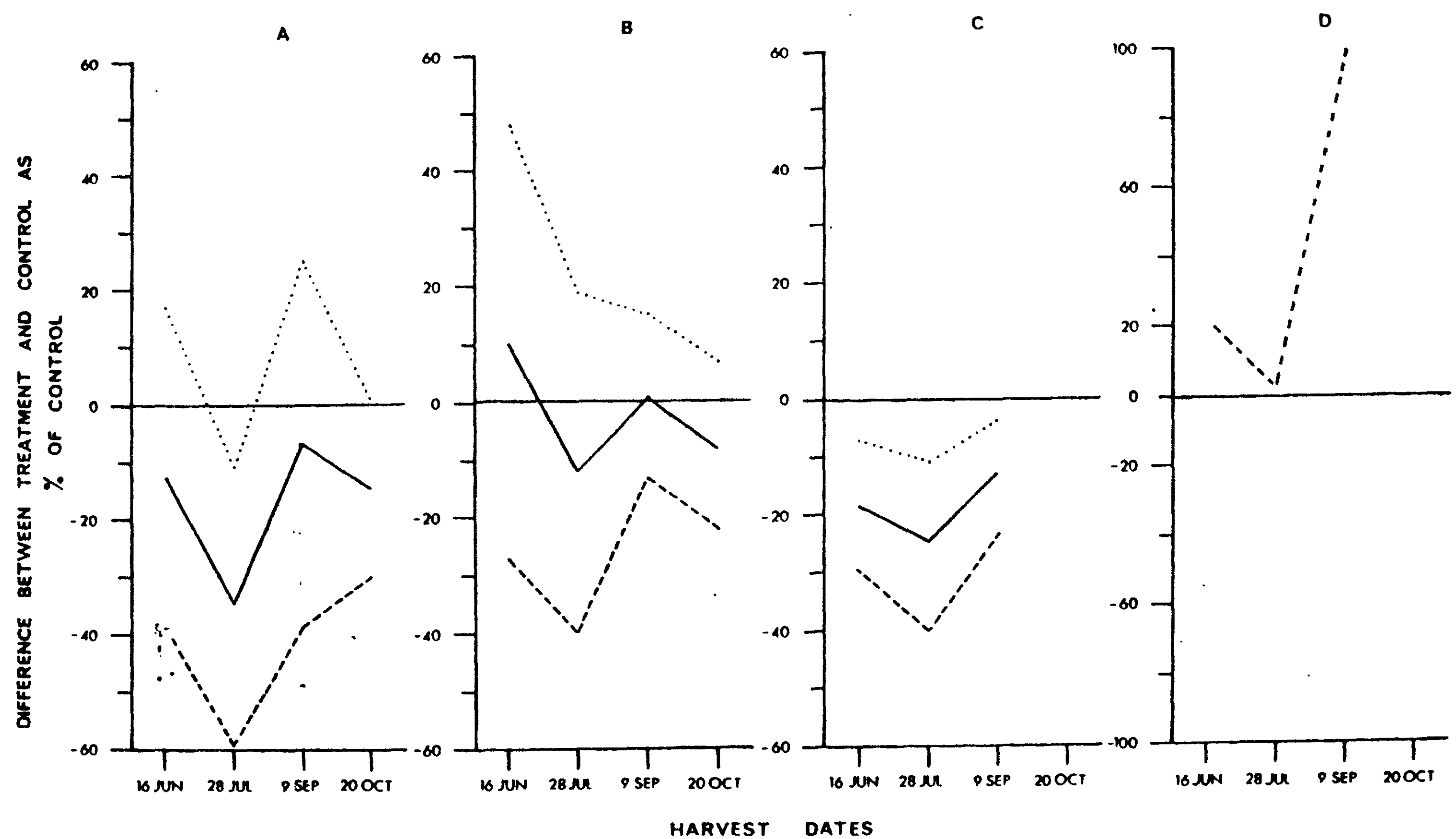


Figure 8. Effect of 1 previous cut on bracken yield (A), stem denisty (B) stem height (C) and leaf area index (D)

...... 1981 cut in 1980 and 1981

--- 1982 cut in 1981 and 1982

——— Mean

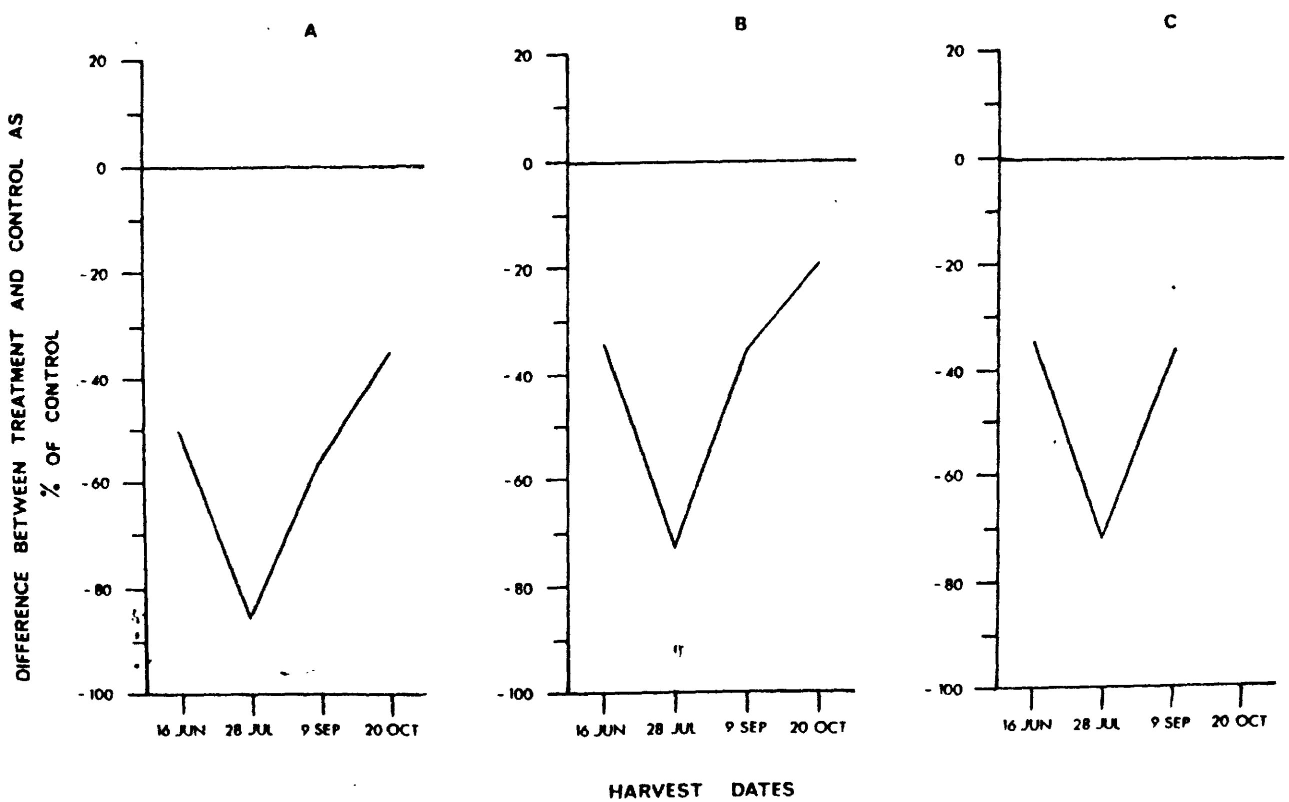


Figure 9. Effect of 2 previous cuts on bracken yield (A), stem density (B) and stem height (C)

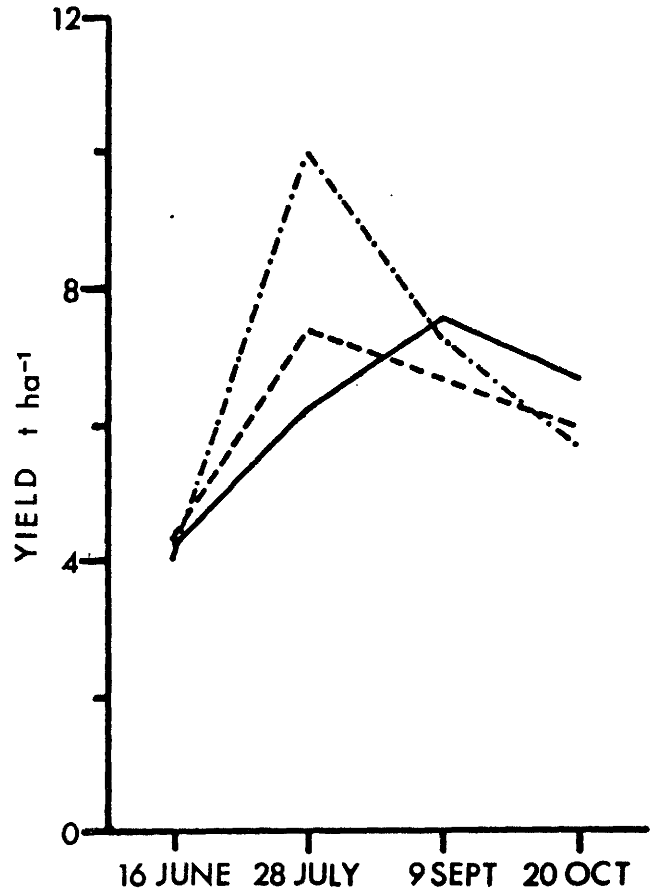


Figure 10. Mean yields over 2 (-·-·) 3 (---) and 4 (——) years of harvesting

4 THE CONVERSION OF BRACKEN TO FUELS

Three basic scenarios have been developed for the conversion of bracken to fuels:

a. bracken can be cut annually at peak yield and the fresh material digested to form methane for bottling or driving an electricity generator. This management may result in the eradication of bracken within the short term (4-5 years).

b. bracken could be cut at peak yield but on a short rotation basis so that fuel production can be integrated with increased stocking rates. The resulting biomass could be digested anaerobically.

c. bracken could be maintained as a primary energy crop by harvesting annually in autumn, probably with occasional rest years, and the resulting bracken would be converted into solid fuel.

In order to develop these scenarios further, bracken has been experimentally converted into methane and solid fuel.

4.1 The anaerobic digestion of bracken

Bracken cut on 28 July 1981, when yields would be maximal and in the region of 9 t ha^{-1}, was processed in a 5 l laboratory anaerobic digestor using a retention time of 100 days. The water content of the bracken and the yields of biogas obtained are taken from Stafford and Hughes (1981) and listed in Table 3.

Table 3. Energy from bracken by anaerobic digestion

1 tonne fresh bracken	=	270 kg volatile soils
270 kg volatile solids	=	108 m^3 biogas
108 m^3 biogas (@ 22.4 MJ/m^3)	=	2.42 GJ
1 tonne fresh bracken (@ 70% moisture and 20.0 KJ G^{-1})	=	6.00 GJ
Efficiency of conversion (excluding process energy)	=	40%

The efficiency of conversion is rather low and the end product is a relatively inconvenient fuel. Also if the biogas were bottled or used to generate electricity, then the efficiency of energy recovery would further diminish. This factor, together with the high cost of storing fresh bracken throughout the year and the possible need for fertilizer replacement

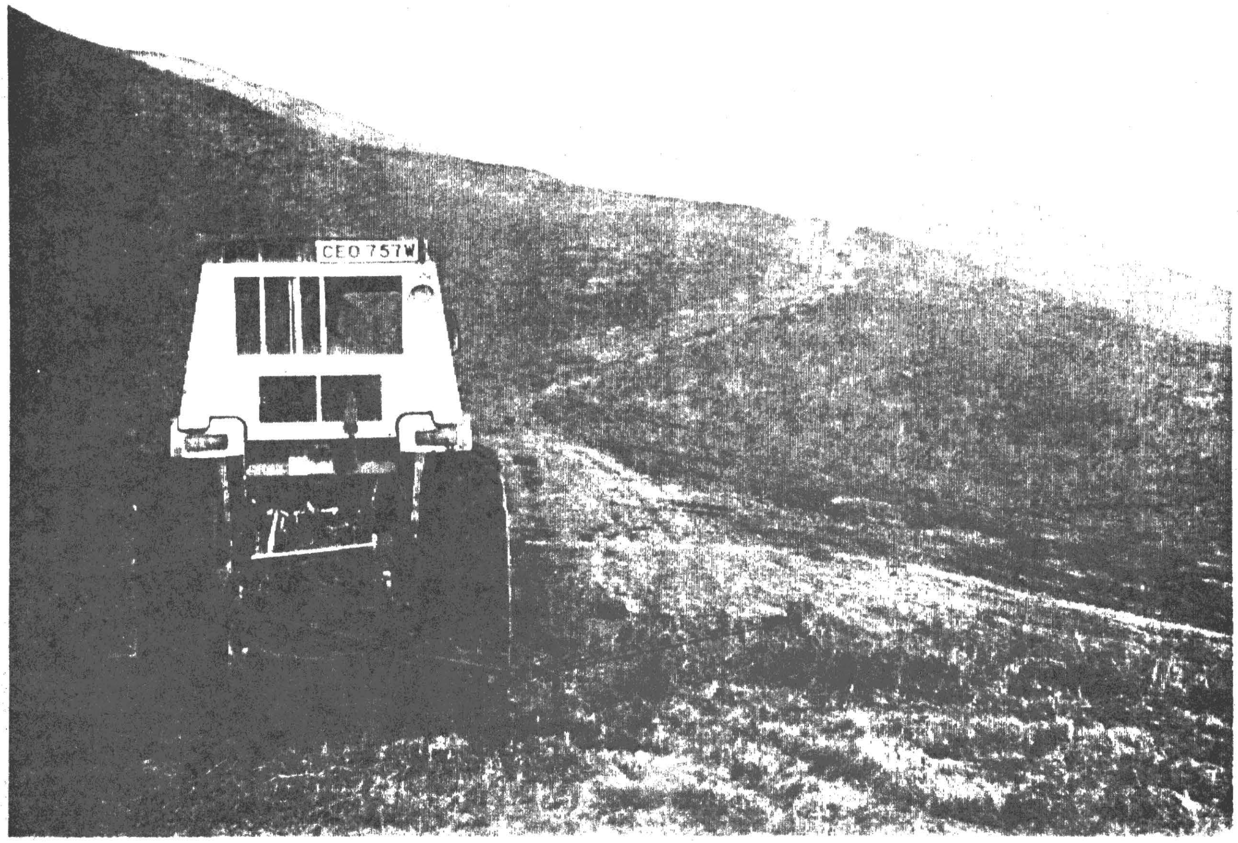


Plate I. Trial harvest of bracken in Cumbria

Plate II. Baling windrowed bracken

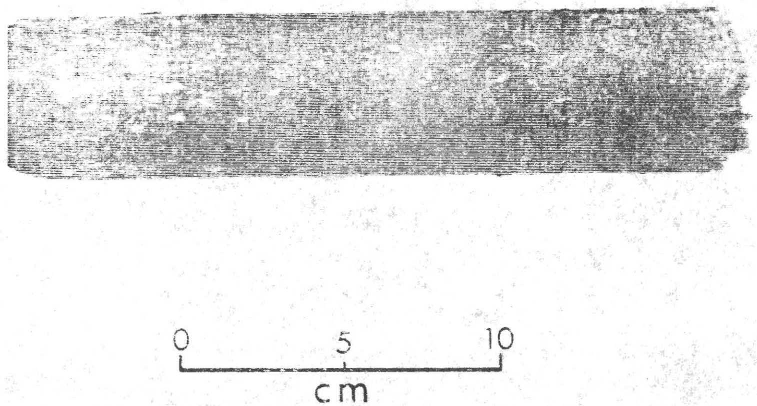
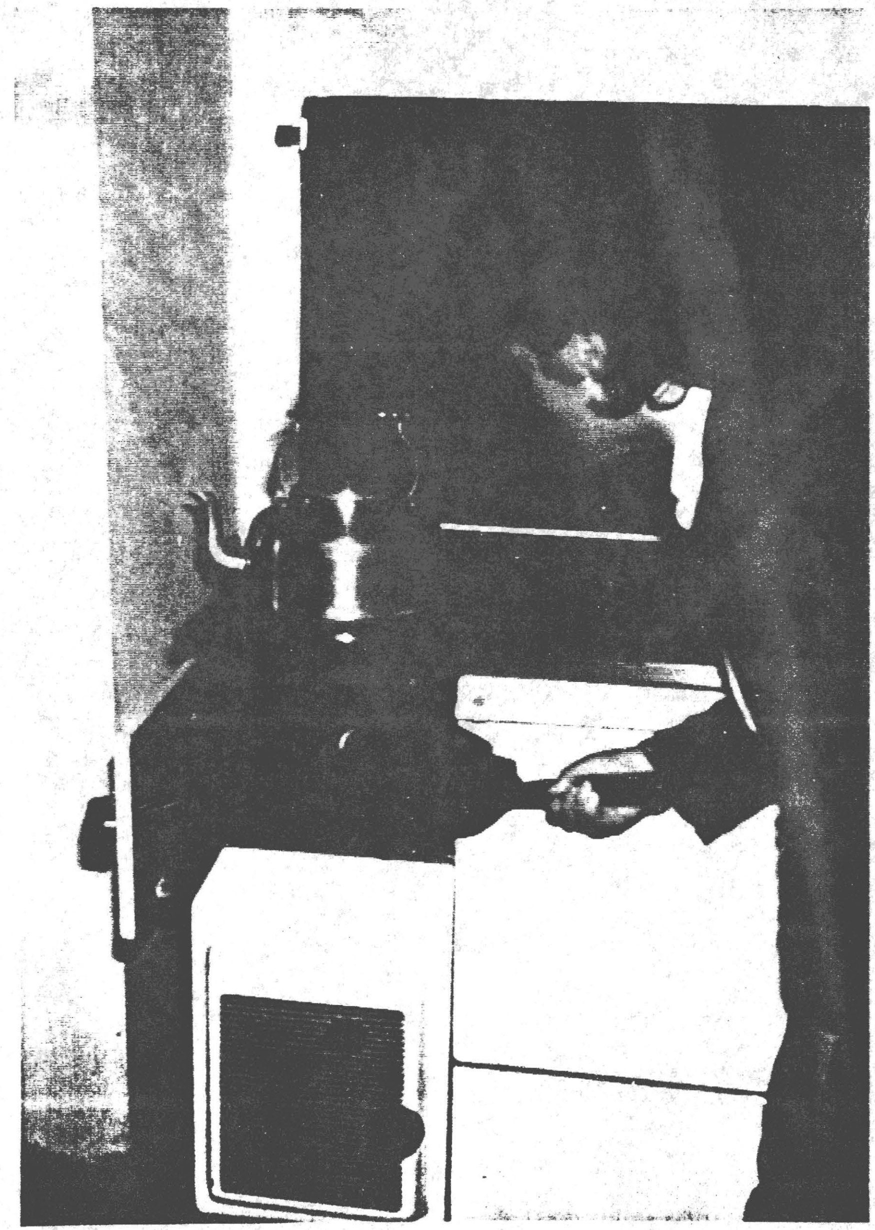


Plate III. Sample bracken pellet

Plate IV. Tirolia stove operating on bracken pellets



(Table 5), mean that the anaerobic digestion of bracken could only be justified if (a) the bracken were to supplement a main feedstock, eg cattle slurry, to an existing digestor, (b) a large area of bracken were to be controlled or eradicated, (c) the digestor residues were of sufficient value as fertilizer. The last possibility should be researched further as bracken is rich in potassium and has already been used commercially as a compost.

4.2 Conversion to solid fuel

Dry bracken can be converted into solid fuels of various bulk densities. Solid fuels, particularly those of high bulk densities, have many advantages as a fuel:

a. they are cheap to transport

b. they are easy to handle, eg hopper feeding

c. they are resistant to decomposition and will store well

d. they are a versatile feedstock, eg for direct combustion in domestic stoves or for gasification and conversion to a premium liquid fuel.

The degree of compaction required depends upon the conversion process to be used. As the cost of compaction increases with increasing bulk densities (Table 4), it is important to match the compaction process and the end use of the fuel. For example, farm buildings with boilers fired by straw bales (eg Passat HO) require only the normal baling process, particularly if the bracken is to be used close to the site of collection. However, where large areas of bracken occur, if bracken is to be transported out of the area of production, or where a versatile fuel for use in domestic stoves, etc, is required, then a high degree of compaction is desirable.

In a tentative assessment of the feasibility of harvesting and compaction, sparse bracken was harvested in October 1981, with a dry matter yield of about 3 t ha^{-1} and a water content of 30%, using a standard tractor and mower (Plate I). The swath was windrowed and picked up with a baler without field drying (Plate II). Standard bales of bracken were then milled using a tractor power-take-off hammer mill and the milled material was dried to 13% moisture content. This material was then pelletized by a Bavaria BP50 pelletizer to give pellets 5.2 cm diameter by 21 cm with a weight of 2.6 kg and a bulk density of 760 kg m^{-3} (equivalent to seasoned oak). These pellets had an energy content of around 18 KJ/g (not measured) and successfully combusted in a Tirolia 72Z stove to drive a domestic central heating system (Plates III and IV).

The efficiency with which the energy can be recovered from solid fuel is probably greatest through direct combustion, when it could be in the order of 70% (assuming a moisture content of 16%) but methanol can be obtained from solid fuel with an efficiency of about 50% (Ader et al. 1981). However, the actual efficiencies of recovering energy from bracken have not yet been determined.

Table 4. Costs, densities and usefulness of different types of compressed bracken[1]

	Dimension (cm)	Weight (kg)	Specific density kg m^{-3}	Cost[2] £ t^{-1}	Application
Big round bale	152 wide	345	98	£ 6.40- 7.80	Fast production on flat land. Easy machine loading. Unlikely use with bracken.
Standard bale	36x46x90	20	128	£ 6.00- 7.50	80 000 balers in UK. Robust. Easy manhandling. Could pick up bracken on flat. Stationary use at foot of slope.
Freeman bale	48x56x120	51	158	£ 7.00- 8.00	Few balers available. Too heavy for manhandling.
Heston bale	120x130x240	700	210	£ 7.50- 8.50	Approaching ideal transport density. Stationary use only with bracken.
NIAE high density bale	60x90x120	160	240	£ ?	Optimum transport density. Prototype.
Briquettes	4x4x5	0.1	480-960	£ 6.00-10.00	High bulk densities. Tumble loading in transporters. Ideal density and size for domestic fires and boilers and industry.
Pellets	1-2 diam.	0.01	800-1120	£12.00-14.00	Very high densities but probably not worth extra energy and expense.

[1]All data refer to straw, but bracken is easier to compress.
[2]Prices for 1980-81. Data variously from Farm Contractors magazine, Leversha (1980), Big Farm Management magazine, Klinner and Johnston (1977), Miles (1980) and Aldridge Bros (pers comm).

5 METHODS AND COSTS OF BRACKEN MANAGEMENT

In order to assess the economic feasibility of using bracken as an energy crop, costings were made of scenarios relating to the production of methane from summer harvested biomass and solid fuel or methanol from autumn harvested biomass (Table 5). These are exploratory costings, based on cutting trials in the 1950s (McCreath & Forrest 1958), and preliminary estimates for compaction and conversion equipment.

Table 5. 1982 costings per dry tonne bracken (20 GJ) assuming yields of 6 t ha^{-1} yr^{-1} for direct burning and gasification and 8 t ha^{-1} yr^{-1} for anaerobic digestion (see Appendix V for full details).

	Direct burning	Gasification to methanol	Anaerobic digeston to methane
Fertilizer costs (Table 1)	£ 8.84	£ 8.84	£ 12.31
Cutting and collection (Appendix IV)	£13.00	£13.00	£ 12.80
Densification	£26.23	£ 8.00	?
Storage (1 year)	£ 2.00	£ 6.00	£ 32.00
Transport (20 km)	£ 3.00	£ 3.00	£ 12.00
Conversion costs	£ 0.00	£53.97	£ 30.00
Total cost	£53.70	£93.51	£ 97.71
Conversion efficiency	70%	50%	45%
Total cost per GJ produced	£ 3.79	£ 9.35	£ 10.86
Price per GJ of convention fuel	£ 1.58(a) £ 3.43(b)	£ 4.56(c) £10.02(d)	£2.94-£5.50(e) £8.90-£9.85(f)
Cost per barrel oil equivalent	£22.44	£55.35	£ 64.29

(a) price of coal to large industrial user and (b) to domestic user; (c) pre-tax motor spirit; (d) post tax motor spirit; (e) natural gas - 80-800 therms yr^{-1}; (f) propane 15-47 kg cylinder.

Biomass harvested in autumn contains fewer nutrients than in summer, but the cost of replacing nutrients removed by harvests in either season are comparable with other agricultural crops (Table 2). The lack of any effect of fertilizers on bracken yield (Section 3.3) indicates complete and expensive fertilizer replacement will not be required.

Cutting and collection costs in summer and autumn are very similar, because the higher summer yields are balanced by slower working rates and higher moisture contents. Detailed costing in Appendix VI examine 3 different harvesting schemes for summer or autumn harvesting. The cheapest option in summer is a combination of 4 tractors and men, 2 trailers, a flail harvester and a buckrake, whilst in autumn a system is suggested using a modified Unimog 4-wheel drive truck/tractor with side mounted flail harvester, carrying and tipping loads of around 1 tonne into high-sided farm trailers for transport to the farm.

Densification costs for the autumn crop are based on high density pellets (Table 3), but less compaction may produce an acceptable fuel at lower cost. Compaction of the summer harvest is not expected, other than that which occurs naturally in siloes. Vacuum storage in large polythene tubes is a possibility (Klinner & Johnston 1977), but the costs have yet to be established.

Storage, transport and conversion costs are derived from other work in the Department of Energy's Fuel from Biommass Programme, as detailed in Appendix V.

The above calculations exclude the cost of land. This is because there is no financial return from land dominated by bracken. If bracken were to be controlled by the herbicide Asulam, a cost (including 50% subsidy) of £160 ha^{-1} (Appendix VI) would be incurred. Only in the case of unusually successful spraying on particularly fertile areas could stocking rates be increased by 1 ewe ha^{-1} (HFRO 1979), which might generate £40 $ha^{-1}yr^{-1}$ extra revenue (including further subsidies). This is comparable to the profit which a farmer could make on harvesting and baling bracken at a cost of £13 t^{-1} and selling bales to a pellet manufacturing company at £20 t^{-1}.

Finally, the prices quoted for the agricultural operations are based on contractor rates. If the farmer were to harvest and process his own bracken, these costs could be significantly reduced.

It is concluded from these analyses that bracken solid fuels have immediate potential, whereas the anaerobic digestion of bracken could only be justified for other reasons (see Section 4.1). More accurate costings of bracken fuel production are now required using up-to-date harvesting equipment, combustion tests and gasification trials.

6 ENVIRONMENTAL IMPACT

6.1 Land use change

Almost any change in land use gives rise to protest: witness the complaints when forests are planted in British uplands, but also the outcry when they are felled at maturity. Natural vegetation, particularly the heather and bracken of British uplands, is an important element of scenery and there may be strong resistance on visual amenity grounds to proposals to modify the character of the land. However, on nature conservation grounds, there may be arguments for the management of natural vegetation through cropping schemes. Bracken cropping, for example, could allow the farmer to improve the quality of some of his pasture whilst dedicating other areas to regular production of an energy crop. In this way, the costs of herbicide control will be saved and upland farms can be profitably and more intensively managed whilst preserving the existing land use.

6.2 Harvesting

The influence of new types of machinery is uncertain, but in harvesting steep slopes it will be necessary to move away from present tractor designs to vehicles with lower centre of gravity, and perhaps onboard storage of material. Safety aspects should improve. Bracken areas are normally remote from main roads, and heavy transport is unlikely to gain access. The most likely scenario is, therefore, for small-scale operations directed towards local use of the fuel, and environmental impacts during harvesting will be limited to some removal of large stones, improvement of access tracks and increased traffic on minor roads.

6.3 Effects on vegetation and land

Intensive harvesting will cause disturbance and diminish the nutrient status of the soil. However, as mentioned earlier, autumn harvesting is less serious in this regard, particularly if bracken beds were rested every 4-5 years. Also, there is little evidence of bracken growth being limited by nutrients, and it appears that bracken soils have a significant reserve of fertility (Braid 1959). Removal of the litter layer during harvesting facilitates grass reseeding in those areas which the farmer intends to convert to pasture. Other species like bluebell or foxglove may be established in ungrazed areas, and increased floristic diversity will be of environmental benefit. Water run-off from cropped hillsides could be more rapid, with attendant risks of soil erosion, but the surface mat of living rhizomes and roots should retain much of the nutrient which would be lost in, for example, a clear-felled forest.

6.4 Fuel processing and distribution

Most processing would be on farm or in small localized facilities. It is likely that bracken could be combined with other combustible wastes for pelletizing or gasification. Fresh fronds could also be mixed with animal slurry to improve the efficiency of anaerobic digestion, and the residues from digestors have obvious value as a fertilizer. These scenarios suggest a role for bracken processing and fuel generation within the normal pattern of agricultural activities. Few conflicts are envisaged, rather a stimulation of the rural economy, increased employment and greater independence from the national delivery systems of conventional fuels.

6.5 Aspects of fuel use

Combustion of biomass can be an inefficient process, releasing large amounts of the products of partial combustion which include particulates and polycyclic hydrocarbons (Allaby & Lovelock 1980). However, much less sulphur dioxide will be released than from burning an equivalent quantity of fossil fuel. Globally, the release of carbon dioxide will be balanced by its use by plants. Biogas for use in reciprocating engines needs to be scrubbed for hydrogen sulphide because of potential damage to engines. Unless removed, H_2S would also be the precursor of SO_2 in simple combustion of biogas for heat, leading to unwelcome emission of acid gases. The relatively high ash content of some fresh biomass could lead to problems of caulking in thermal conversion units though bracken appears to produce less ash than its equivalent of coal and, when burnt efficiently, emits little smoke.

Precautions will have to be taken to contain dust in the case of fuels compressed from dried material, risks being anticipated from explosion and effects of inhalation. Use of biogas digestors will require suitable codes of practice to minimize the risk of gas leakage. The toxic substances associated with harmful effects of bracken ingestion will not survive combustion but could possibly be discharged in residues from anaerobic digestion. This may preclude residue application to stock-grazed areas.

7 CONCLUSION

The 3 year assessment study of bracken as an energy crop has demonstrated that this species has considerable potential as a renewable source of energy. This study indicates that the use of bracken as an energy crop can be biologically, environmentally, technologically and economically feasible.

However, much research remains to be undertaken to develop long term management options for bracken infested areas. The testing and economic assessment of harvesting and densification machinery is necessary before bracken biofuels can become commercially available, and the combustability of the fuels in various forms should be characterized. Recommendations for research and development leading to the commercial production of bracken biofuels are contained in the RECOMMENDATIONS section of this report.

Although the most immediate impact for bracken biofuels is in rural areas close to the site of production, the great extent of bracken in Great Bitain indicates that these fuels could also make significant national and regional impacts. Strategies for the use of bracken biofuels and their possible geographical impacts are further considered in the Overview Volume (Volume V).

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Dankaert Ltd processed a batch of chopped material into pellets.

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APPENDIX I

METHODS

Field site

On a vigorous stand of bracken at Lindale, Cumbria (map ref. SD 418813), east facing with an inclination of 13°; solid geology is Silurian slate. Cows and sheep were present in low numbers, the sheep being absent in summer. A 2-strand barbed wire fence was erected as a precaution against disturbance from cows.

Experimental design

Based on a 3 x 3 m quadrat (Figure I.1) which included a 1 x 1 m sample square surrounded by a 1 m buffer zone, the total size of the plot was 48 x 36 m. The 4-replicated year treatment blocks were randomly placed and each contained 4 fertilizer treatment blocks. Within each of these 6 x 6 m blocks were 4 randomly arranged quadrats for harvest at different times within the year (Figure I.2).

Harvest dates	H_1	H_2	H_3	H_4
	16 June	28 July	8 Sept	20 Oct

Standing vegetation was cut on the specified dates as close as possible to ground level. In the initial harvest of each quadrat all standing material including standing dead was gathered, but low-growing associated species and compacted, detached litter were excluded. Material from the central 1 m^2 sample area was kept separate and returned to the laboratory in polythene sacks, stems being kept intact for later measurements. The outer area of the 3 x 3 m quadrat was cleared and the cuttings discarded off-site. This zone acted as access within the site and as a buffer between adjacent treatments.

Fertilizer levels	F_1	F_2	F_3	F_4
	No application	0.5 t ha^{-1}	1 t ha^{-1}	2 t ha^{-1}

Fisons "Regular" 20:10:10 NPK granules were applied by hand during available dry days in late April or early May. Care was taken not to trample the sample areas and to ensure an even spread of granules over the 3 x 3 m quadrats.

Year treatments	Y_1	Y_2	Y_3
	Cropped in 1980,81,82	Cropped in 1981,82	Cropped in 1982 only

Differences in frequency of harvest were designed to assess the effect of cutting on subsequent yields.

APPENDIX I (contd)

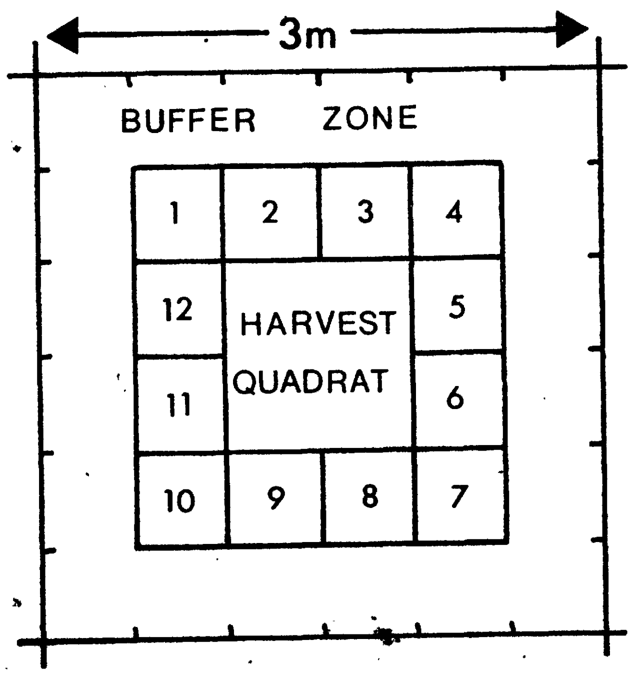

Fig. I.1 Basic sampling unit at the field site.

Laboratory analyses

Fresh weight of whole samples was recorded soon after sampling and a short period of storage at 4° C was usually necessary before the samples could be analysed. A stem count was made and 5 fronds selected at random for stem diameter (at ground level) and height (from cut to tip of newest central pinna) measurements. Each frond was then partitioned into rachis and pinna fractions and the remainder of the quadrat sample was dried in a ventilated oven at 80° C to constant weight. After 1980, increasing amounts of associated plant species occurred and this material was weighed separately but found to be insignificant in biomass terms.

APPENDIX I (contd)

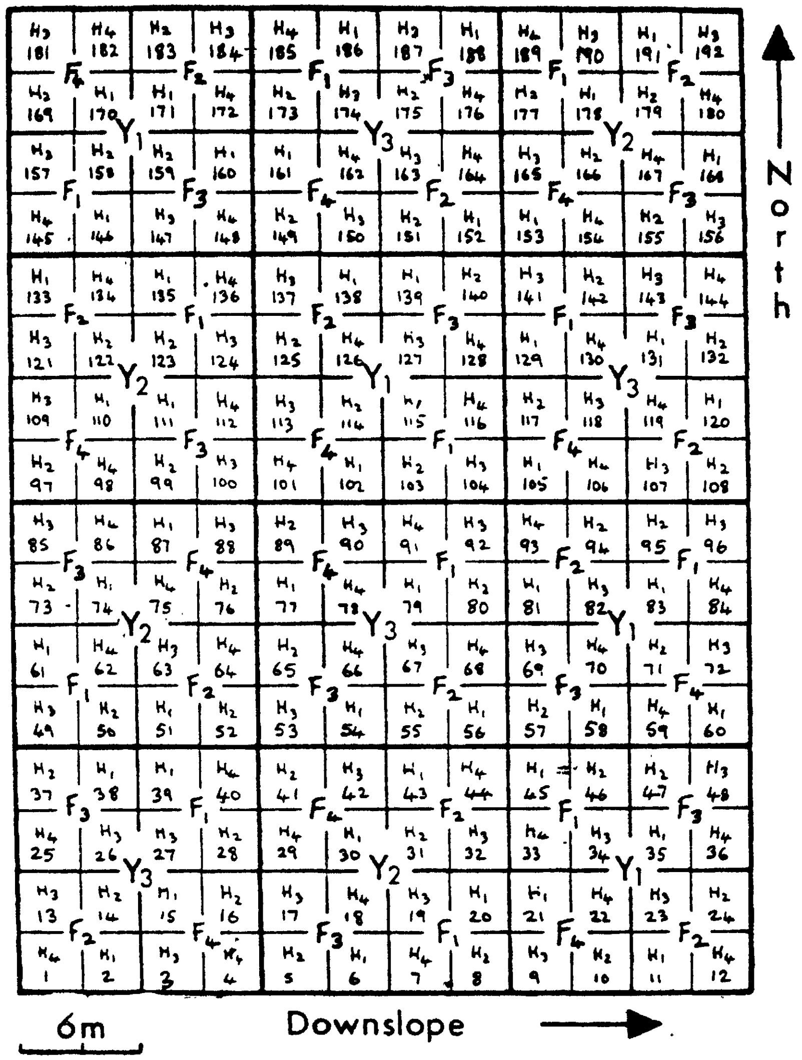

Figure I.2 Layout of bracken field site. Top of the slope is to the left and North is at the top. Each quadrat was assigned an individual number.

APPENDIX II

Statistical Results: overall split plot analysis of variance

Bracken yield

	df	ss	ms	F	Results
Years	2	4 936 829	2 468 414	38,74	$P \leq 0.001$
Error (1)	9	573 432	63 715	1,65	
Fertilizers	3	507 173	169 058	5,12	$P \leq 0.01$
Years x Fertilizers	6	472 533	78 756	2,39	$P > 0.05$
Error (2)	27	891 371	33 014	0,85	
Harvest dates	3	1 031 858	343 953	8,89	$P < 0.001$
Years x Dates	6	2 323 961	387 327	10,01	$P < 0.001$
Fertilizers x Dates	9	272 648	30 294	0,78	$P > 0.05$
Years x Fertilizers x Dates	18	353 427	19 635	0,51	
Error (3)	107 (1)	4 140 392	38 695		
Total	190	15 503 625			

APPENDIX II (contd)

Bracken stem density

	df	ss	ms	F	Results
Years	2	7706.8	3853.4	10.38	P<0.01
Error (1)	9	3339.9	371.1	3.26	
Fertilizers	3	466.5	155.5	1.35	P>0.05
Years x Fertilizers	6	1180.4	196.7	1.71	P>0.05
Error (2)	27	3108.0	115.1	1.01	
Harvest dates	3	341.7	113.9	1.0	P>0.05
Years x dates	6	3776.2	629.4	5.53	P<0.01
Fertilizers x Dates	9	1566.1	174.0	1.53	P>0.05
Years x Fertilizers x Dates	18	2612.5	145.1	1.27	
Error (3)	108	12293.8	113.8		
Total	191	36391.9			

APPENDIX II (contd)

Bracken stem height

	df	ss	ms	F	Results
Years	2	97301.3	48650.7	97.68	P<0.001
Error (1)	9	4482.5	498.1	2.07	
Fertilizers	3	8466.0	2822.0	9.52	P<0.001
Years x Fertilizers	6	2617.5	436.2	1.47	P>0.05
Error (2)	27	8004.0	296.4	1.23	
Harvest dates	2	68693.5	34346.7	142.68	P<0.01
Years x Dates	4	12851.8	3212.9	13.35	P<0.001
Fertilizers x Dates	6	3778.5	629.8	2.62	P<0.05
Years x Fertilizers x Dates	12	17332.8	273.8	1.14	
Eeror (3)	72		240.7		
Total	96				

APPENDIX III

STATISTICAL RESULTS: ANALYSES OF DATA PRESENTED IN THE FIGURES

Data source	Comparison	Statistical test	Results
Bracken yield			
Fig. 3A	(a) between harvest times	two way anovar	P<0.001 (F = 35.65 with 3 and 11 degrees of freedom)
	(b) between years (previously uncut)		P<0.001 (F = 14.4 with 2 and 11 degrees of freedom)
	(c) Interaction		P<0.05 (F = 4.09 with t and 11 degrees of freedom)
Fig. 3B	between peak yields at Lindale, Lowick and Chisworth sites	one way anover	P>0.05 (F = 0.14 with 2 and 10 degrees of freedom)

Data source	Comparison	Statistical test	Results
Bracken frond density			
	(a) between harvest times		P>0.05 (F = 3.08 with 3 and 11 degrees of freedom)
Fig. 6A	(b) between years (previously uncut)	two way anovar	P<0.001 (F = 16.06 with 2 and 11 degrees of freedom)
	(c) Interaction		P>0.05 (F = 2.02 with 6 and 11 degrees of freedom)
Bracken stem height			
	(a) between harvest times		P<0.001 (F = 475.27 with 2 and 8 degrees of freedom)
Fig. 6B	(b) between years (previously uncut)	two way anovar	P<0.001 (F = 143.48 with 2 and 8 degrees of freedom)
	(c) Interaction		P<0.001 (F = 20.28 with 4 and 8 degrees of freedom)

APPENDIX III (contd)

Data source	Comparison	Statistical test	Results
Bracken leaf area index			
	(a) between harvest times		P<0.05 (F = 7.08 with 2 and 5 degrees of freedom)
Fig. 6C	(b) between years (previously uncut)	two way anovar	P>0.05 (F = 14.03 with 1 and 5 degrees of freedom)
	(c) Interaction		P>0.05 (F = 0.89 with 2 and 5 degrees of freedom)
Bracken yield			
	(a) between fertilizer treatments		P<0.05 (F = 4.03 with 3 and 15 degrees of freedom)
Fig. 7	(b) between harvest times	two way anovar	P<0.05 (F = 5.09 with 3 and 15 degrees of freedom)
	(c) Interaction		P>0.05 (F = 0.41 with 9 and 15 degrees of freedom)

APPENDIX III (contd)

Data source	Comparison	Statistical test	Results
Bracken yield			
	(a) between harvest times		$P<0.01$ ($F = 12.42$ with 3 and 7 degrees of freedom)
Fig. 8A	(b) between 1981 uncut and 1981, cut in 1980	two way anovar	$P>0.05$ ($F = 1.03$ with 1 and 7 degrees of freedom)
	(c) Interaction		$P>0.05$ ($F = 2.07$ with 3 and 7 degrees of freedom)
	(a) between harvest times		$P<0.01$ ($F = 16.37$ with 3 and 7 degrees of freedom)
Fig. 8A	(b) between 1982 uncut and 1982, cut in 1981	two way anovar	$P<0.01$ ($F = 51.98$ with 1 and 7 degrees of freedom)
	(c) Interaction		$P<0.05$ ($F = 6.31$ with 3 and 7 degrees of freedom)
Bracken stem density			
	(a) between harvest times		$P<0.05$ ($F = 6.47$ with 3 and 7 degrees of freedom)
Fig. 8B	(b) between 1981 uncut and 1981, cut in 1980	two way anovar	$P<0.01$ ($F = 13.06$ with 1 and 7 degrees of freedom)
	(c) Interaction		$P>0.05$ ($F = 2.5$ with 3 and 7 degrees of freedom)

APPENDIX III (contd)

Data source	Comparison	Statistical test	Results
Bracken stem density			
	(a) between harvest times		P<0.05 (F = 5.36 with 3 and 7 degrees of freedom)
Fig. 8B	(b) between 1982 uncut and 1982 cut in 1981	two way anovar	P<0.01 (F = 19.8 with 1 and 7 degrees of freedom)
	(c) Interaction		P>0.05 (F = 2.24 with 3 and 7 degrees of freedom)
Bracken stem height			
	(a) between harvest times		P<0.001 (F = 658.9 with 2 and 5 degrees of freedom)
Fig. 8C	(b) between 1981 uncut and 1981 cut in 1980	two way anovar	P<0.01 (F = 18.02 with 1 and 5 degrees of freedom)
	(c) Interaction		P<0.05 (F = 7.86 with 2 and 5 degrees of freedom)
	(a) between harvest times		P<0.001 (F = 196.08 with 2 and 5 degrees of freedom)
Fig 8C	(b) between 1982 uncut and 1982 cut in 1981	two way anovar	P<0.001 (F = 228.3 with 1 and 5 degrees of freedom)
	(c) Interaction		P<0.05 (F = 12.81 with 2 and 5 degrees of freedom)

APPENDIX III (contd)

Data source	Comparison	Statistical test	Results
Bracken yield			
	(a) between harvest times		P<0.01 (F = 11.15 with 3 and 7 degrees of freedom)
Fig. 9A	(b) between 1982 uncut and 1982 cut in 1980 + 1981	two way anovar	P<0.001 (F = 148.25 with 1 and 7 degrees of freedom)
	(c) Interaction		P<0.001 (F = 22.44 with 3 and 7 degrees of freedom)
Bracken stem density			
	(a) between harvest times		P>0.05 (F = 1.22 with 3 and 7 degrees of freedom)
Fig. 9B	(b) between 1982 uncut and 1982 cut in 1980 + 1981	two way anovar	P<0.001 (F = 61.42 with 1 and 7 degrees of freedom)
	(c) Interaction		P<0.01 (F = 10.06 with 3 and 7 degrees of freedom)
Bracken stem height			
	(a) between harvest times		P<0.001 (F = 661.31 with 1 and 5 degrees of freedom)
Fig. 9C	(b) between 1982 uncut and 1982 cut in 1980 + 1981	two way anovar	P<0.001 (F = 661.31 with 1 and 5 degrees of freedom)
	(c) Interaction		P<0.001 (F = 47.01 with 2 and 5 degrees of freedom)

APPENDIX IV. NOTES ON POSSIBLE BRACKEN HARVESTING SYSTEMS

Cost estimates for bracken harvesting rely heavily on trials made by the West of Scotland College of Agriculture and the Scottish Machinery Testing Station in the early 1950s. These trials were designed to test the efficiency of different types of cutting machinery as part of bracken control programmes. Whilst they did not collect the cut bracken the tests did prove useful information on working rates, idle time, energy consumption and the costs appropriate at that time.

This Appendix builds on the experience of the cutting trials and uses costs appropriate to systems of forage harvesting in the upland situation. The help and practical experience of J B McCreath and J Morris-Eyton is gratefully acknowledged, although all parties, and any sensible enterpreneur, will regard this exercise as no substitute for a well monitored field harvesting trial.

During the cutting trials, from 1951 to 1952, the Henderson Slasher and the Ferguson Mower (both now obsolete) suffered 25% breakdown time and a further 23% idle time. Thus, whilst an operational rate of up to 0.73 ha/hr was achieved, the overall rate was closer to 0.5 ha/hr (Table 1). 62.5 MJ/ha of diesel fuel was expended during the cutting operations. Updating tractor, machine and man hours (to 1981) gave an operational cost of around £6/ha and an overall cost of £12/ha (McCreath 1981 and pers comm), but it is thought unreliable to use these figures in the context of energy harvesting.

Table 1. Working rates for bracken cutting trials (McCreath pers comm)

		Hectares cut per hour	
Averages over:		Henderson Slasher	Ferguson Mower
3 seasons at Bowmont	(Actual)	1.8	1.1
	(Overall)	0.9	0.5
4 seasons at Comrie	(Actual)	1.2	1.1
	(Overall)	0.8	0.8

Thus, theoretical harvesting schemes have been postulated for the summer and autumn seasons, and 3 different systems are suggested for each. The following assumptions are common to all systems.

Terrain is suitable.

All work is done on a contract basis.

Contractors' rates (where available) are for the 1981 season at the rate per hour pertaining to grassland but at a much higher rate per hectare.

APPENDIX IV (contd)

Table 2. Estimated contractor charges for summer harvesting

System	I		II		III	
	£/hour	£/ha	£/hour	£/ha	£/hour	£/ha
Mowing	-	-	14	35	14	35
Harvesting	14	35	14	35	32	80
Transporting	27	67.5	27	67.5	7	17.5
TOTAL	41	102.5	55	137.5	5	132.5
Cost/tonne (fresh)	£ 3.70		£ 5.00		£ 4.00	
Cost/tonne (dry)	£12.80		£17.20		£16.60	

Notes

a. Mowing is assumed to take 0.4 ha/hr, and other operations are scaled to minimize idle time.

b. System I assumes:

Tractor + man + flail harvester	@	£14/hr
2 tractors + 2 men + 2 trailers	@	£20/hr
Tractor + man + buckrake	@	£ 7/hr

c. System II assumes:

Tractor + man + flail mower	@	£14/hr
Tractor + man + harvester	@	£14/hr
2 tractors + 2 mean + 2 trailers	@	£20/hr
Tractor + man + buckrake	@	£ 7/hr

d. System III assumes:

Tractor + man + flail mower	@	£14/hr
2 self-loading foragers + 2 men	@	£32/hr
Tractor + man + buckrake	@	£ 7/hr

e. Double chopping is not advised in any system due to the likelihood of clogging.

f. Yield based on 8 tonnes dry wt/ha and 27.5 t/ha fresh wt.

g. Although System I appears to be the cheapest, it should be noted that this includes only a single chop. Fine maceration may be essential for efficient anaerobic digestion, and if so then a precision chopper outfit (tractor, chopper and man) may need to be hired, at a cost (£16/hr) which would add around £13 per dry tonne. The determining factor here being the rate at which material could be hand forked into a stationary chopper.

APPENDIX IV (contd)

Table 3. Estimated contractor charges for autumn harvesting

System	IV		V		VI	
	£/hour	£/ha	£/hour	£/ha	£/hour	£/ha
Mowing	14	28	-	-	3	81
Harvesting	14	28	20	40	3	45
Transporting	27	52	19	38	-	3
TOTAL	56	108	39	78	6	129
Cost/tonne (fresh)	£ 9.6		£ 7.8		£12.9	
Cost/tonne (dry)	£16.0		£13.0		£21.5	

Notes

a. Mowing is assumed to take 0.5 ha/hr, and other operations are scaled to minimize idle time.

b. Yield is assumed to be 10 t/ha fresh wt and 6 t/ha dry wt.

c. System IV assumes:

Tractor + man + flail mower	@	£14/hr
Tractor + man + harvester	@	£14/hr
2 Tractors + 2 men + 2 trailers	@	£20/hr
Tractor + man + buckrake	@	£ 7/hr

d. System V uses a modified Unimog 4-wheel drive truck/tractor with side mounted flail harvester, carrying and tipping loads of around 1 tonne into high-sided farm trailers for transport to the farm. It assumes:

Unimog + man + flail harvester	@	£20/hr
Tractor + man + 2 trailers	@	£12/hr
Tractor + man + buckrake	@	£ 7/hr

e. System VI assumes 1 man with scythe cutting at a rate of 37 hrs/ha and £3/hr (taking 30% idle time). Another man works for half the time loading bracken onto a sledge and returning home. Motive power has been costed to pull the sledge, but the traditional use of horse power may be preferable on difficult terrain.

f. Stationary baling costs would be around £12/tonne, but this can be avoided if briquetting is planned.

g. These costs generally allow for contractor charges. If the farmer harvests his own bracken the rates could be reduced by 30-50%. However, the cheapest system involves machinery which the farmer may not feel justified in purchasing, and harvesting on slopes is a risky task which may better be performed by specialists.

h. The cheapest delivery of bracken to a farm based pelletizer uses System V, but this would not permit field drying of the cut. It is uncertain how such a disadvantage should be costed.

APPENDIX V. ECONOMIC ASSUMPTIONS USED IN CALCULATING COSTS OF BRACKEN DERIVED FUELS. See Table 5.

a. The autumn yield (for direct burning and gasification) is taken as 6 t $ha^{-1}yr^{-1}$ since an average of 6.9 t ha^{-1} yr^{-1} was attained over 3 years of harvesting).

b. The summer yield (for anaerobic digestion) is taken as 8 t ha^{-1} yr^{-1} since yields of 9.6, 8.4 and 6.3 t ha^{-1} were obtained in 3 successive years of harvesting.

c. Fertilizer costs assume complete replacement of nutrients removed in harvesting. Using observed concentrations in summer (harvest 2) of 1.9% N, 0.24% P, 2.01% K, and in autumn (harvest 4) of 1.38% N, 0.12% P, 1.30% K. Observed yields from previously uncut plots averaged 9.26 t ha^{-1} yr^{-1} in summer and 7.01 t ha^{-1} yr^{-1}.

d. For cutting and collection costs see Appendix IV.

e. Densification of chopped bracken would not be required prior to gasification in fluidized-bed units, but it is necessary for smaller gasifiers. Cost of low-quality briquettes is from Miles (1980). Densification for direct combustion requires a higher-quality product, and is more costly. The estimate used in Table 5 is for a mobile briquetting machine, manufactured by Ecobriquette ApS of Denmark (Plate II, Volume V). Altenecon Ltd of Salisbury are acknowledged for these data.

Straw briquetting plant, mobile type

Production and capital costs at production rate of 1 t/hr

Basis:

Manning:	1 man in 1 shift	Man hours:	1840 hrs/yr
Utilization	0.75	Operating hours:	1380 hrs/yr
Production:	1380 t/yr	Fuel consumption:	25 litre/hr
Machinery cost:	£68,400.00	Building cost:	£10,000.00
		£/ton	£/ton
Wages:	1840 x 3/1380	4.00	
Fuel cost:	25 x 17.6	4.40	
Insurance:		0.25	
Maintenance:		1.00	
Dry binder:		1.56	
Production cost:			11.21
Machinery: (interest 12% depreciation over 5 years)			
68,400.00 x .12/ (1 - 1.12^{-5}) / 1380			13.74
Buildings: (interest 12% depreciation over 10 years)			
10,000.00 x .12/ (1 - 1.12^{-10}) / 1380			1.28
Production + capital cost:			26.23

APPENDIX V (contd)

f. Storage costs are updated from Dunn & Haskew (1979).

g. Transport costs assume £1/tonne and 10p/kilometer (Dunn & Haskew 1979)

h. Steam gasification costs are based on Ader et al. (1981) assuming a plant with 250 t/day methanol output and an intake of 490 t/day dry matter. Labour and capital related costs (71% of total costs) are £106/t methanol or £53.97/t feedstock.

i. Anaerobic digestion costs update Wheatley & Ader (1979) assuming capital and running costs of 7.5 p m^{-3} in a 100 m^3 digestor producing 400 m^3 of biogas from 1 dry tonne of bracken (Table 3).

APPENDIX VI. BRACKEN CONTROL GRANTS PAID BY THE DEPARTMENT OF AGRICULTURE AND FISHERIES FOR SCOTLAND (PERS COMM)

Date	Grant Scheme[1]	Area (Ha)	Grant Paid[2]	Grant/ha[3] £
1977	FCGS	1 457	65 649	45.06
	FHDS	-	-	-
1978	FCGS	1 409	88 221	62.61
	FHDS	18	4 439	246.61
1979	FCGS	1 362	83 229	61.11
	FHDS	251	16 032	63 87
1981	FCGS/AHGS	517	31 070	60.10
	FHDS/AHDS	1 172	63 572	54.24
1982	FCGS/AGDS	768	56 583	73.67
	FHDS/AHDS	993	41 448	44.42
1983	FCGS/AGDS	567	44 957	79.29
	FHDS/AHDS	1 574	81 823	51.98

Notes

[1]The Farm and Horticulture Development Scheme (FHDS) and the Farm Capital Grant Scheme (FCGS) were superseded during 1980 by 2 similar schemes, the Agriculture and Horticulture Development Scheme (AHDS) and the Agriculture and Horticulture Grant Scheme (AHGS). The AHDS provides grants for modernization under an approved development plan, including bracken clearing, and is partly financed by the EEC. The AHGS is wholly financed by the Exchequer and is towards investment in individual items of capital expenditure. From 1/12/83 bracken control is not eligible for this grant outwith designated Less Favoured Areas (LFAs).

[2]To qualify for 50% grant under the old FHDS/FGCS regulations, bracken control operations must include follow-up treatments involving some liming and perhaps re-seeding. This 50% figure continues under the new schemes but only in LFAs. The standard rate for bracken control outwith the LFAs rose from 25% to 32.5% on 1/2/80 for the FGDS/AHDs scheme, and from 20% to 22.5% for the FCGS/AHGS scheme.

[3]Because of the uncertainties explained above, with different rates of grant being contained in the total figures, it is difficult to derive a reliable estimate for the current cost of bracken control. Nevertheless, it seems likely that the AGDS expenditure in 1983 will be almost entirely composed of payments eligible at the 50% rate, and the level of grant at £79.29/ha suggests that total costs for bracken control are now around £160/ha.

PART II : Cordgrass - *Spartina anglica*

CONTENTS

SUMMARY

1. Cordgrass is a highly productive new species which has colonized 120 km^2 of British estuaries since 1870. It occurs naturally on under utilized land.

2. Above-ground standing crops of natural stands can reach 22 t ha^{-1} while the annual production of shoots commonly reaches 12 t ha^{-1}.

3. Weather has a significant effect on annual yields, which vary by 35%. Fertilizers, however, do not increase yields even after 3 successive annual crops have been removed, and fertilizer applications would be of little or no significance in the management of cordgrass as an energy crop in the short term.

4. Cordgrass shoots have an energy content of 17.8 kJ g^{-1} which varies little throughout the growing season.

5. The mineral nutrient content of shoots in summer is much greater than that in autumn but insoluble ash contents are always high, mainly as a result of internal silica bodies and silt adhering to the plant surface.

6. A mean yield of 12.9 t ha^{-1} yr^{-1} could be obtained by harvesting shoots of cordgrass in summer for each of 3 years. Harvesting in autumn, at this frequency, resulted in a slightly lower mean yield of 11.3 t ha^{-1} yr^{-1}. The reductions in yield due to harvesting for 3 successive years were very low: 13% when harvested in summer and only 1% when harvested in autumn.

7. Cordgrass could be maintained as a long term energy crop and would probably require only minimal applications of a nitrogen fertilizer. However, rest years would probably be necessary as part of a long term management plan.

8. The oceanic climate of Britain, together with the estuarine habitat of cordgrass, prevents on-site drying of cordgrass. It is most likely, therefore, that this species will be anaerobically digested to produce fuel. A trial digestion showed a 39% efficiency of energy recovery.

9. Favourable observations on the silage making capacity of cordgrass suggest that either more efficient anaerobic digestion should be possible, or that crop fractionation could be used to separate protein-rich leaf juices from the residual fibres which would be pelletized and combusted.

10. There should be no technological difficulties in harvesting or planting cordgrass, as a range of equipment and methods has been used on similar growth forms in similar habitats.

11. Tentative costings for the production of solid fuel from reeds give \$35 to \$50 t^{-1} but adequate costings for fuel from cordgrass can only be established from harvesting trials.

12. The environmental impact of harvesting cordgrass should be small. Although areas of cordgrass may be less aesthetically pleasing than areas of sandy beach, the maintenance of cordgrass, and its establishment in new locations can enhance the conservation of wildfowl and the stabilization of foreshore concurrently with the production of fuel.

RECOMMENDATIONS

1. These studies have assessed the cordgrass resource and the manner in which it could be harvested; however, the likely conversion routes have hardly been investigated. The single trial anaerobic digestion was disappointing, but evidence that cordgrass makes excellent silage suggests that continued funding should enable more succesful digestion techniques to be applied. Thermal conversion of end of season harvests is unlikely to be justified because of the high water and mud content of the biomass. However, younger leaves should be tested in crop fractionation machinery to establish whether the yield of protein and the quantity of squeeze-dried fibres will be sufficient to ensure that the combined operations of fractionation and thermal conversion are economically viable.

2. Cordgrass grows in estuarine conditions and will therefore require specialized harvesting equipment. Suitable low ground-pressure machinery has been used to harvest reeds in freshwater lakes and estuaries, but the technical and economic feasibility of these harvesting methods should be demonstrated on an experimental area of saltmarsh.

3. Cordgrass can maintain high yields even after 3 years of annual harvesting. It is important, however, to determine the effect of mechanical harvesting over a much longer period of time, and to investigate the effect of introducing rest years.

4. When the harvesting of existing areas of cordgrass has been shown to be technically and commercially feasible, further investigation should be made of the mechanical methods of establishing new swards on the many areas of estuarine habitat which are not currently in productive use.

1 INTRODUCTION

Earlier research on the potential of natural vegetation as a source of biofuels identified a group of species which could be harvested from their existing locations with minimal effects on traditional land use (Callaghan et al. 1978; Lawson et al. 1980). The potential of bracken, which is particularly widespread and productive has been described in the first volume of this series (Callaghan et al. 1984a).

Cordgrass, like bracken, occurs on land which has few uses beyond the conservation of wildlife. It can be an unwelcome intruder into previously bare intertidal areas and several local authorities have used Dalapon herbicide sprayed from helicopters to control its spread. Cordgrass is ecologically and geographically much more restricted than bracken but it is highly productive and should, therefore, be regarded positively as a resource rather than a nuisance species of otherwise unusable estuarine land.

Preliminary studies on the production and nutrient composition of cordgrass (Callaghan et al. 1981) confirmed the potential of the species as an energy crop, but little was known about the way it could best be managed, how it would react to repeated harvesting, or the cost of producing biofuels from it. A 3-year experimental programme was, therefore, established to investigate these questions and to verify the predictions made by Callaghan et al. (1981) that annual harvesting in autumn would reduce subsequent yields less than summer harvesting, and that the addition of fertilizers would be less necessary than to a dry land crop because of the plentiful supply of nutrients in estuarine waters.

2 BIOLOGY OF CORDGRASS

2.1 Description

Common cordgrass, Spartina anglica, is a stout, perennial grass of sheltered coasts and estuaries (Plate I). It reaches a height of 50-130 cm at maturity and reproduces prolifically both by water-borne seeds and by lateral spread of rhizomes below the mud surface. The species occupies muddy shores below existing salt marsh and also some of the higher vegetation zones in the coastal succession (Clapham et al 1962).

2.2 History and distribution

Cordgrass is a new species, presumed to have arisen close to where it was first recorded in Southampton Water in 1870 (Hubbard 1968). Its parent species, Spartina maritima, and the American S. alterniflora gave rise to a sterile hybrid which later acquired pollen fertility and began its rapid spread from the first locality at Lymington in 1892. By 1907, many thousand hectares of tidal mudflats between Sussex and East Dorset had been covered. Since then it has extended its range around the coast of England and Wales but appears to meet a climatic limit on the east coast of Scotland. The last estimate (Ranwell 1967a) of its total area on the coast of Great Britain was 120 km^2. During the last decade the species has made significant advances in occupying mudflats in Wales and the north, but there have been reductions in cordgrass dominance of some of the original southern sites (Goodman et al. 1959). There appear to be some areas, like NE England, into which cordgrass could yet spread or be introduced.

2.3 Growth patterns

Cordgrass shows late and slow development. Emergence of new shoots occurs in late May and peak biomass is often not reached until November. In some years, spring tides and summer rainfall increase the rate of growth but, when drought and neap tides combine, growth is extremely slow. Flowering culms usually mature in September and seed set is in October, the seeds being dispersed by tides. Green leaves and stems often persist through the winter and, together with the mat of fallen material and a dense rhizome network, make cordgrass a most effective agent for trapping water-borne sediment. In severe winters, heavy storms, high tides and ice plates may flatten all standing matter and the following season's stems will be entirely new growth.

2.4 Yield

Annual productions of 9.6 and 9.8 t ha^{-1} have been recorded by previous researchers (Ranwell 1961; Jefferies 1972). In harvesting trials in the Severn Estuary, Hubbard and Ranwell (1966) achieved a yield in mid-August of 5.2 t ha^{-1}, but higher yields could have been expected if the trial had continued later into the autumn. Callaghan et al. (1981) found a peak above ground standing crop of current year's growth ranging from 6.1 to

* All yield figures in this document are oven dry metric tonnes ha^{-1}.

16.8 t ha^{-1}, and they reported a water content of 60% in living leaves and 30% in standing dead leaves. Below ground productivity has not been recorded, but standing crop varied from 4.1 to 14.2 t ha^{-1} (Callaghan et al., 1981).

* All yield figures in this document are oven dry metric tonnes ha^{-1}.

2.5 Nutrients

Areas of cordgrass receive nutrients dissolved in tidal waters and contained in silt particles which accrete amongst the mat of rhizomes and dead leaves. Large amounts of K, Mg, Na and Mn are contained in seawater and most silts provide a plentiful supply of phosphorus. In the upper areas of a salt marsh, plant yields may be increased by P-fertilizer applications (Tyler 1967; Piggott 1969), but in the lower marsh, dominated by cordgrass there is no evidence of phosphorus limitation (Broome et al. 1975; Haines & Dunn 1976). Pomeroy (1970) even estimated that 500 years' supply of phosphorus was available in the rooting zone of a stand of Spartina alterniflora.

Several studies have demonstrated a nitrogen limitation on saltmarsh vegetation (Ryther & Dunstan 1971; Valiela & Teal 1974; Sullivan & Daiber 1974). However this effect may be small or non-existent (Patrick & Delaune 1976; Gallagher 1975), and evidence that many marshes are net exporters of nitrogen (Axelrad 1974; Stevenson et al. 1977) indicates that marshes may have more nitrogen available to them than can be utilized. One possible explanation for the wide variation in response to nitrogen is the interrelationship with salinity effects: nitrogen additions appear to increase soil salinity, and this in turn forces the plant to expend more energy absorbing nitrogen in the form of ammonium ions (Chalmers 1979).

Concentrations of N, P and K in leaves and stems of cordgrass decrease exponentially during the early stages of growth and then follow a steady decline for the rest of the growing season (Figure 1a). Levels of nitrogen and phosphorus are comparatively high, bearing in mind that ash averages around 24% of the total dry weight (Figure 1a). Less potassium is present, particularly in young leaves, than in bracken or knotweed.

Losses of N, P and K during senescence are considerable (77%, 78% and 82% respectively), but much of this nutrient will be translocated below ground and stored overwinter in the rhizomes, as described for bracken. Soluble carbohydrate, starch and fat concentrations are low when compared with other species (Hubbard & Ranwell 1966), and show less clear seasonal trends (Figure 1b).

Above ground samples have been measured with ash concentrations as high as 37% (Callaghan et al. 1981). Some of this is in the form of internal silica bodies but much of the insoluble ash is from silt adhering to the surface of the plants. This ash fraction reduces the utilizable yield of biomass and must be considered in relation to the subsequent fuel conversion processes.

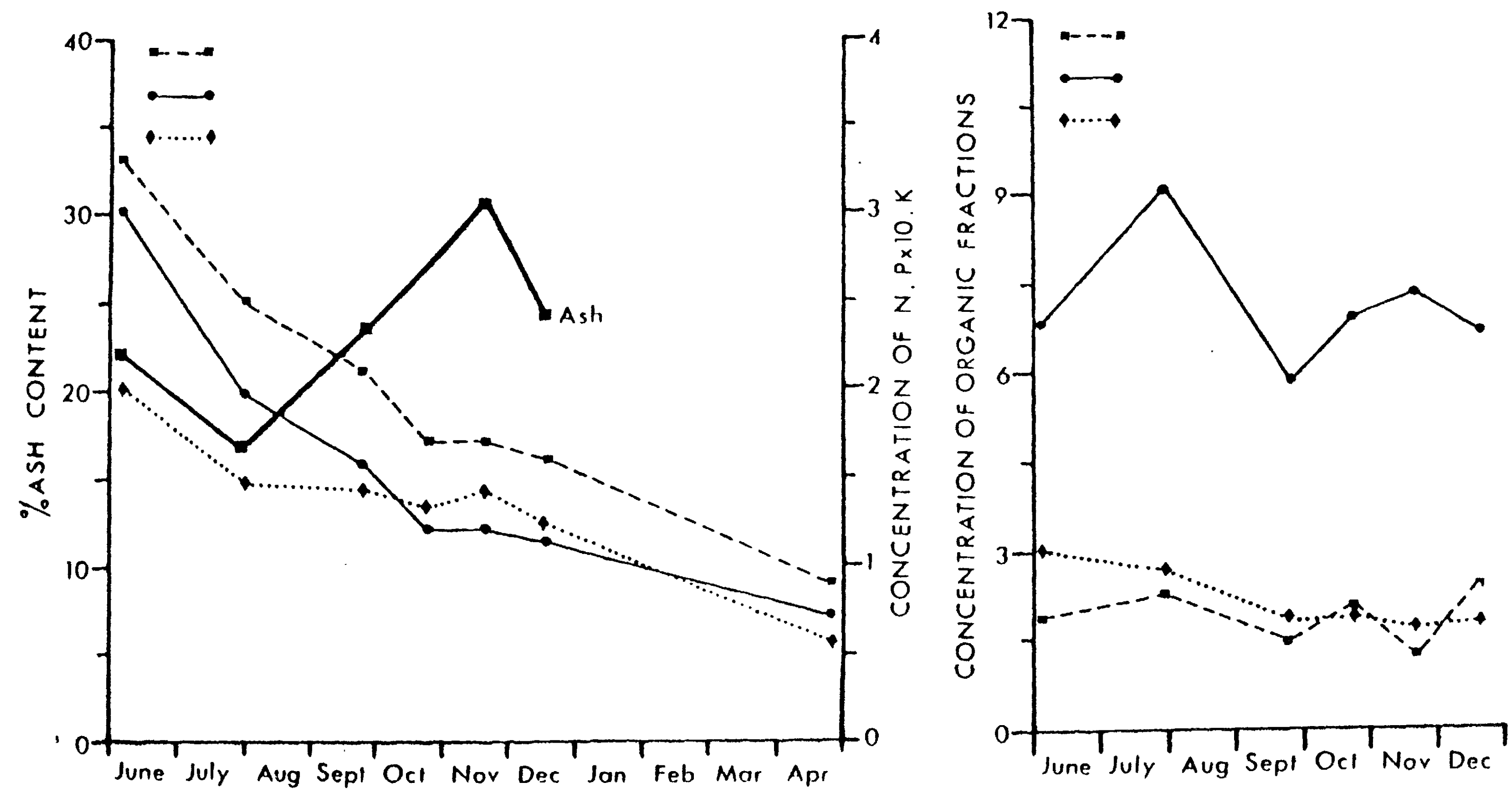

Figure 1. The seasonal trends of concentrations of inorganic (A) and organic (B) nutrients in shoots of cordgrass (% dry weight)

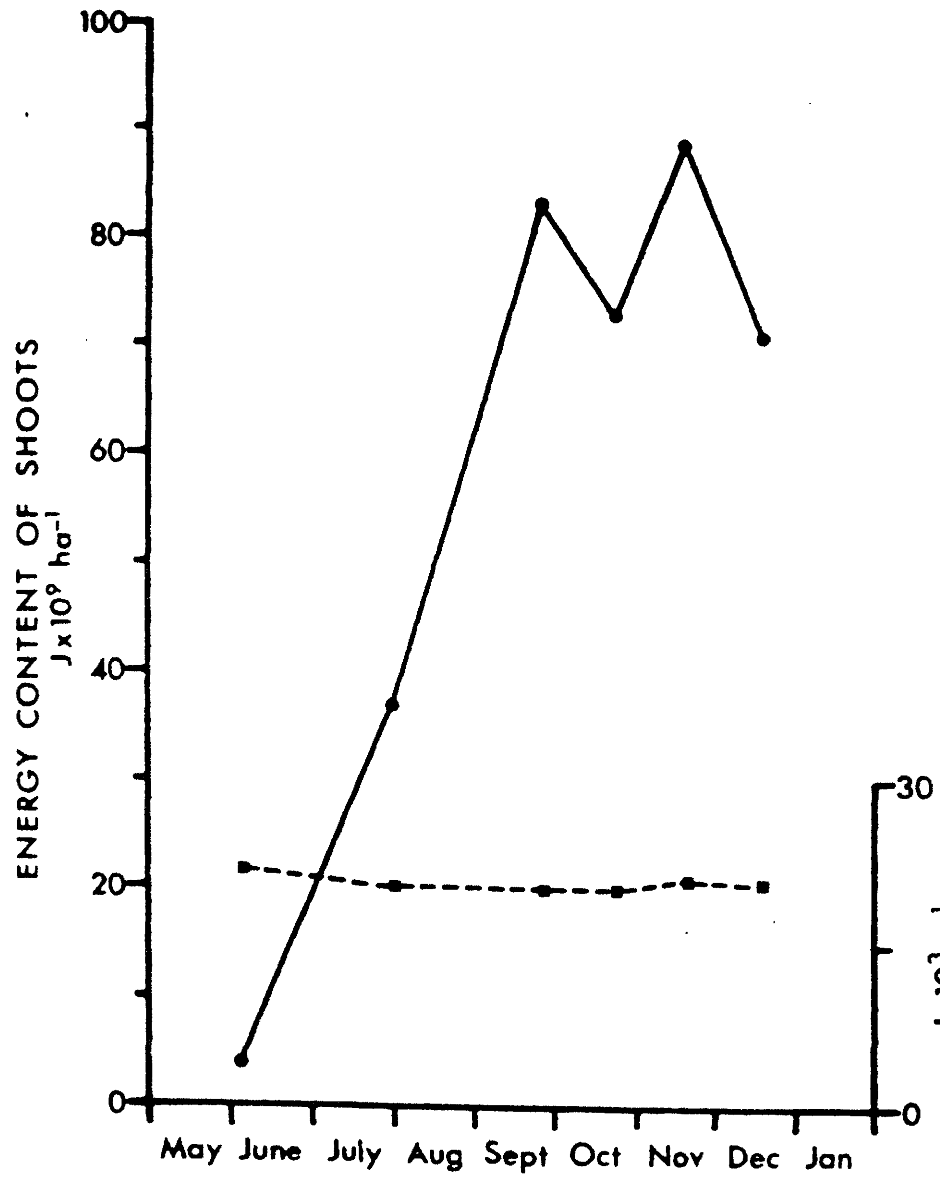

Figure 2. Energy values of cord grass

(——) content of shoots unit area^{-1}
(---) content of shoots g^{-1}

2.6 Energy value

The energy content of shoots, in terms of dry weight is 17.8 kJ g^{-1}, which is similar to many other species, and rather high for an aquatic plant (Callaghan et al. 1978 and 1981). Seasonal fluctuations are slight, and the total energy content of a crop of cordgrass is therefore primarily determined by seasonal dry weight trends (Figure 2).

2.7 Uses of cordgrass

Coastal mudflats are of no economic value, so the ability of cordgrass to colonize these areas either for grazing or to hasten the process of complete reclamation was quickly recognized (Oliver 1925). At Carentan in Normandy, an area of about 6 km^2 has spread within 17 years from a single introduction. Such deliberate introductions have hastened the spread of this species, and in the late 1960s Ranwell (1967a) listed the world resources of cordgrass at 250 km^2. He now reports (pers comm) that a similar area has been established in China from plants supplied in 1965.

The rapid accretion of silt fostered by the cordgrass raises the salt marsh level and gradually changes site conditions, bringing the plants of higher levels of salt marsh into an advantageous position over cordgrass. Sea meadowgrass, *Puccinellia maritima*, and red fescue, *Festuca rubra*, are valuable for sheep grazing and present a safe roost to coastal birds, a lower turf height being much preferred to the tall cordgrass shoots. With the correct management, establishment of cordgrass on mudflats could be a stage in the creation of new areas of short-turf salt marsh. In the USA the cordgrass areas of the Carolina coast have been regarded as a valuable resource and considerable expertise has been developed (Woodhouse et al. 1972) in the propagation and management of the native species, *Spartina alterniflora*. This technology could be applied to common cordgrass in Britain.

2.8 Cordgrass control

The benefits of cordgrass spread, as outlined above, have been balanced against the loss of existing wildlife habitat and the undoubted scenic intrusion of new beds of cordgrass into previously clear expanses of sand. The presence of adjacent areas of cordgrass may further impede current flow and make new areas subject to mud accretion and changes in the character of a beach from sand to silt and mud.

In southern England, the original eelgrass and algal community at the base of the salt marsh has been almost totally replaced by cordgrass (Ranwell 1967b). Scenic, beach quality and wildlife considerations have led local authorities and conservation bodies such as the Nature Conservancy Council to adopt preventative spraying, usually from the air with the herbicide Dalapon. Uprooting seedlings can be effective but is very labour intensive. Germination of seed occurs only in some years, so it may be possible through vigilance to eradicate young plants as and when they arise in new areas, but well-established patches are virtually impossible to eradicate. However, it is now possible to consider cordgrass, like bracken, in a positive way as a possible resource for the production of biofuels and as an agent for reclaiming coastal lands.

3 EXPERIMENTAL ASSESSMENT

3.1 Objectives and methods

The main objectives in the assessment of cordgrass as energy crop were almost identical to those previously presented for bracken (Callaghan et al. 1983), ie:

1. to establish an experimental site,
2. to measure yield in relation to applications of conventional fertilizer,
3. to assess the effects of time and frequency of harvesting on yield and regrowth,
4. to monitor the effects of climatic variables on yield,
5. to assess the digestibility of fresh cordgrass in an experimental anaerobic digestor,
6. to develop strategies for utilizing cordgrass,
7. to extend these results to a national level,

In order to measure yield in relation to fertilizer applications, time and frequency of harvesting and weather (objectives 2-4), an experimental site of 0.17 ha was established in 1980 at Southport, Merseyside (SD 354 206). A randomized split-split plot design was developed (see Appendix I) in which the following factors were assessed.

a. The effect of weather.

   Cordgrass was cut from previously undisturbed quadrats in 1980, 1981 and 1982. Differences between years, therefore, are entirely the result of weather conditions.

b. The effect of fertilizer.

   Each treatment was subdivided into 4 fertilizer regimes applied annually in April.

c. The effect of cutting.

   The regrowth of cordgrass in relation to frequency of harvesting was assessed after cutting a single previous cut (assessment in 1981 after cutting in 1980 and assessment in 1982 after cutting in 1981) and after 2 previous cuts (assessment in 1982 after cutting in 1980 and 1981). Each of the above treatments was repeated for 4 harvest dates to allow an assessment of regrowth in relation to time of harvesting.

The results of the experiment were subjected to a split-split plot analysis of variance (Appendix II) and more detailed comparisons were made using 2-way analyses of variance. The overall analysis showed that there were no significant effects of fertilizer inputs on yields (Appendix II). Consequently, fertilizer treatments are combined in the remaining comparisons.

Biomass collected from the above experiment on 21 November (ie green biomass) was processed by Dr D Stafford in an anaerobic digestor at Cardiff to determine the efficiency of digestion. The results from the field and conversion trials were formulated in suggested management options for the use of cordgrass. Local, regional and national impacts were also assessed (objectives 6-7), and are considered in Volume V of this series (Callaghan et al. 1984e).

3.2 The effect of weather on the performance of cordgrass

Cordgrass achieved its highest yields over the months of September, October and November in the years 1980 to 1982. The highest yield of living material (13.6 t ha^{-1}) was achieved in 1981, whereas lower yields and faster senescence took place in 1982 (Figure 3). These trends agree with those previously reported for bracken during the same years (Callaghan et al. 1984a). The association of high yields of living tissue with high yields of dead tissues (Figures 3A and B) suggests that at least some of the dead material harvested from previously undisturbed plots represents the current year's growth. The high total yield of 22.1 t ha^{-1} during 1981 (Figure 3C) must, however, include a significant proportion of dead tissues produced during 1980.

The differences in cordgrass yields between years are only slightly correlated with differences in stem density and stem height (Figures 4A and B). Interestingly the high yield in 1981 was achieved from a smaller leaf area index than that in 1980 (Figure 4D), a trend which has already been described for bracken (Callaghan et al. 1983a). As in the case of bracken, leaf area indices are very high when compared with agricultural crops, but are generally lower than those of bracken.

The performance of cordgrass in each of the 3 years investigated is probably related to spring frosts, air temperatures, tides and storms. Information on weather conditions collected at Southport (Figures 5 & 6) are similar to those collected at Merlewood (Callaghan et al. 1984a) but yearly differences appear insufficient to account for the variations in yield of cordgrass. It would be expected, however, that the drought which affected bracken during 1980 would be irrelevant in the estuarine habitat of cordgrass and that local effects due to the great exposure of the foreshore vegetation would be dominant. The observations on yields under varying weather conditions suggest that 9.6 to 13.6 t ha^{-1} yr^{-1} can be harvested during the months of September, October and November and that the time of harvesting is not critical in relation to size of yield.

3.3 The effect of fertilizer applications

Evidence from the literature (Section 2.5) suggested that cordgrass yields may be increased by an application of nitrogen, but that there is unlikely to be an effect from applications of phosphorus or potassium. Nevertheless, to maintain continuity of treatment between the 3 study species, and to examine the relationship between any fertilizer effect and the intensity of harvesting, various levels of mixed fertilizer (20N: $10K_2O$: $10P_2O_5$) were applied annually to the Southport study site over a 3 year period.

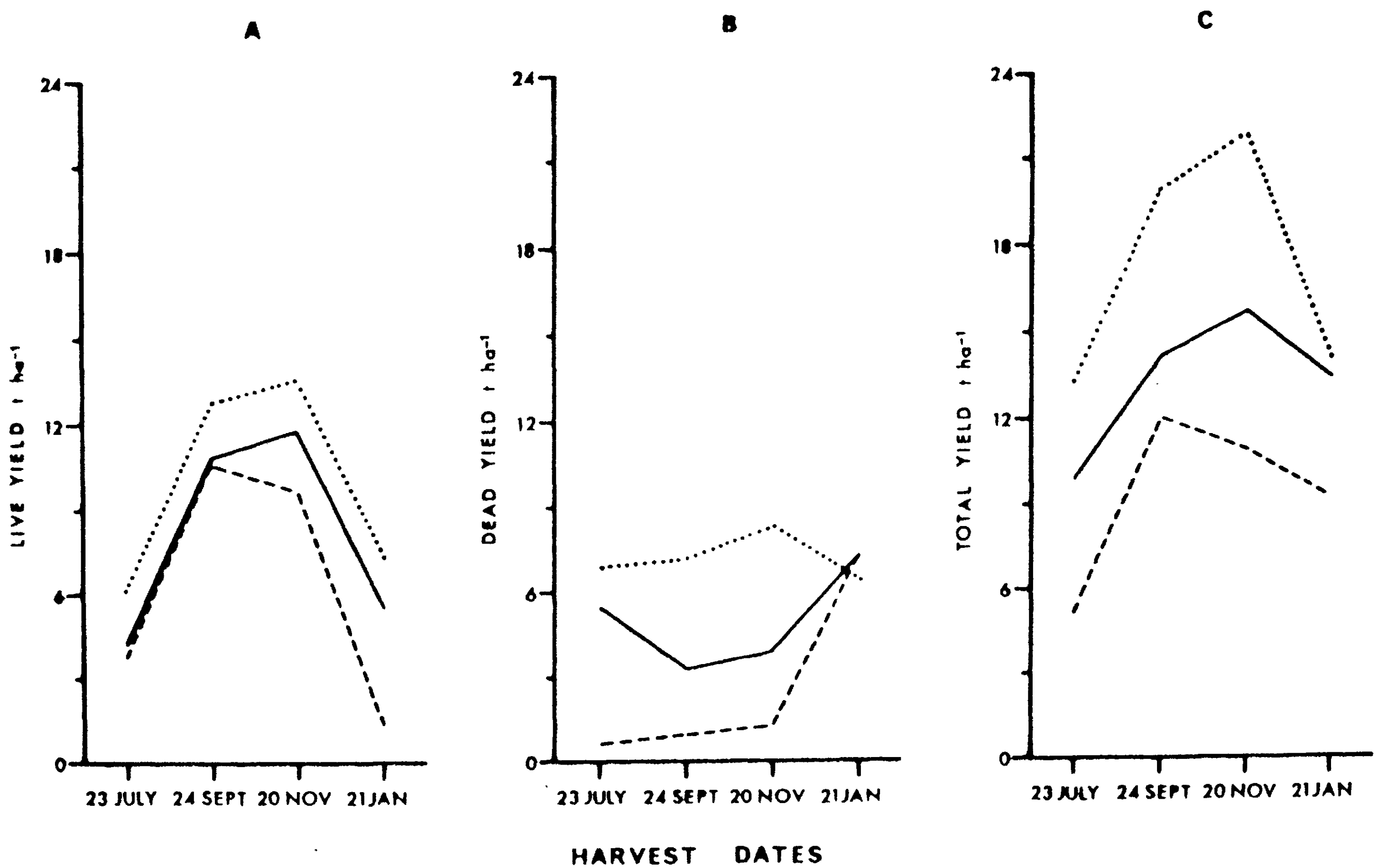

Figure 3. Seasonal development of cordgrass yields in 1980 (——), 1981 (···) and 1982 (---)

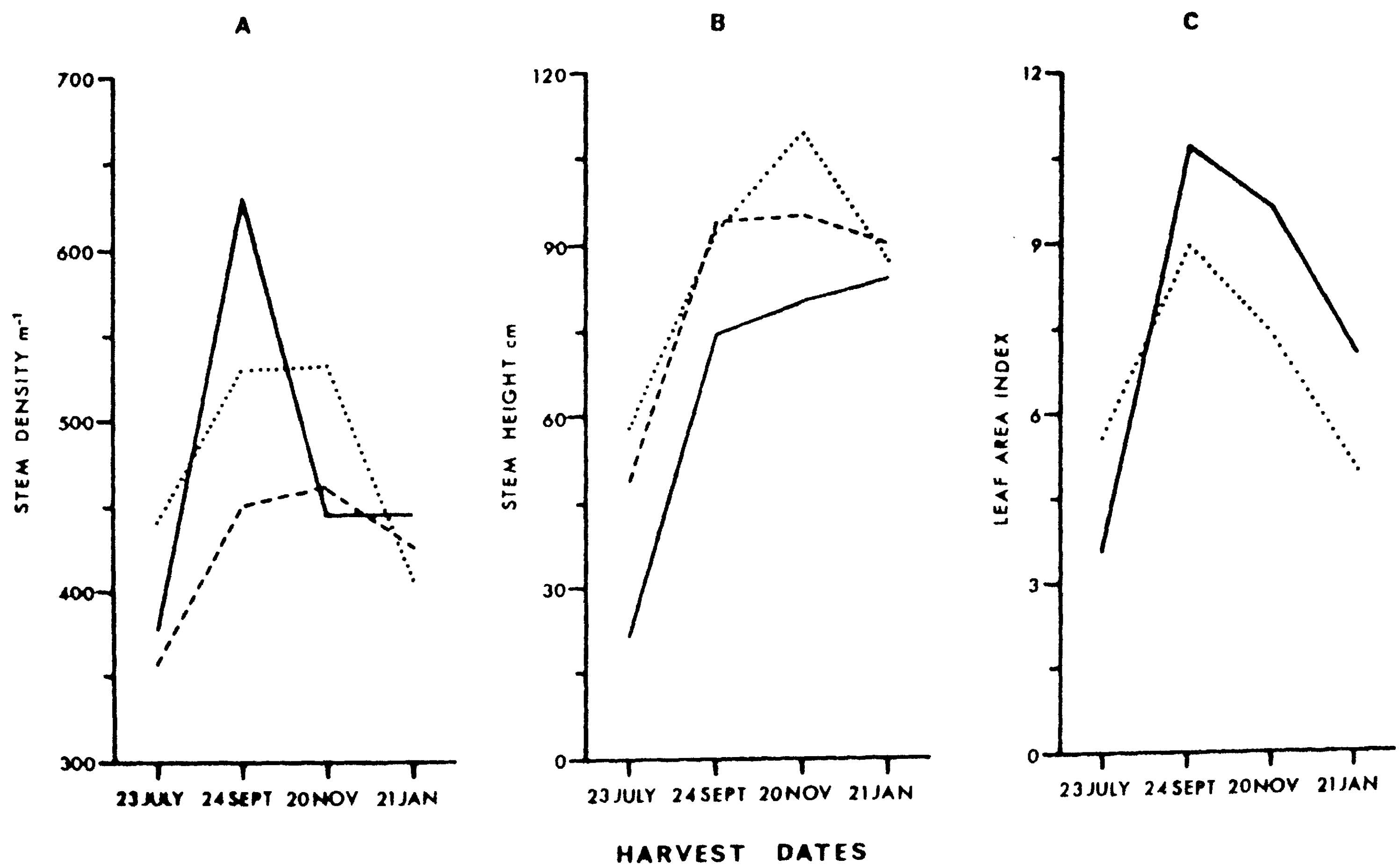

Figure 4. Seasonal development of cordgrass stem density (A), stem height (B) and leaf area index (C) in 1980 (——), 1981 (···) and 1982 (---).

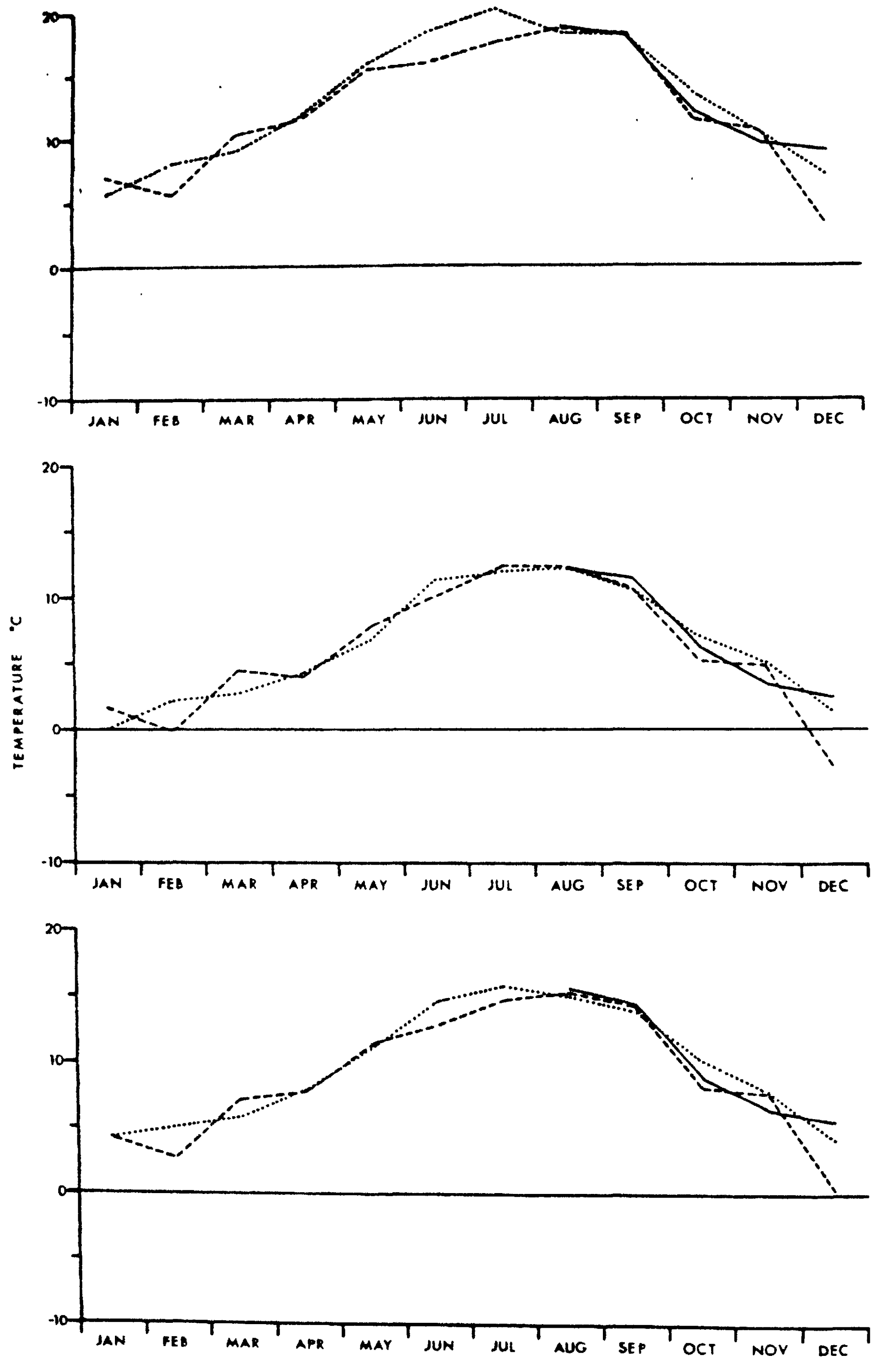

Figure 5. Monthly maximum (A), minimum (B) and mean (C) temperatures recorded at Southport in 1980 (——), 1981 (---) and 1982 (···)

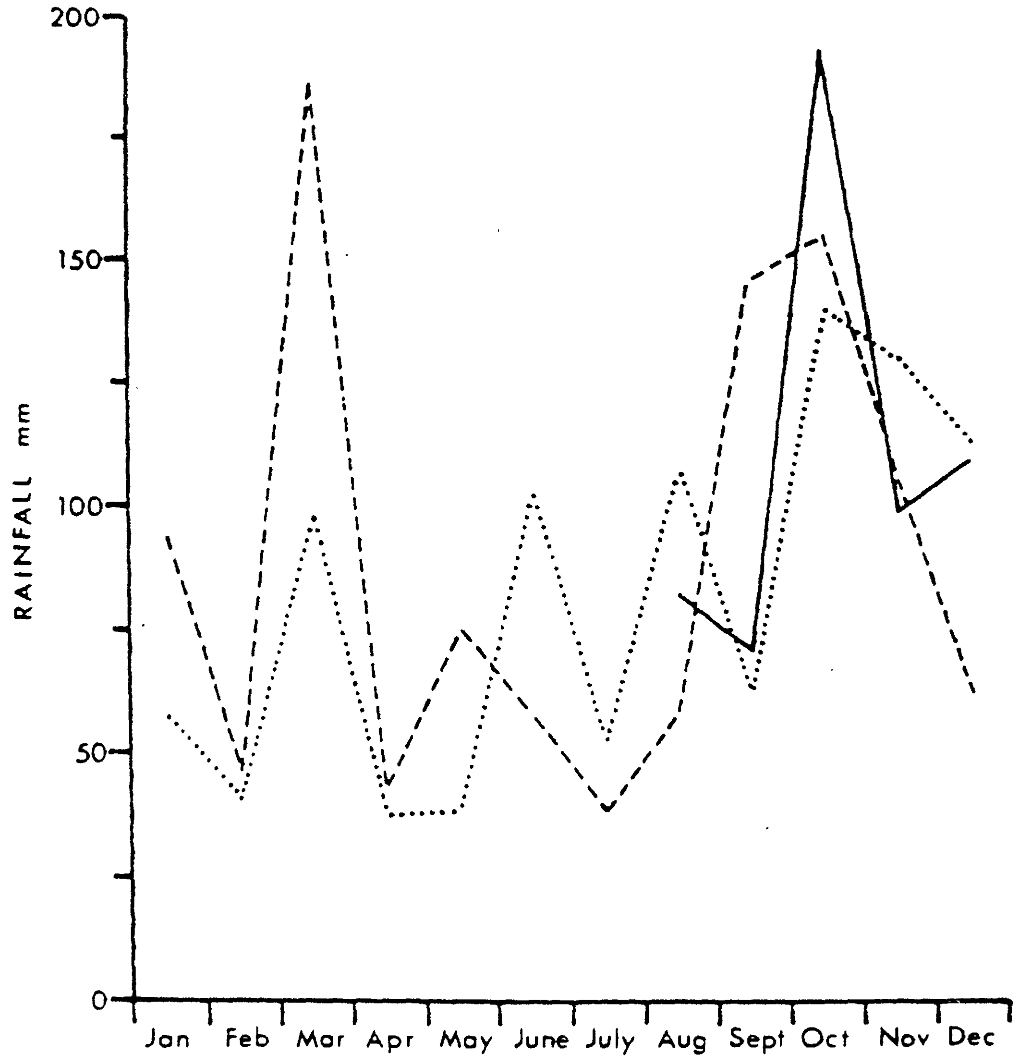

Figure 6. Rainfall monthly totals at Southport recorded in 1980 (——), 1981 (---) and 1982 (···)

No significant response was observed in previously unharvested quadrats (Appendix II), and only in those quadrats receiving 3 successive annual harvests was a slight response identified. This was present in stem height measurements and not in yield (Figure 7). Thus it may be inferred that nutrient supply at the Southport site is adequate at least for 3 years of continuous harvesting.

In the longer term it may be necessary to contemplate replacement of the nitrogen removed in harvests. Assuming 3 years of continuous harvesting this amounts to approximately 155 kg ha^{-1} from November harvests and 113 kg ha^{-1} from harvests in January. The total replacement cost would be around £69.5 ha^{-1} and £52.7 ha^{-1} respectively (Nix 1982 & Farm Contractor Magazine, June 1983).

3.4 The effect of frequency and date of cutting

Callaghan et al. (1981) predicted that harvesting perennial herbaceous plants in autumn, after translocation of nutrients to rhizomes had occurred, would depress subsequent yields less than harvesting in summer. This was verified experimentally for bracken (Callaghan et al. 1983a) and can also be observed with cordgrass (Figure 8A).

The harvesting of cordgrass in summer depressed yields in the following summer by 60%, whereas harvesting in autumn depressed yields, by only 19% (Figure 8A). Harvesting in mid-summer reduced stem density, stem height and leaf area index in the following summer (Figures 8B,C,D), whereas harvesting in early summer greatly increased shoot density in the following year.

When cordgrass had been harvested in the 2 previous years, yield in the third summer was depressed by only 13%, whereas autumn harvesting decreased yields by only 1% (Figure 9A). In the third year of annual harvesting, yields were maintained by an increased density (Figure 9B) of smaller shoots (Figure 9C).

Although yields of cordgrass were depressed by summer harvesting, a high mean yield of 15.4 t ha^{-1} yr^{-1} could be attained over a 2-year period, whereas a mean of 12.9 t ha^{-1} yr^{-1} was attained over a 3-year period. With autumn harvesting, these yields were 11.6 and 11.3 t ha^{-1} yr^{-1} respectively (Figure 10). These yields are high for annually harvested perennial vegetation on underutilized land, but the trend of decreasing yield suggests that occasional rest years would be required at some stage to sustain the vegetation as an annual energy crop. Bryce (1941), on the other hand, gives a casual report of no yield reductions after 3 years of continuous harvesting, and observation does suggest that a large part of the decrease in yield reported here may be caused by trampling during harvesting rather than a gradual weakening of the plant. The optimum rotations of harvesting and resting remain, therefore, to be determined, and may in part depend upon the harvesting machinery employed.

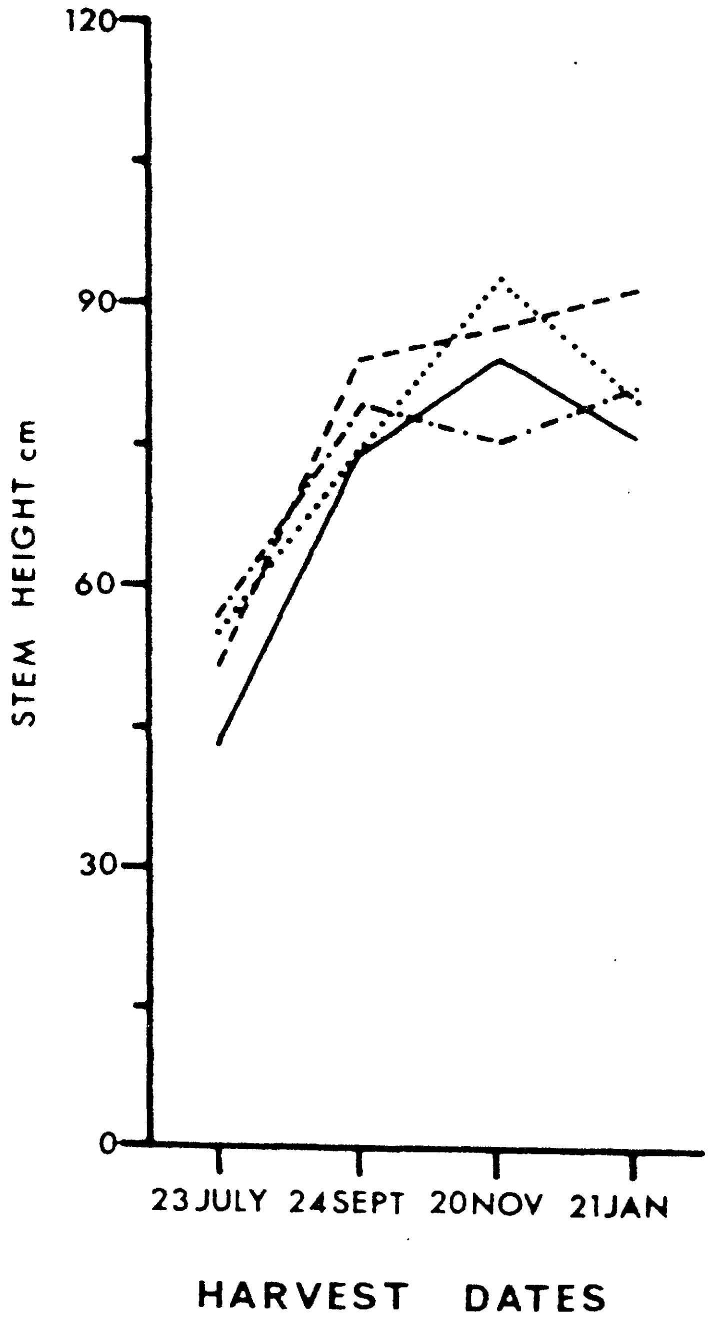

Figure 7. Effect of the level of fertilizer application on cordgrass stem height after 3 years of harvesting

—— 0g m^{-2}
--- 50g m^{-2}
··· 100g m^{-2}
-·-·200g m^{-2}

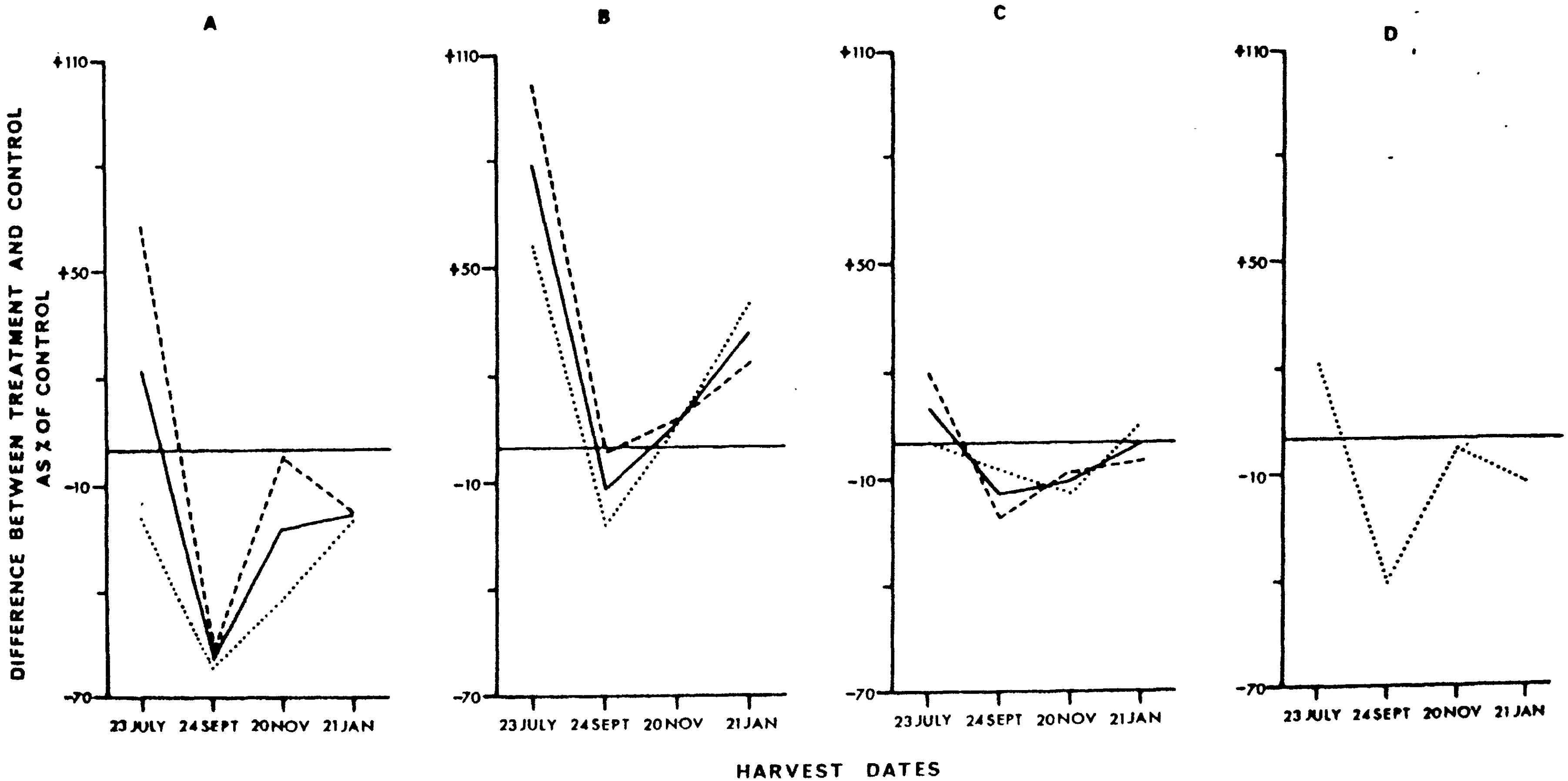

Figure 8. Effect of 1 previous cut on cordgrass yield (A), stem density (B), stem height (C) and leaf area index (D)

--- 1981 cut in 1980 and 1981 on the same date
... 1982 cut in 1981 and 1982 on the same date
—— mean

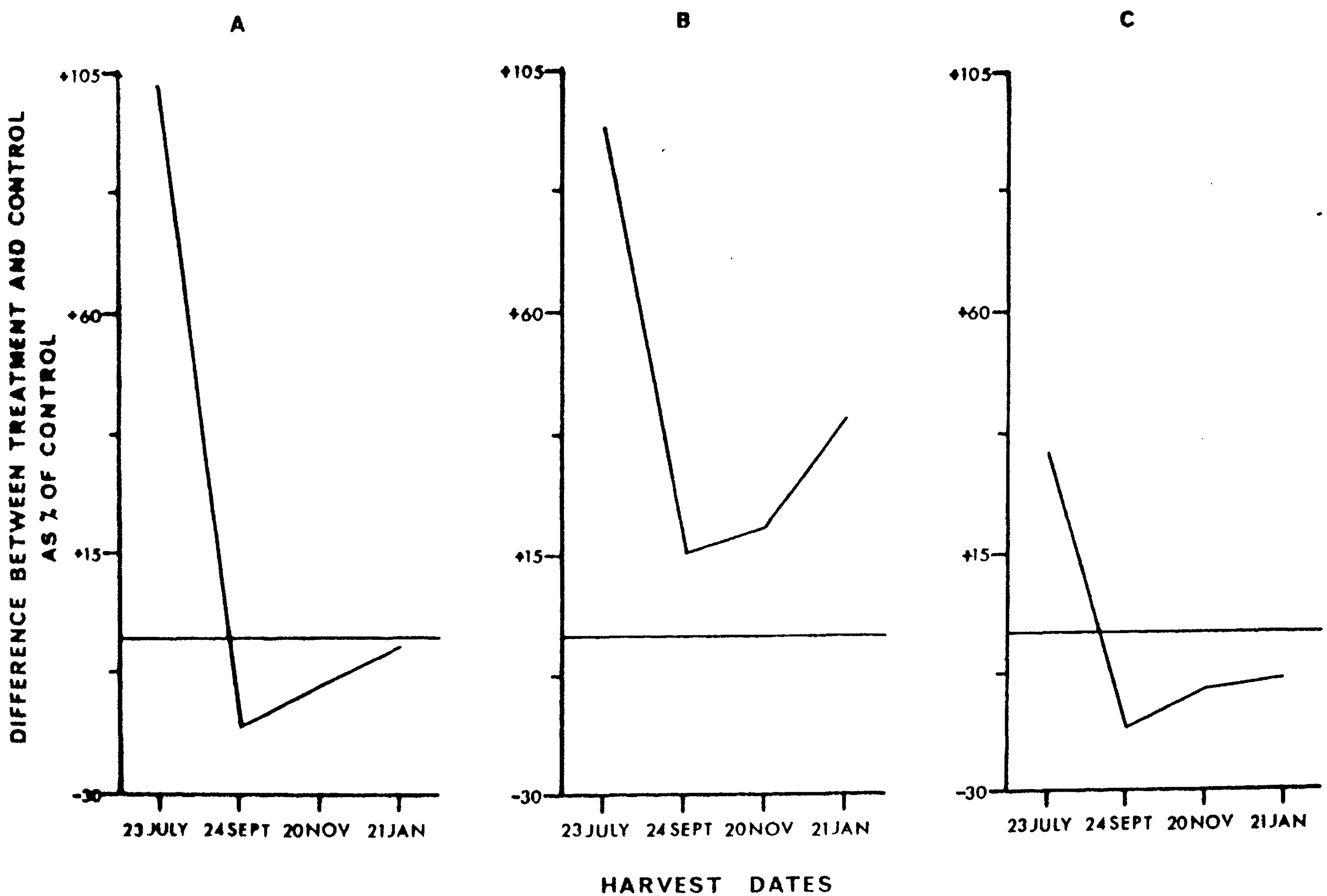

Figure 9. Effect of 2 previous cuts on cordgrass yield (A), stem density (B) and stem height (C). Harvests were carried out on the same date in each of the 3 years.

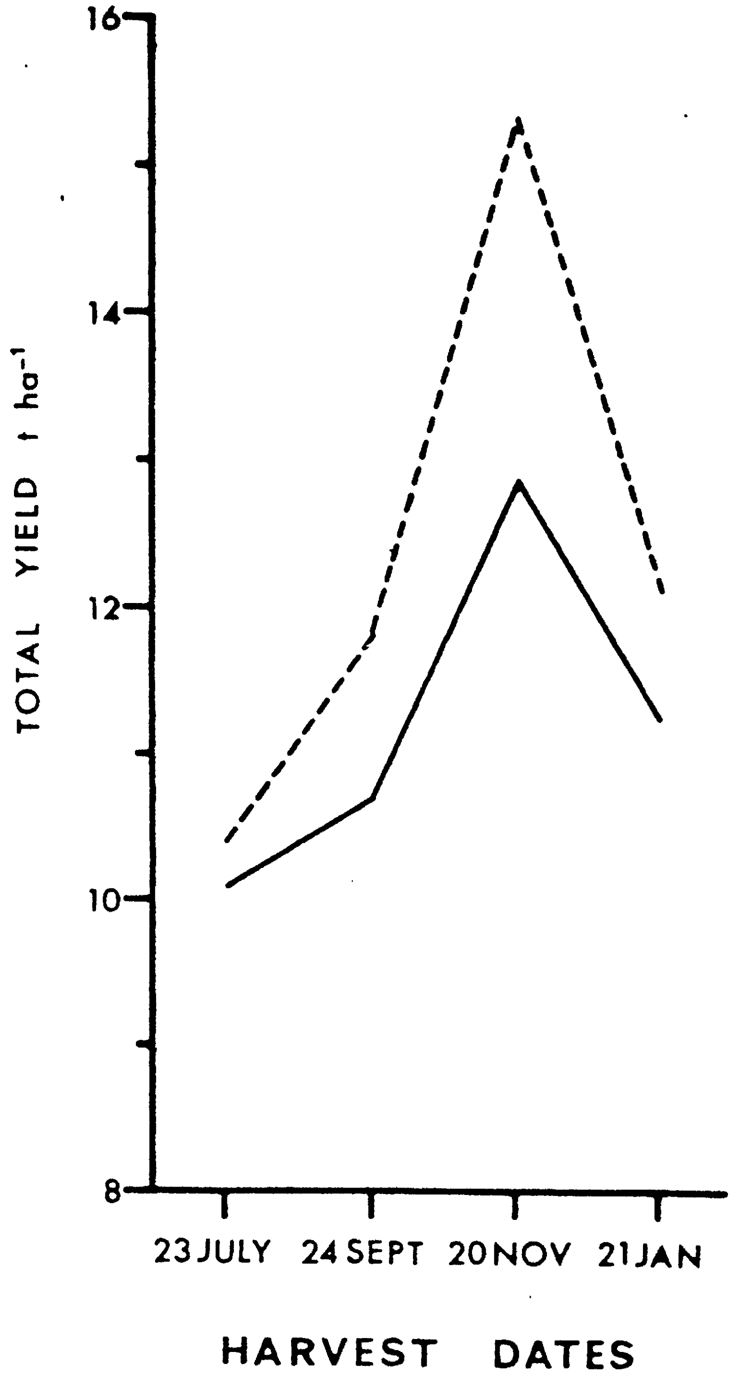

Figure 10. Mean yields of cordgrass in the same sample area after harvesting annually for 2 (---) and 3 (——) years

4 THE CONVERSION OF CORDGRASS TO FUELS

Conversion methods for cordgrass are similar to those described for bracken. Alcoholic fermentation or enzymatic hydrolysis to ethanol is not considered a likely near-term option for these species, so discussion has centred on thermal conversion or anaerobic digestion.

Cordgrass harvests over the first 3 years had an average moisture content of 78%, and, since drying in situ is impossible, it is unlikely that thermal conversion methods would be economic. Also, ash contents of up to 38% have been measured in cordgrass leaves, and this may cause caulking problems in combustion units.

Nevertheless, Have (1982) has generated supplies of low grade heat from very wet organic wastes, using an efficient heat exchange and gas scrubbing system. This system is claimed to be economically viable. Cordgrass is preferentially grazed by animals, and has a high feeding value as silage (Hubbard & Ranwell 1966; Bryce 1941). This indicates that crop fractionation to separate protein-rich leaf juices from the residual fibres could well be viable with this species, but partial composting may be necessary to soften the leaves sufficiently for juice to be extracted (Das & Ghatnekar 1981). Fractionation involves considerable pressure and dries the residues to a point where they may be economically used in a pelletizer. Pellets have not yet been produced from cordgrass, but one anticipated problem is rapid wear on the die and piston caused by passage of large quantities of silt and leaf silica.

Anaerobic digestion of cordgrass, harvested around September when digestible yield is at a maximum, is the most likely conversion method. Samples collected on 24/9/80 were processed in a 5 l anaerobic digestor with a 100 days hydrolic retention time (Table I). The yield of 0.38 m^3 kg^{-1} volatile solids is lower than achieved with Japanese knotweed or bracken, but is comparable to that from other crops and wastes (Loll 1976). Inefficient digestion of plants with high salt concentrations has been reported (Gosh et al. 1976) but modified digestor designs, with high solids retention times, can produce methane at more than 70% efficiency (Fannin et al. 1982).

TABLE I (Stafford & Hughes 1981)

Energy recovery from cordgrass by anaerobic digestion

1 tonne fresh cordgrass	=	249 kg volatile solids
249 kg volatile solids give		95 m^3 biogas
95 m^3 biogas	=	2.12 GJ
and 1 t fresh cordgrass contains (@ 70% moisture and 18.2 kg g^{-1})		5.46 GJ
Therefore, efficiency of conversion (excluding process energy)	=	38.8%

5 METHODS AND COSTS OF CORDGRASS MANAGEMENT

5.1 Establishment

Whilst cordgrass may cover in excess of 120 km^2 around the British coast, there are many areas into which it could be introduced as an energy crop. Spartina species have been established throughout the world as a means of stabilizing and reclaiming land (Chapter 2) and experience therefore exists in planting techniques. Cordgrass spreads naturally by both vegetative and sexual means, and Bryce (1941) indicates that a closed cover can be attained in 3 years with cuttings planted as much as 1 m apart. Plantation methods have been automated (Woodhouse et al. 1972) and are similar to the techniques used for rice, and in trial energy plantations of reedmace (Typha latifolia) - Pratt et al. 1983) or reed (Bjork & Graneli 1978). Seedlings or portions of rhizomes could be planted using a low ground-pressure cabbage or bulb planter, but it is unlikely that the process can be fully automated and manual labour will still be required to position the plants within the furrows made by the planter. Reeds have been successfully established by aerial sowing of seed on 36 000 ha of newly created Dutch Polder (Hemminga & van der Toorn 1970), and this may also be a means of rapidly creating energy plantations of cordgrass around the British coasts.

5.2 Harvesting

Whilst mechanical planting methods are well established, only one experimental mechanical harvest of cordgrass has been made (Hubbard & Ranwell 1966). In this a Bolens 9 hp horticultural tractor was fitted with track-grip tyres and used to power a 1.2 m cutter bar. Only 0.4, was harvested, and the trial was designed to assess the silage making qualities of cordgrass rather than its potential as an energy crop.

Techniques used in reed harvesting should be applicable to cordgrass. The most appropriate reed harvesting platform is the Seiga Giant Tortoise (Plate II). This operates on 6 balloon tyres, and has a ground pressure of 40 g cm^{-2} when empty and less than 100 g cm^{-2} when stacked with a 3 tonne load. Other reed harvesting operations have employed half-tracks or full tracks (Meier 1978). Recent development of harvesting machinery in Sweden has included chopping and blowing cut reed portions into a trailed, low ground-pressure, forage waggon.

Harvesting of reed and reedmace normally takes place at the end of autumn or during winter, at a time when the leaf moisture content has declined, perhaps to as little as 20% (Graneli et al. 1982). Senescent shoots of cordgrass, however, do not dry out significantly during the damp British winters, and this will reduce the dry weight which can be carried in a trailer and will also involve drying costs prior to thermal conversion.

Artificial control of the water level on areas of rushes and reeds can considerably increase yields by eliminating the effects of frosts or droughts (Rodewald-Rudescu 1974), and sluices are also used in autumn to ensure that the ground is sufficiently dry to carry the weight of harvesting vehicles. On saltmarshes, however, it is unlikely that sluice systems will be constructed, and cordgrass harvests should be timed to coincide with periods of neap tide.

As indicated in Chapter 2, the below ground biomass of cordgrass can be more than double the above ground standing crop. Given the ability of this species to spread rapidly by vegetative means into new areas of saltmarsh, it is possible to consider harvesting some of this below ground biomass. Friend (1982) suggested biannual strip harvesting of reedmace, leaving undisturbed zones from which regeneration could take place. Such a scheme may be possible with cordgrass, particularly in sandy areas, but it is uncertain whether the engineering difficulties and costs involved in rhizome harvesting will be justified, even in the long term.

5.3 Economic implications

Prototype machinery is currently being developed for large-scale energy cropping of reeds (Graneli et al. 1982), and only tentative estimates are published for the cost of generating a combustable fuel in the form of powder or pellets. Harvest costs have been quoted for reeds in Sweden of \$50 per tonne (Bjork & Graneli 1978), although more recently it was estimated that reeds could be chopped, harvested and transported to a local store for around \$35/tonne (Runnerus 1980). A Rumanian fibre-board factory is said to have paid \$85/tonne for dry reeds (De La Cruz 1978), and Friend (1981) has estimated that cattails could be established in plantations and harvested for \$45 per tonne for the stalks and \$57 for the rhizomes.

Reed harvesting in this country is highly labour intensive, and is aimed at the production of high quality thatching bundles. These are currently sold at £0.80 per bundle (Habgood pers comm), which converts to around £220 per dry tonne! The paucity of economic information on harvesting schemes for emergent aquatic plants has been stressed in a review by Kresovich et al. (1981), and, as cordgrass has no agricultural analogue in this country, adequate costings are dependent upon the establishment of a harvesting trial.

6 ENVIRONMENTAL IMPACTS

6.1 Biomass production

The planned use of areas of cordgrass for biomass should cause few environmental problems. Harvesting during autumn would enable the continued breeding of birds during the nesting season, but the removal of biomass may decrease the rate of sediment accumulating and foreshore stabilization. Mechanized harvesting equipment is designed to have minimal effect on the vegetation through compaction so that site disturbance leading to erosion is not envisaged as a problem resulting from site management. Indeed, as the effect of continued harvests is to increase stem density, the net effect of harvesting may be to increase the trapping of silt.

If cordgrass proves to be a successful energy crop, the artificial establishment of new areas under the crop would lead to increased habitats for wildfowl and the stablization of new areas of foreshore. Holiday resorts may, however, regard the encroachment of vegetation upon their mudflats with some displeasure.

6.2 Biomass conversion

The conversion of cordgrass to fuel and its subsequent use should provide no greater environmental impact than the conversion of other species (Callaghan et al. 1983a),

Operations would, presumably, be carried out by municipal authorities or contractors and this new industry could lead to some local stimulation of the economy.

The combustion of cordgrass, if carried out inefficiently, could lead to the release of particulates and polycyclic hydrocarbons but much less sulphur dioxide would be released than from burning equivalent quantity of fossil fuel. Generally, the use of biomass as a fuel has the advantage that over a large area the release of CO_2 from burning biomass is balanced by its uptake during photosynthesis.

7 CONCLUSION

Cordgrass is a very productive species of completely unutilized land. Its ecology suggests that it would make an ideal energy crop: in that fertilizer treatments are unnecessary, the crop is resilient to frequent harvesting, and the species can be introduced easily into new estuarine habitats to stabilize the foreshore. Harvesters are already in operation for similar types of plants and the management of cordgrass is technologically feasible. Further studies are required, however, into the economics of managing comparatively small areas of vegetation.

It is perhaps the conversion of cordgrass to usable fuels which presents the greatest problem in the exploitation of cordgrass as an energy crop. High ash contents may introduce problems of caulking during thermal conversion, and high moisture levels may make the process uneconomic. Anaerobic digestion, particularly when associated with secondary products such as protein or fertilizer, may prove an economically feasible option. Further investigation is required, however, into the technical and economic feasibility of managing this resilient and high yielding crop and converting it into usable fuels.

8 ACKNOWLEDGMENTS

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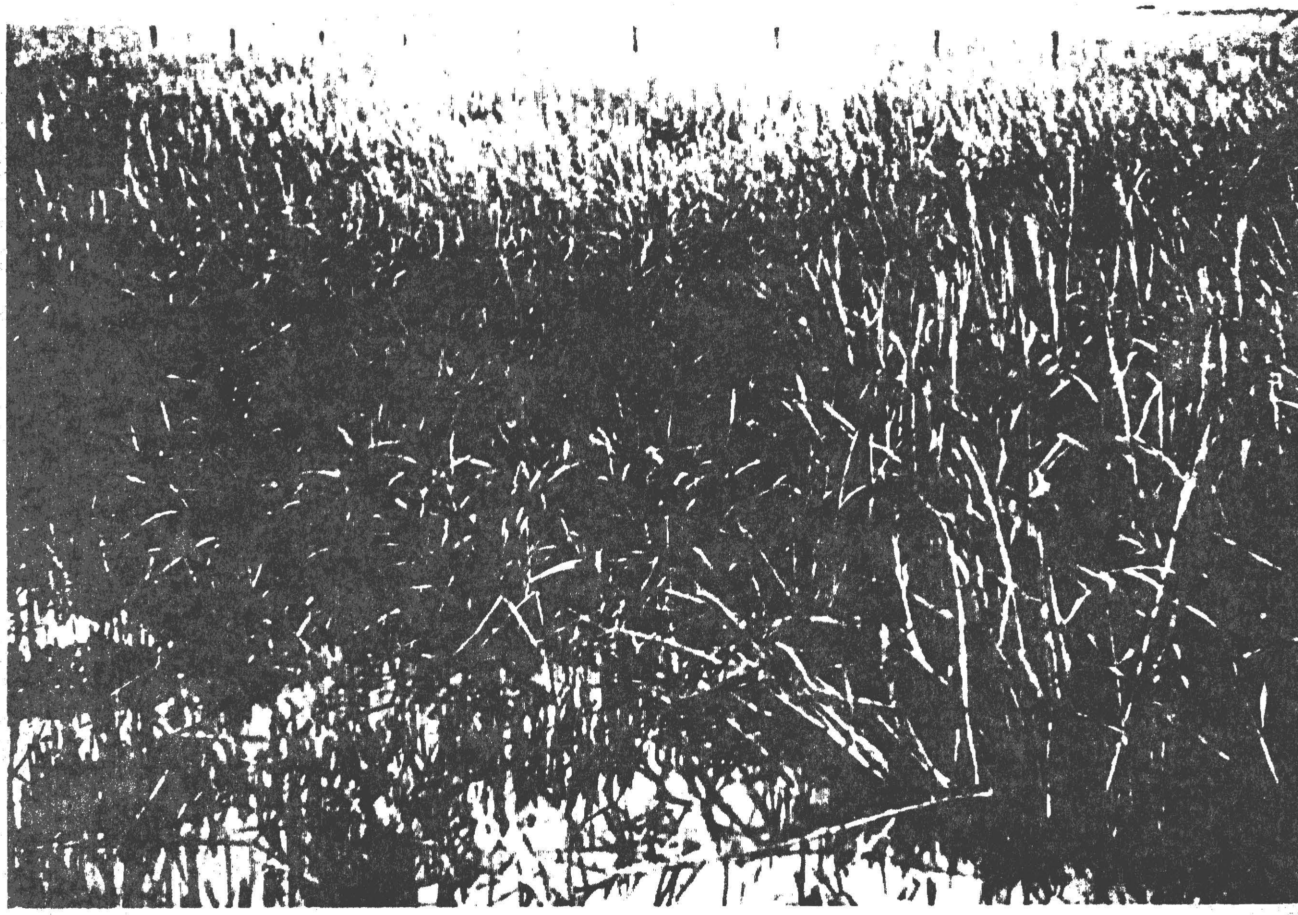
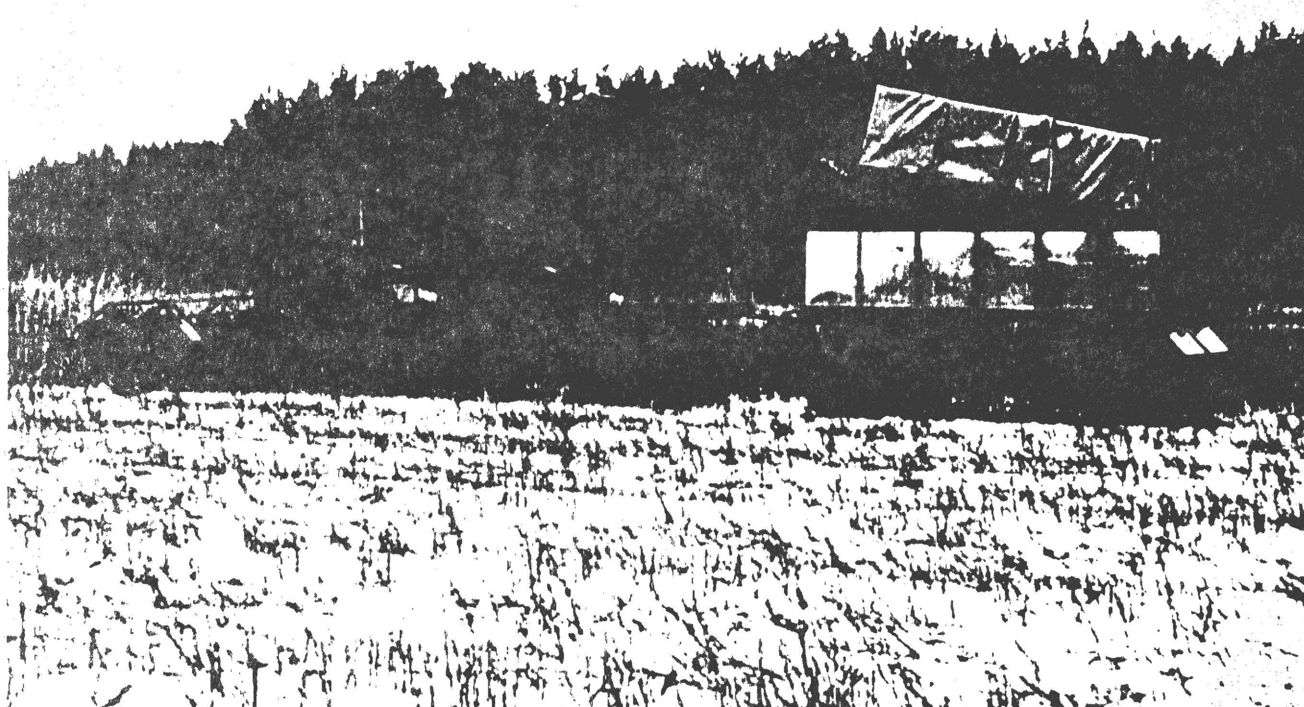


Plate I. Cordgrass (*Spartina anglica*), showing regrowth from quadrats cut at different times of year.

Plate II. A Seiga Giant Tortoise harvesting reeds for energy in Sweden. This has a ground pressure of 40 $g\ cm^{-2}$ when empty and 100 $g\ cm^{-2}$ with a 3 tonne load.



APPENDIX I

Methods

Field site

On a vigorous stand of cordgrass at Southport, Merseyside (map ref. SD 354206). The site lies at 3 m AOD on a coastal mud flat which is subject to tidal flooding and decomposition of silt.

Experimental design

Based on a 3 x 3 m quadrat (Figure I.1) which included a 1 x 1 m sample square surrounded by a 1 m buffer zone, the total size of the plot was 48 x 36 m. The 4-replicated year treatment blocks were randomly placed and each contained 4 fertilizer treatment blocks. Within each of these 6 x 6 m blocks were 4 randomly arranged quadrats for harvest at different times within the year (Figure I.2).

Harvest dates	H_1	H_2	H_3	H_4
	23 July	24 Sept	20 Nov	21 Jan

Standing vegetation was cut on the specified dates as close as possible to ground level. A 25 x 25 cm quadrat was placed randomly in the sample area, and the stems within it counted. In the initial harvest of each quadrat all standing material including standing dead was gathered. Material from the central 1 m^2 sample area was kept separate and returned to the laboratory in polythene sacks, stems being kept intact for later measurements. The outer area of the 3 x 3 m quadrat was cleared and the cuttings discarded off-site. This zone acted as access within the site and as a buffer between adjacent treatments.

Fertlizer levels	F_1	F_2	F_3	F_4
	No application	0.5 t ha^{-1}	1 t ha^{-1}	2 t ha^{-1}

Fisons "Regular" 20:10:10 NPK granules were applied by hand during available dry days in late April or early May. Care was taken not to trample the sample areas and to ensure an even spread of granules over the 3 x 3 m quadrats.

Year treatments	Y_1	Y_2	Y_3
	Cropped in 1980,81,82	Cropped in 1981,82	Cropped in 1982 only

Differences in frequency of harvest were designed to assess the effect of cutting on subsequent yields.

Laboratory analyses

Fresh weight of whole samples was recorded soon after sampling and a short period of storage at 4° C was usually necessary before the samples could be analysed. 10 stems were selected at random for height (from cut to tip of newest leaf) measurements. The samples were dried in a ventilated oven at 80° C to constant weight. The dry weights were recorded to determine yield.

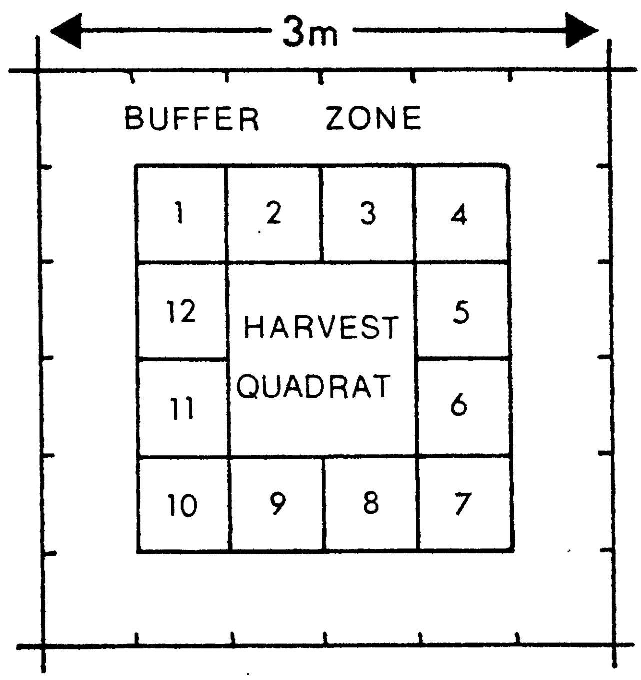


Figure I.1 Basic sampling unit at the field site

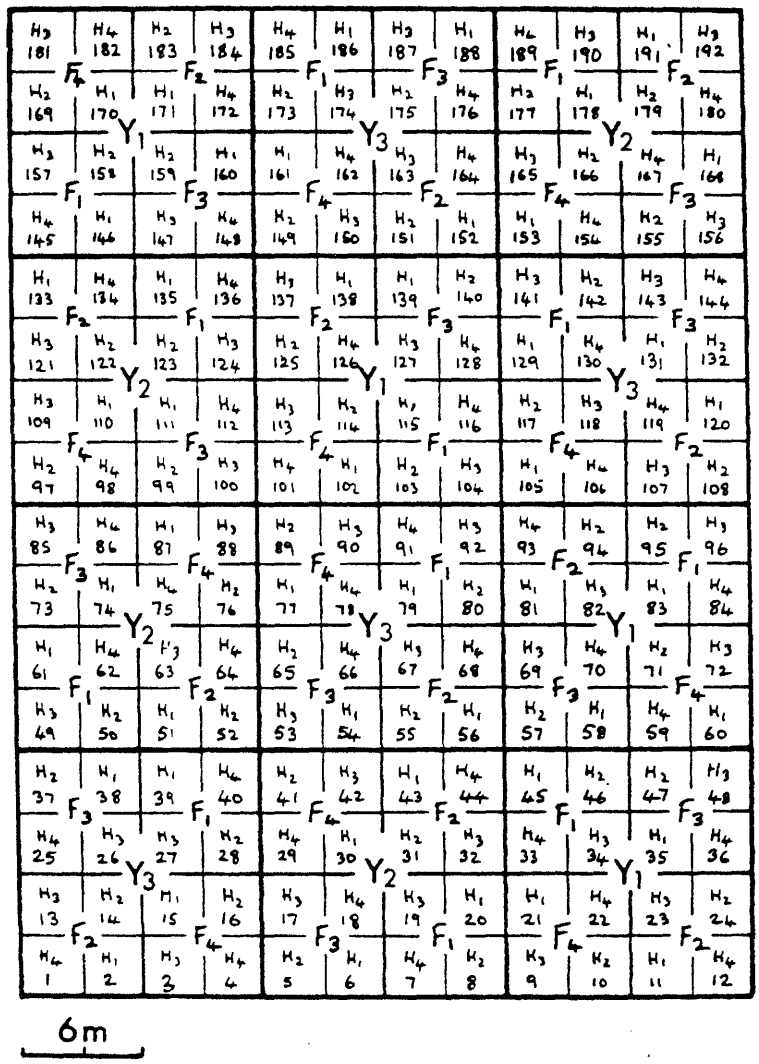


Figure I.2 Layout of cordgrass field site

APPENDIX II

STATISTICAL RESULTS: OVERALL SPLIT-SPLIT-PLOT ANALYSIS OF VARIANCE

Cordgrass yield

	df	ss	ms	F	Results
Years	2	1074402	537201	8.34	$P < 0.05$
Error (1)	9	579628	64403	0.76	
Fertilizers	3	896992	298997	2.73	$P > 0.05$
Years x Fertilizers	6	263486	43914	0.41	$P > 0.05$
Error (2)	27	2953736	109398	1.29	
Harvest dates	3	2701015	900338	10.61	$P < 0.001$
Years x Dates	6	5287273	881212	10.37	$P < 0.001$
Fertilizers x Dates	9	580368	64485	0.76	$P > 0.05$
Years x Fertilizers x Dates	18	1053445	58525	0.69	$P > 0.05$
Error (3)	108	9163432	84847		
Total	191	24553779			

Cordgrass stem density

	df	ss	ms	F	Results
Years	2	979082	489541	8.17	$P < 0.05$
Error (1)	9	539541	59949	1.72	
Fertilizers	3	112974	37658	1.07	$P > 0.05$
Years x Fertilizers	6	68473	11412	0.32	$P > 0.05$
Error (2)	27	952767	35288	1.01	
Harvest dates	3	367929	122643	3.51	$P < 0.05$
Years x Dates	6	724654	120776	3.46	$P < 0.01$
Fertilizers x Dates	9	170139	18904	0.54	$P > 0.05$
Years x Fertilizers x Dates	18	464474	25804	0.74	$P > 0.05$
Error (3)	108	3767740	34886		
Total	191	8147773			

Cordgrass stem height

	df	ss	ms	F	Results
Years	2	1335.6	667.8	1.66	P > 0.05
Error (1)	9	3616.5	401.8	3.08	
Fertilizers	3	445	148.3	0.99	P > 0.05
Years x Fertilizers	6	598.9	99.8	0.67	P > 0.05
Error (2)	27	4023.3	149.0	1.14	
Harvest dates	3	55380	18460	141.38	P < 0.001
Years x Dates	6	4241.5	706.9	5.41	P < 0.001
Fertilizers x Dates	9	830.9	92.3	0.7	P > 0.05
Years x Fertilizers x Dates	18	1480.6	82.3	0.63	P > 0.05
Error (3)	108	14101.7	130.6		
Total	191	86053.9			

APPENDIX III

STATISTICAL RESULTS: ANALYSES OF DATA PRESENTED IN THE FIGURES

Data Source	Comparison	Statistical test	Results
Cordgrass live yield	a) between harvest times		P<0.001 (F = 125.43 with 3 and 11 degrees of freedom)
Fig 3A	b) between years (previously uncut)	2-way anovar	P<0.001 (F = 35.58 with 2 and 11 degrees of freedom)
	c) Interaction		P>0.05 (F = 2.72 with 6 and 11 degrees of freedom)
Cordgrass dead yield	a) between harvest times		P<0.001 (F = 18.91 with 3 and 11 degrees of freedom)
Fig. 3B	b) between years (previously uncut)	2-way anovar	P<0.001 (F = 46.46 with 2 and 11 degrees of freedom)
	c) Interaction		P<0.001 (F = 9.41 with 6 and 11 degrees of freedom)
Cordgrass total yield	a) between harvest times		P<0.001 (F = 26.88 with 3 and 11 degrees of freedom)
Fig. 3C	b) between years (previously uncut)	2-way anovar	P<0.001 (F = 56.8 with 2 and 11 degrees of freedom)
	c) Interaction		P>0.05 (F = 2.34 with 6 and 11 degrees of freedom)
Cordgrass stem density	a) between harvest times		P<0.001(F = 11.57 with 3 and 11 degrees of freedom)
Fig. 4A	b) between years (previously uncut)	2-way anovar	P>0.05 (F = 3.31 with 2 and 11 degrees of freedom)
	c) Interaction		P>0.05 (F = 2.82 with 6 and 11 degrees of freedom)

Data Source	Comparison	Statistical test	Results
Cordgrass stem height	a) between harvest times		$P<0.001$ ($F = 395.75$ with 3 and 11 degrees of freedom)
Fig. 4B	b) between years (previously uncut)	2-way anovar	$P<0.001$ ($F = 41.68$ with 2 and 11 degrees of freedom)
			$P<0.001$ ($F = 10.88$ with 6 and 11 degrees of freedom)
Cordgrass Leaf area index	a) between harvest times		$P<0.001$ ($F = 34.81$ with 3 and 7 degrees of freedom)
Fig. 4C	b) between years (previously uncut)	2-way anovar	$P<0.05$ ($F = 6.5$ with 1 and 7 degrees of freedom)
	c) Interaction		$P<0.05$ ($F = 6.37$ with 3 and 7 degrees of freedom)
Cordgrass stem height	a) between fertilizer treatments		$P<0.05$ ($F = 3.95$ with 3 and 15 degrees of freedom)
Fig. 7	b) between harvest times	2-way anovar	$P<0.001$ ($F = 78.65$ with 3 and 15 degrees of freedom)
	c) Interaction		$P<0.05$ ($F = 3.19$ with 9 and 15 degrees of freedom)
Cordgrass total yield	a) between harvest times		$P<0.01$ ($F = 9.95$ with 3 and 7 degrees of freedom)
Fig. 8A	b) between 1981 uncut and 1981, cut in 1980	2-way anovar	$P<0.001$ ($F = 73.93$ with 1 and 7 degrees of freedom)
	c) Interaction		$P<0.01$ ($F = 9.66$ with 3 and 7 degrees of freedom)

Data Source	Comparison	Statistical test	Results
Cordgrass total yield	a) between harvest times		$P<0.01$ ($F = 9.15$ with 3 and 7 degrees of freedom)
Fig. 8A	b) between 1982 uncut and 1982, cut in 1981	2-way anovar	$P>0.05$ ($F = 5.45$ with 1 and 7 degrees of freedom)
	c) Interaction		$P<0.01$ ($F = 10.55$ with 3 and 7 degrees of freedom)
Cordgrass stem density	a) between harvest times		$P>0.05$ ($F = 3.16$ with 3 and 7 degrees of freedom)
Fig. 8B	b) between 1981 uncut and 1981,cut in 1980	2-way anovar	$P<0.05$ ($F = 10.07$ with 1 and 7 degrees of freedom)
	c) Interaction		$P<0.01$ ($F = 9.83$ with 3 and 7 degrees of freedom)
Cordgrass stem density	a) between harvest times		$P>0.05$ ($F = 1.04$ with 3 and 7 degrees of freedom)
Fig. 8B	b) between 1982 uncut and 1982, cut in 1981	2-way anovar	$P<0.05$ ($F = 10.25$ with 1 and 7 degrees of freedom)
	c) Interaction		$P<0.05$ ($F = 4.77$ with 3 and 7 degrees of freedom)
Cordgrass stem height	a) between harvest times		$P<0.001$ ($F = 243.82$ with 3 and 7 degrees of freedom)
Fig. 8C	b) between 1981 uncut and 1981, cut in 1980	2-way anovar	$P<0.01$ ($F = 13.77$ with 1 and 7 degrees of freedom)
	c) Interaction		$P<0.01$ ($F = 13.89$ with 3 and 7 degrees of freedom)

Data Source	Comparison	Statistical test	Results
Cordgrass stem height	a) between harvest times		$P<0.001$ ($F = 259.05$ with 3 and 7 degrees of freedom)
Fig. 8C	b) between 1982 uncut and 1982, cut in 1981	2-way anovar	$P<0.05$ ($F = 11.54$ with 1 and 7 degrees of freedom)
	c) Interaction		$P<0.01$ ($F = 22.19$ with 3 and 7 degrees of freedom)
Cordgrass total yield	a) between harvest times		$P<0.01$ ($F = 9.98$ with 3 and 7 degrees of freedom)
Fig. 9A	b) between 1982 uncut and 1982, cut in 1981 and 1980	2-way anovar	$P>0.05$ ($F = 0.33$ with 1 and 7 degrees of freedom)
	c) Interaction		$P<0.05$ ($F = 7.39$ with 3 and 7 degrees of freedom)
Cordgrass stem density	a) between harvest times		$P>0.05$ ($F = 0.35$ with 3 and 7 degrees of freedom)
Fig. 9B	b) between 1982 uncut and 1982, cut in 1981 and 1980	2-way anovar	$P<0.001$ ($F = 35.71$ with 1 and 7 degrees of freedom)
	c) Interaction		$P<0.05$ ($F = 4.53$ with 3 and 7 degrees of freedom)
Cordgrass stem height	a) between harvest times		$P<0.001$ ($F = 243.82$ with 3 and 7 degrees of freedom)
Fig. 9C	b) between 1982 uncut and 1982 cut in 1981 and 1980	2-way anovar	$P<0.01$ ($F = 13.77$ with 1 and 7 degrees of freedom)
	c) Interaction		$P<0.01$ ($F = 13.89$ with 3 and 7 degrees of freedom)

PART III : Japanese knotweed - *Reynoutria japonica*

C O N T E N T S

SUMMARY

1 Japanese knotweed and giant knotweed growing naturally as hedges on waste ground in Britain are among the most productive land plants in this country achieving yields of 25 to 37 t ha^{-1} in a year. On harsh derelict ground, a fairly extensive natural area of Japanese knotweed yielded 11 t ha^{-1} yr^{-1}.

2 Because of the potentially very high production of Japanese and giant knotweed, and their limited extent in this country, areas of land would be planted with these species and dedicated to energy crop production. Initially these areas would be underutilized urban waste land, motorway and road verges, railway embankments and hedgerows totalling up to 7 500 km^2 in Great Britain. In the longer term, both species may replace some agricultural crops and pastures or be integrated with single stem tree plantations to produce protein from leaves and fuel from stems.

3 In order to investigate methods of managing these species as energy crops, an area of 0.17 ha was planted in 1980 with unrooted rhizome cuttings of Japanese knotweed at 4 m^{-2} but only a small area of the much rarer giant knotweed was established.

4 Observations over a 3 year period showed that the yield of Japanese knotweed increased significantly but that, after 3 years, the yield was very low at 3 t ha^{-1} yr^{-1}. Low yields resulted from drought after planting, an insufficient density of planted cuttings and consequent competition with weed species. Recent observations of the plantation confirm that, in the absence of effective weed control, average yields are small, below 5 t ha^{-1} yr^{-1}, even after 5 years.

5 Subsidiary experiments comparing yields of Japanese knotweed and giant knotweed at various planting densities showed that increased planting densities lead to greatly increased yields: giant knotweed yielded 5 t ha^{-1} yr^{-1} after 1 year when planted at a density of 25 m^{-2} and was generally more productive than Japanese knotweed.

6 Fertilizers significantly increased the yields of Japanese knotweed both on unharvested plots and on plots which had been harvested in previous years. However, fertilizers produced a greater increase in the yield of weed species. As yields decrease rapidly in autumn, Japanese knotweed would be harvested when green at peak biomass and agricultural levels of fertilizers would be required at a cost of about £102.00 ha^{-1}. Nutrients could be replaced from anaerobic digestor residues.

7 Both Japanese and giant knotweed appear to be extremely resilient to repeated harvesting in autumn. Depresssions in yield of 25% were recorded after cutting annually in summer for 2 years but allowing the crop to remain undisturbed during the year of planting. At one site, giant knotweed grew to a height of 3.5 m after removing shoots and rhizomes for 2 consecutive years.

8 Japanese knotweed would be planted initially from cuttings, allowed to become established and then harvested annually in summer using forage harvesting techniques designed for silage making. The biomass could be digested anaerobically to give biogas with a high level of efficiency of energy recovery of 57%, or it could be combusted to give low grade heat up to 80°C using a technique developed in Denmark. Other thermal conversion methods could also be used after expressing water by compaction prior to and during briquette production, which simultaneously generates heat for pre-drying the crop.

9 Assuming a 10 year cycle for a plantation of Japanese knotweed, with a mean yield of 12 t ha^{-1} yr^{-1} and anaerobic digestion as the conversion method, the net present value of the plantation would be £780 ha^{-1} yr^{-1}. This corresponds to an annual Gross Margin of £127.50, which cannot compete with arable or horticultural crops but does suggest that it is economic to establish Japanese knotweed on waste land. Supplementary uses of Japanese knotweed, such as the production of fertilizers or fodder from digestor residues, and the separation of leaves for animal feed, could lead to the commercial viability of Japanese knotweed plantations even on agricultural land.

10 The environmental impacts of plantations of Japanese or giant knotweed are minor. Japanese knotweed may be troublesome as an invasive weed escaping from plantations but herbicidal control and stock grazing can prevent this. Both species would lead to the improvement of soil on derelict sites and the potential exists for integration with other land uses.

11 As both species reproduce vegetatively in Great Britain and, therefore, represent a depauperate gene pool, there should be ample opportunities for improving yields by selection and breeding from foreign populations which naturally produce seed. The potential of these 2 species, particularly giant knotweed, is still incompletely understood.

RECOMMENDATIONS

1 Although the contract specified that a Japanese knotweed plantation be established and monitored for 3 years, this plantation has now been observed for 5 summers. The continued inability of knotweed to compete with weed species on many parts of the site suggests that selective weed-killer together with ploughing or rotavating should be applied next year, in an effort to distribute the knotweed rhizomes and establish a more even sward.

2 Greater biological understanding of the requirements for healthy establishment of the 2 knotweed species is required and can be gained through smaller scale experiments involving different soil types, moisture levels and types of propagation. Both species do produce seed in continental Europe, and in this country could be induced to do so in a greenhouse. Seedlings may offer a more effective and economic method of establishment.

3 With both species there is considerable scope for selecting and breeding high-yielding genotypes and this should be investigated.

4 Both species appear sensitive to wind exposure, and their intercropping with tree species should be investigated on a small scale.

5 If knotweed can be induced to yield around 15 t ha^{-1} yr^{-1} in plantations, it will then be necessary to investigate the mechanical separation of leaf and stem material, and the potential of the foliage to meet ruminant feed requirements. This would be a step towards the replacement of significant areas of pasture with this dual-purpose crop.

1 INTRODUCTION

Many successful invasive weed species of Great Britain show attributes which can be exploited in the development of energy crops. They are fast growing, have high reproductive rates, propagate easily, become established quickly on disturbed land, soon assume dominance over competing plant species, and have potential for genetic improvement. Japanese knotweed (Reynoutria japonica, Plate I) is one of the most productive invasive weed species of this country (Callaghan et al. 1981) and, because of its prodigious rate of spread, is one of the 2 land plants on which legal controls have been established (Wildlife & Countryside Act 1981). Estimates of the yields of Japanese knotweed vary from 11 dry t ha^{-1}, in a large continuous stand (1 ha), to an exceptional 25 dry t ha^{-1} for "hedges" of this species (Callaghan et al. 1981). However, because this weed is found naturally in only small areas and is usually associated with disturbance, no reliable estimates of yield exist for extensive monocultures. Indeed, if this plant were to be used as an energy crop, it would not be harvested from its present site of distribution, as is the case for bracken and cordgrass (Callaghan et al. 1984 a, b), but would be planted on land dedicated to the production of biofuels. It can therefore be termed a 'dedicated energy crops', in contrast to the more widespread 'opportunity energy crop'. If efforts to reduce the amount of agricultural land producing food surpluses within the EEC (6 million ha - Meinhold & Kogl 1983) are successful, it can be expected that agricultural land will become available for the development of high-yielding energy crops such as Japanese knotweed.

Related to Japanese knotweed is the species giant knotweed (R. sachalinensis Plate II). This species also has exceptionally high yields (Callaghan et al. 1981) and produces greater height growth than Japanese knotweed, while having much larger leaves. However, giant knotweed occurs very infrequently in Great Britain and exists only as small isolated stands.

In general, little is known about the production biology of these species and the only way to assess their potential as energy crops is to establish experimental monocultures. Consequently, a 3-year programme was developed, with main emphasis on Japanese knotweed (material of giant knotweed was too scarce), to develop a monoculture and investigate the ways in which this new crop should be managed for biofuel production.

Plate I. Japanese knotweed (*Reynoutria japonica*)

Plate II. Giant knotweed (*Reynoutria sachalinensis*)

2 BIOLOGY OF JAPANESE KNOTWEED

2.1 Description

Japanese knotweed is a rhizomatous perennial whose stout, annual stems ascend from a woody base to up to 3 m in height. The characteristic cuspidate-shaped leaves are borne alternately on reddish stems. The species is fully described by Lousley and Kent (1981). Reproduction is by rhizome-spread or fragmentation, often assisted by dispersal of fragments from weeded gardens in infested areas to illicit disposal sites. The probability of survival is extremely high and exceeds 90% in our propagation trials. Flowers are produced but the white-winged seeds are rarely seen in Britain and there is no evidence for spread from seed. Rhizomes are up to 5 cm in diameter, fleshy to woody, with annual growth rings in large specimens. Emery (1983) has estimated some rhizomes to be at least 10 years old. Large woody masses, which may be older, arise at the base of established clumps, new buds being produced each year.

2.2 Distribution and extent

Japanese knotweed was introduced to Britain in 1825 and is now well established in most areas, usually on roadsides, urban and rural waste ground and riverbanks. Its natural range in Japan includes early successional stages on newly-formed soils on volcanoes (Yoshioka 1974). In Britain its advance in the west has been stronger than in the east (Conolly 1977) and spring frost is implicated as a limitation. Callaghan _et al._ 1981 estimated the total extent at only 3.1 km^2 using the ITE land classification method, although such a small area is unlikely to be predicted accurately. It is, however, locally very abundant and the species is becoming a prominent and sometimes troublesome feature of waysides and urban sites. It is likely to continue to extend its distribution, although legislation exists to control its spread (Wildlife & Countryside Act 1981, Schedule 9).

2.3 Growth patterns

Buds produced on rhizomes and root crowns begin to extend in April and unless the young shoots receive frost damage the stems achieve full height in early June, the leaf canopy continuing to extend by the development of axillary shoots. Leaves often remain green until November, but with the onset of frosts, browning and leaf shedding occur. Large stems have a diameter of up to 5 cm and are extremely persistent. Fallen leaves are also slow to decompose and frequently form a dense litter layer which appears to restrict the survival of other plant species. In established stands, the distribution of stems is strongly aggregated into clumps.

2.4 Yield

In extensive natural stands (c 1 ha) at 2 locations (Callaghan _et al._ 1981) shoots, of Japanese knotweed yielded a maximum of 10-11 dry tonnes per hectare and below-ground biomass was an additional 12 t ha^{-1}. Water content of shoots in June is over 80%, reducing to 73% in October. Samples of Japanese knotweed from natural strips along roadsides yielded 25 t ha^{-1} because of hedge-effects (in which the photosynthetic canopy extends from the ground to the top of the canopy on both sides of the row).

2.5 Nutrients

Peak concentrations of N, P and K are found in shoots during early stages of growth, declining steadily after maturity and rapidly during senescence (Figure 1a). The nutrient elements are present in high concentrations in the rhizomes during the winter months, suggesting the importance of internal transport of nutrients to the storage organs during the senescence of aerial shoots. Stems become tough, woody and lignified as the season progresses.

During active growth the starch content is relatively high. Soluble carbohydrate concentration is relatively low and decreases rapidly during stem senescence (Figure 1b).

2.6 Energy value

The energy content of Japanese knotweed shoots declines slightly over the growing season (Figure 2) from 19.5 kJ g^{-1} to 18.4 kJ g^{-1}, but the energy yield of a crop is primarily a function of biomass. The range of values given above is similar to the mean of 18.3 kJ g^{-1} recorded for many other species (Callaghan *et al*. 1978).

2.7 Giant knotweed

This species, *Reynoutria sachalinensis*, was introduced shortly after Japanese knotweed but is much less widespread. Giant knotweed has a growth habit similar to that of Japanese knotweed but its stems are taller (usually over 3 m). It has much larger (up to 30 cm long), oblong leaves, lower stem density and a reduced capacity for vegetative spread. Some of its most vigorous British stands are in northern Scotland. Its natural distribution to the north of Japan suggests a greater cold hardiness than Japanese knotweed and its yield potential may be higher.

2.8 The current uses of Japanese knotweed and giant knotweed

Japanese knotweed was introduced into Great Britain during the last century as a garden plant. Although its attraction as an ornamental plant has long since waned in the face of problems of preventing spread into unwanted areas, a variegated variety was presented at the 1983 Chelsea Flower Show. Giant knotweed was apparently also introduced into Great Britain to test its qualities as a forage plant. Farmers in Wensleydale planted the species at the base of hill sides and noted that horses were especially fond of the leaves (Conolly 1977). However, the boggy habitats appeared to be unsuitable (Conolly pers comm) and there are no records of further trials.

2.9 Control of Japanese knotweed

Infested sites of Japanese knotweed include roadsides, riverbanks, cemeteries, parks, and woodland nature reserves. The inconvenience of this weed arises from its dominant growth habit, which prevents the occurrence of desirable plant species. Intensive grazing or weeding reduces knotweed to a negligible biomass, but these methods are unlikely to achieve permanent eradication. Indeed, weeding activities have contributed to the spread of rhizomes to many new localities. Herbicidal control is a more effective but rather expensive approach, and persistence and vigilence are necessary due to the great ability of rhizome fragments to survive maltreatment.

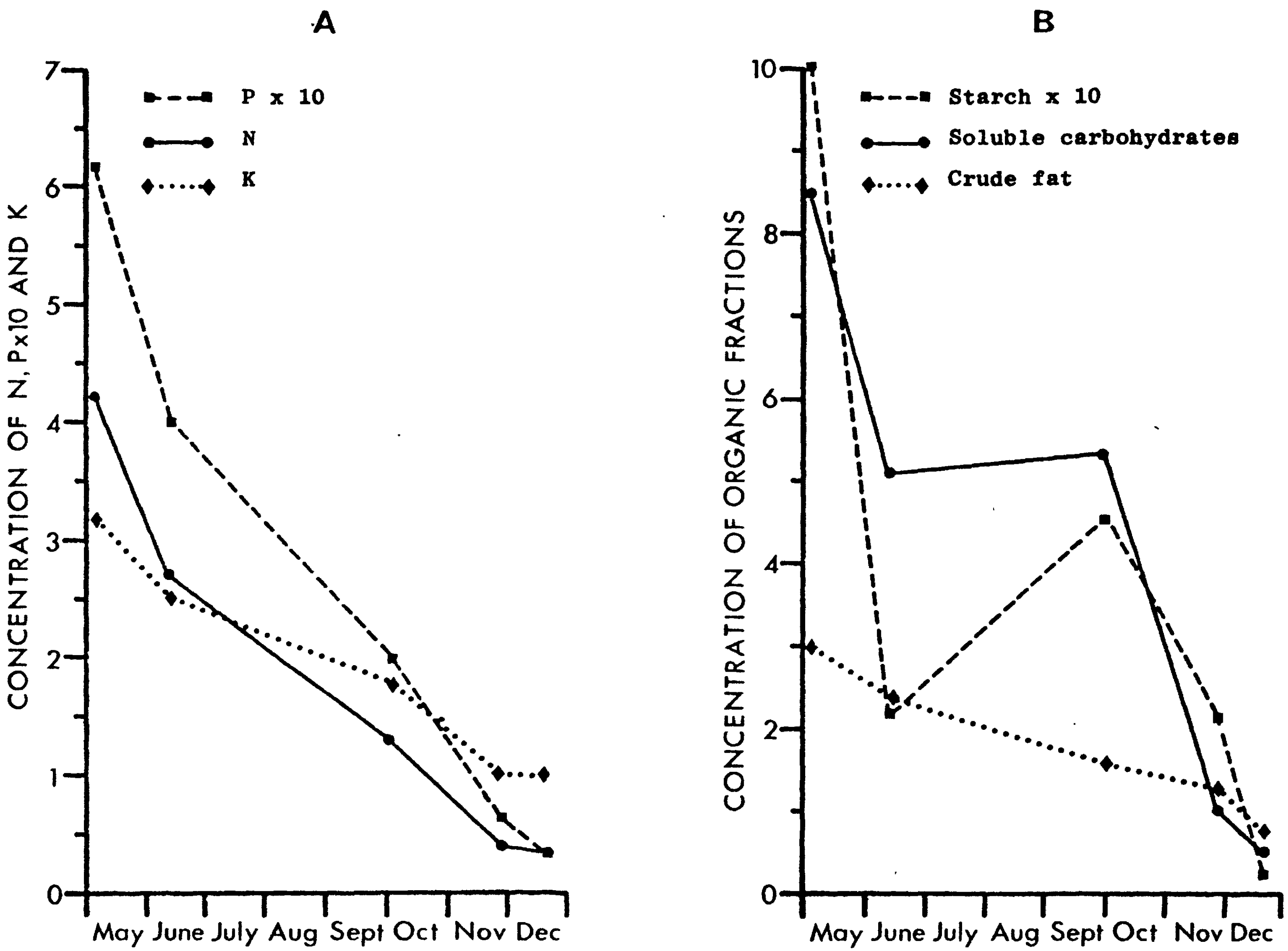


Figure 1. The seasonal trends of concentrations of inorganic (A) and organic (B) nutrients in shoots of Japanese knotweed (% dry weight).

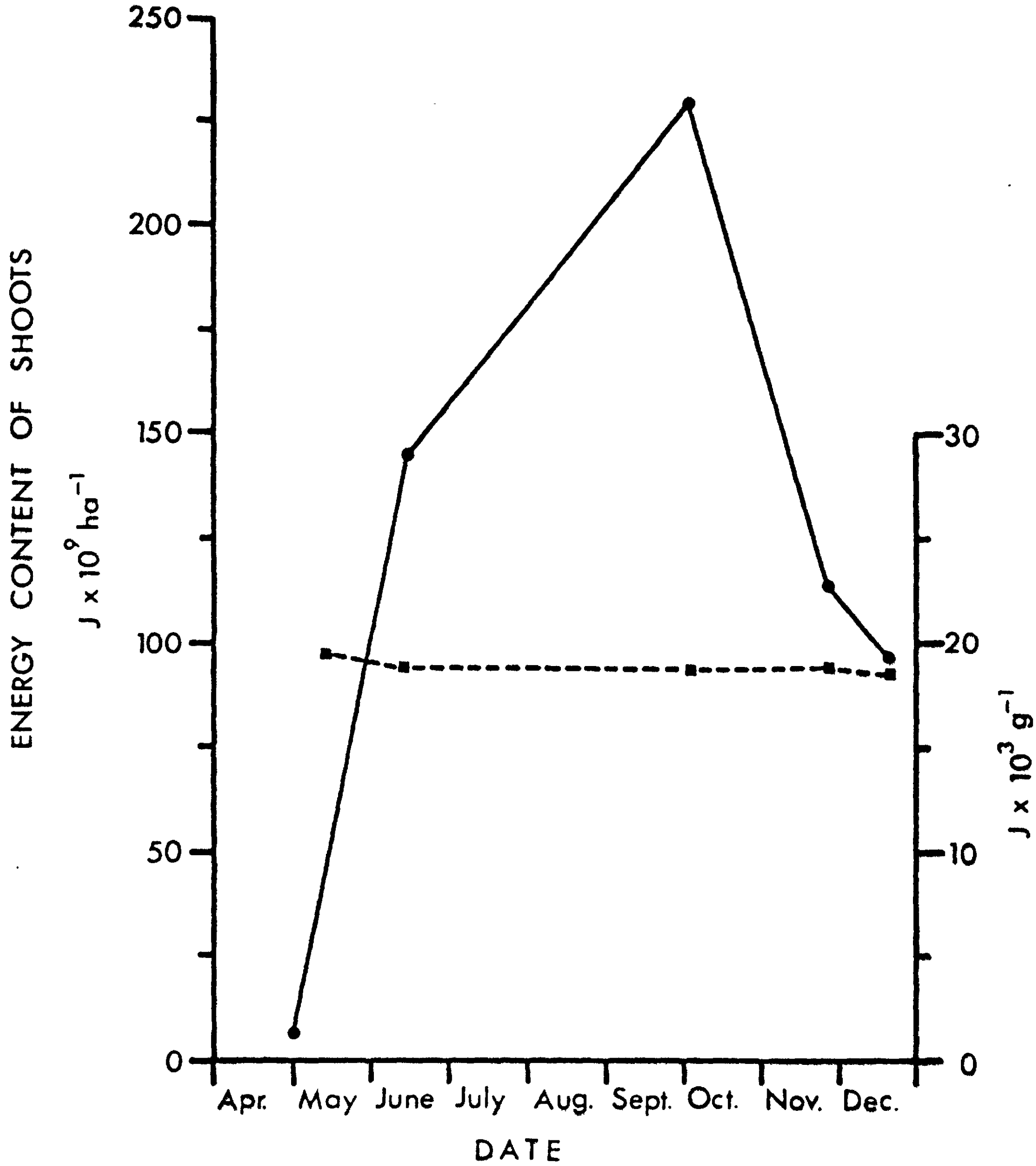


Figure 2. Energy values of Japanese knotweed
(——) content of fronds unit area $^{-1}$
(---) content of fronds g^{-1} (including ash)

3 EXPERIMENTAL ASSESSMENT

3.1 Objectives and methods

The main objectives in the assessment of knotweed as an energy crop were:

1 to establish an experimental site;

2 to assess the effects of planting densities on yield;

3 to measure yield in relation to applications of conventional fertilizer;

4 to assess the effect of time and frequency of harvesting on yields and regrowth;

5 to monitor the effects of climatic variables and rate of plant establishment on performance;

6 to assess the digestibility of fresh Japanese knotweed in an experimental anaerobic digestor;

7 to develop strategies for planting and harvesting knotweed.

In order to mesure yield in relation to fertilizer applications, time and frequency of harvesting, weather and establishment (objectives 2-4), an experimental site of 0.17 ha was established (Plate III & IV) at Meathop, Cumbria (SD 431815). A randomized split plot design was developed (see Appendix I) in which the following factors were assessed:

a. The effect of weather and establishment on the performance of Japanese knotweed

Japanese knotweed was cut from previously unharvested quadrats in 1980, 1981 and 1982. Differences between years are therefore the result of weather and/or establishment. A subsidiary site near Edinburgh (NT 242630) was established to assess the effects of differing planting densities on the yields of Japanese and giant knotweed (Appendix I).

b. The effect of weeding on the performance of Japanese knotweed

The large biomass of weed species established by 1982 was thought to suppress the yield of Japanese knotweed. The 4 replicates for each treatment during harvests 2 to 4 in 1982, were therefore divided between 2 weeded and 2 non-weeded replicates.

c. The effect of fertilizer applications on the performance of Japanese knotweed

Each treatment was subdivided into 4 levels of fertilizer treatment applied annually in April.

d. The effect of time and frequency of cutting on the performance of Japanese knotweed.

The regrowth of Japanese knotweed in relation to frequency of harvesting was assessed after one previous cut (assessment in 1981 after cutting in

Plate III. Japanese knotweed transplant site at Lindale, Cumbria in March 1980

Plate IV. Established Japanese knotweed at the Lindale transplant site in July 1983 (Pole height = 2m)

1980 and in 1982 after cutting in 1981) and after 2 previous cuts (assessment in 1982 after cutting in 1980 and 1981). Each of the above treatments was repeated for 4 harvest dates to allow an assessment of regrowth in relation to time of harvesting.

3.2 The effect of weather and establishment on the performance of Japanese knotweed

The performance of Japanese knotweed from previously uncut plots varied significantly between the years 1980, 1981 and 1982 (Figures 3 and 4). This variation is compounded of differences between weather conditions, as in the case of bracken (Callaghan _et al_. 1983a), and the establishment and development of this perennial crop which was planted from small (mean 224 g) unrooted rhizome fragments in March 1980. The trend of increasing performance from 1980 to 1981 to 1982 signifies that the rate of establishment is far more dominant than any effects of weather.

In the year of planting (1980), yields of knotweed were very low (maximum = 0.77 t ha^{-1}) due to a low density of planting (4 fragments per m^2) and a drought during the critical period of spring growth (see Figure 5A in Callaghan _et al_. 1983a). During 1981, yields were higher, and in 1982 the peak yield was c 4 times greater than that in 1980. However, yields of previously unharvested knotweed in the 3rd year after planting still averaged only 2.7 t ha^{-1} yr^{-1}, signalling that establishment has been unacceptably slow at this site.

Faster establishment of Japanese knotweed was obtained by increasing the planting density to 16 cuttings m^{-2} (Table 1), and an average giant knotweed yield of 5.4 t $ha^{-1}yr^{-1}$ was achieved at this planting density after less than 2 years. At each planting density, the yields and stem heights of giant knotweed were higher than those for Japanese knotweed (Table 1).

The increased yield of Japanese knotweed during the first 3 years of establishment was associated mainly with an increase in stem height (Figure 4A), and to a lesser extent with stem density (Figure 4B) and leaf area index (Figure 4C).

Less intensive monitoring of the experiment has continued in 1983 and 1984, but knotweed yields have not increased significantly over the 3 t ha^{-1} observed in 1982. In some parts of the site knotweed has established a healthy sward (Plate IV), but in others it has been eliminated by the strong growth of weed species.

3.3 The effect of weeding on the performance of Japanese knotweed

After site preparation in 1980, weed control was not initiated until spring 1982, when one half of the replicate plots received hand weeding and an application of 'clout' (alloxydim-sodium) selective herbicide. However, these treatments were not observed to have had any significant effect upon knotweed yields at mid-summer, and the weed biomass was reduced by only 1.24 t ha^{-1}.

The yield of weeds in the year of planting (1980) averaged 5 t ha^{-1} and in the subsequent year it had risen to 9 t ha^{-1}. It is interesting that this yield should be so high when the average yield of British grassland does not much exceed 5 t ha^{-1} yr^{-1} (Plaskett 1981). Whilst the success on this

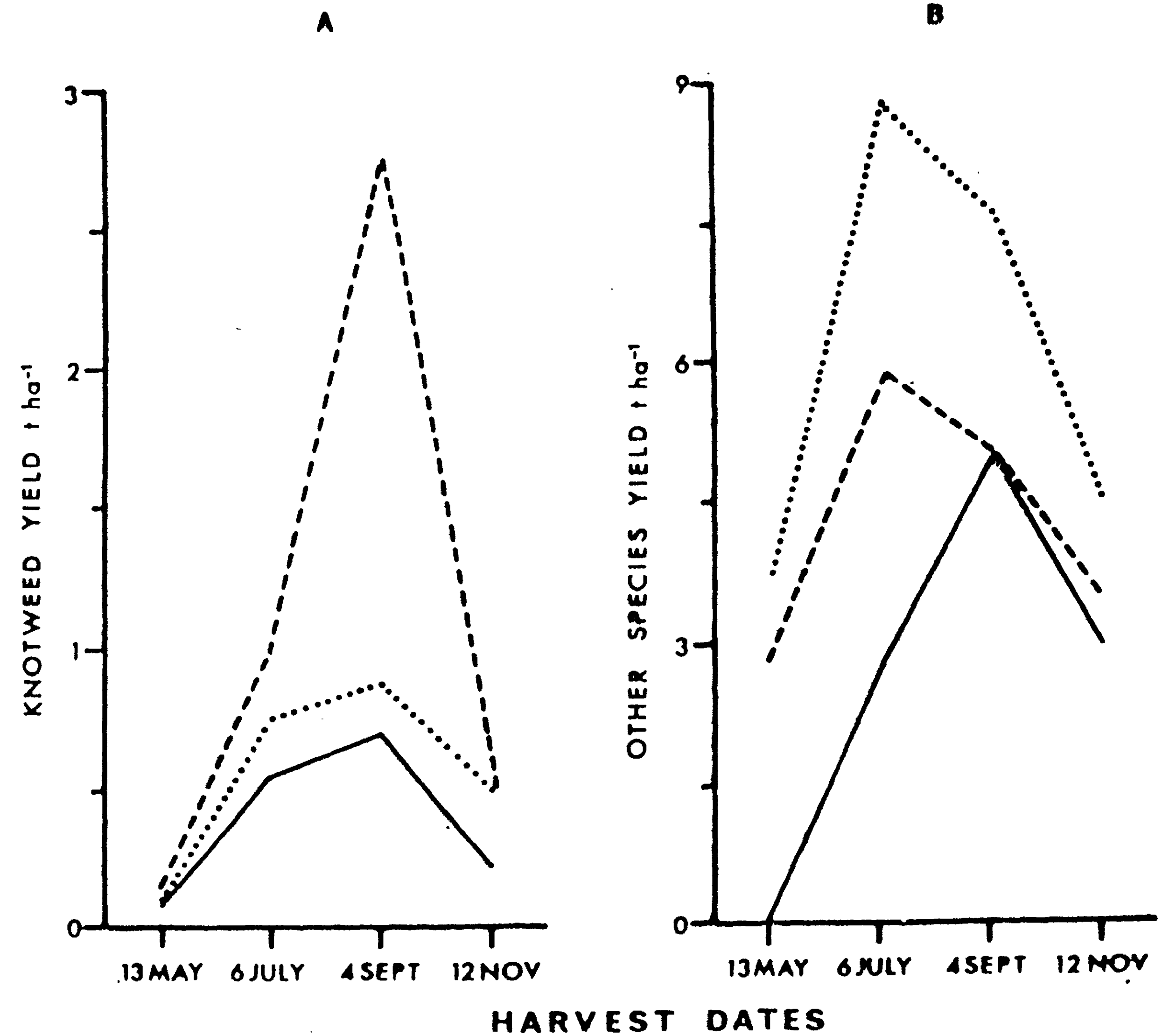


Figure 3. Establishment and seasonal development of the vegetation in previously uncut plots
A Yields of knotweed in 3 years
B Yields of other species growing with the knotweed in 3 years

——— 1980
. 1981
– – – 1982

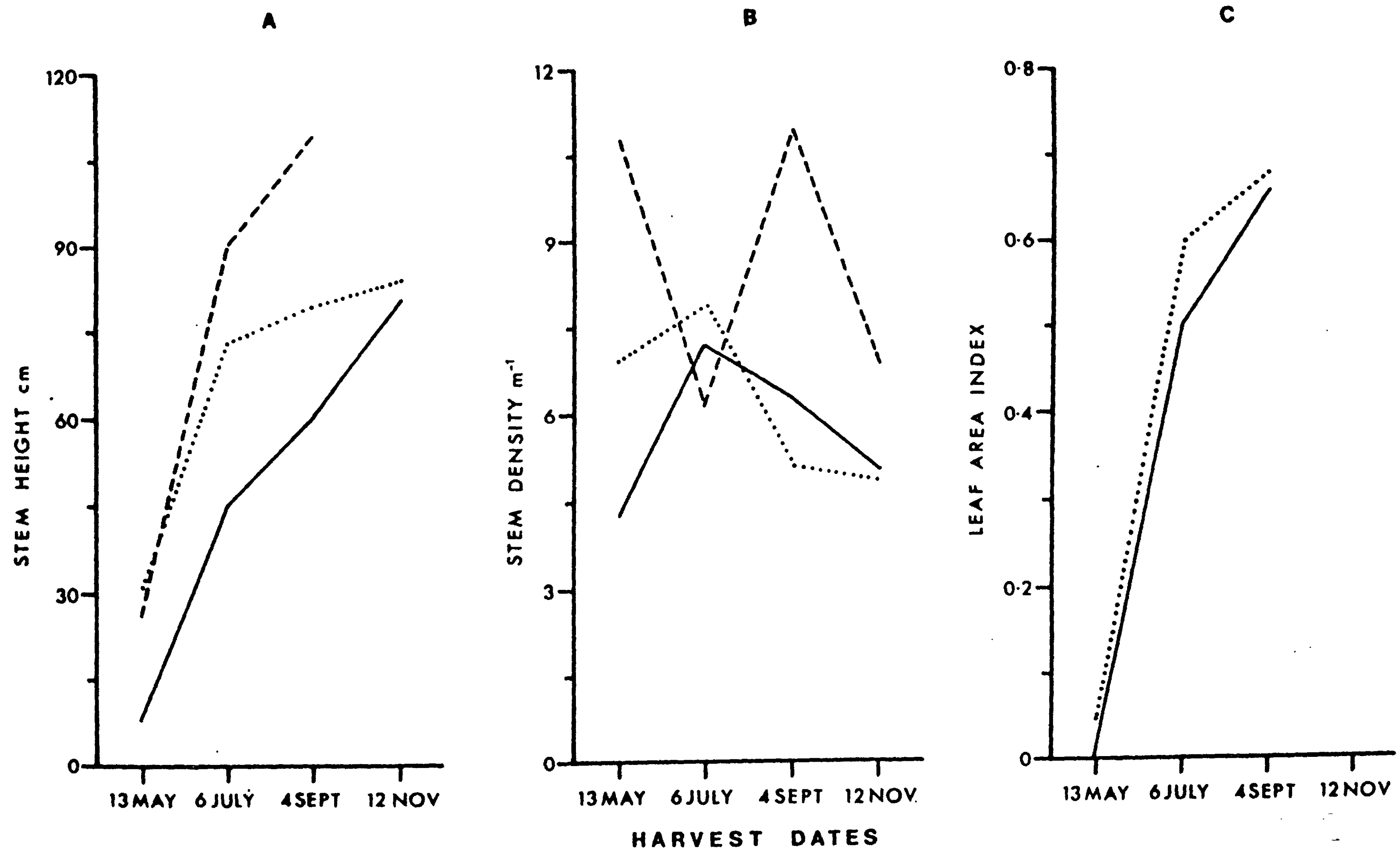


Figure 4. Effect of establishment and weather on stem height (A), density (B) and leaf area index (C) in 1980 (——), 1981 (...), and 1982 (— — —)

Table 1. Effects of planting density on the establishment of monoculture of 2 species of knotweed from March 1981 to November 1982

Japanese knotweed

Planted density (plants m^{-2})	Final density (stems m^{-2})	Plant height (cm)	Estimated yield (t ha^{-1})
4	4.0	75.3	0.23
9	10.7	73.0	0.29
16	25.3	103.7	2.59
25	27.7	107.3	1.09

Giant knotweed

Planted density (plants m^{-2})	Final density (stems m^{-2})	Plant height (cm)	Estimated yield (t ha^{-1})
4	4.0	150.7	2.46
9	11.0	159.7	2.43
16	11.3	157.7	1.28
25	16.3	201.0	5.41

site of species such as nettles and thistles may have significance in indicating their potential as energy crops, the failure of Japanese knotweed to compete with and gradually take over from other herbs and grasses indicates that much greater management effort may be required.

3.4 The effect of fertilizer applications on the performance of Japanese knotweed

The overall statistical analysis (Appendix II) shows that fertilizer applications cause a slightly significant increase in the yield of Japanese knotweed and a highly significant increase in the yields of competing weed species. Analyses of the effect of different applications on plots which were cut for 3 successive years (Figure 5A) show a 4-fold increase in knotweed yield with an application of 100 g m^{-2} (1 t ha^{-1}). However, a doubling of this rate produced no further yield increases. The effect of fertilizer on yield is explained by an increase in stem height (Figure 5B rather than stem density (Figure 5C).

Yields of knotweed do not appear to be more responsive to fertilizers in those plots which are repeatedly harvested, but there is a slightly significant interaction between repeated harvesting and fertilizer application with the yields of the associated weed species (Appendix II).

This is a nutrient poor site, and whilst anaerobic digestion provides digestor residues to be recycled to the plantation, any other conversion scenario would require significant inputs of fertilizer. These inputs should be low however, compared with many agricultural crops, even if a sustained yield of 12 t ha^{-1} yr^{-1} were to be projected for an established monoculture (Table 2).

3.5 The effect of frequency and time of cutting on subsequent yields

When Japanese knotweed is cut at different times in the season, subsequent yields follow a pattern predicted by Callaghan et al. (1981). Thus, after cutting in spring and autumn, regrowth is far less affected than by cutting in summer (Figure 6).

In one treatment, Japanese knotweed was cut during the year of planting (1980), subsequent yields in 1981 were reduced by over 70% in summer and over 30% in autumn (Figure 6A). However, when cut for the first time in the year after planting (1981) subsequent yields in 1982 were depressed by only 25% in summer and increased by almost 60% in autumn. This stimulated growth was associated with an increased density of smaller shoots (Figures 6B and C) and can be expected as this is a weed species which thrives on disturbance which releases many new buds from dormancy. The weeds associated with Japanese knotweed showed an average slight decrease in yield after being cut once before (Figure 6D).

When Japanese knotweed was cut once a year for 3 years, summer yields were depressed by 70% but, again, autumn yields showed a 20% increase (Figure 7A). This increase was associated with a large (50%) increase in the stem density (Figure 7C). The annual species associated with Japanese knotweed showed an opposite trend, in that their yield was least depressed after summer harvesting (Figure 7D). This would result from a large component of species which, when cut in autumn, are prevented from setting seed.

The actual yields of Japanese knotweed which were obtained by cutting for 2 and 3 years are very small (Figure 8A) due to the initial slow establishment of the crop (Figure 3A). However, starting with bare ground a mean yield of Japanese knotweed and other species (Figure 8B) of about 6 t ha^{-1} yr^{-1} could be obtained by harvesting in summer for 3 years. The stimulation of stem density and yields of Japanese knotweed by cutting in autumn suggests that it might be possible to maintain significant autumn yields while establishing a productive monoculture.

Table 2. Scenarios for fertilizer applications (kg ha^{-1}) to energy crops of Japanese knotweed

	Nutrients removed in knotweed biomass		Nutrients currently applied to agriculture[1]
	Summer Cut	Autumn Cut	
N	25	142	158
P	3.6	23	72
K	58	205	183
Total cost of[2] replacement	£102	£27	£120

Notes: [1]Main crop potatoes selected as analogues for rhizomatous knotweed plants, Church (1975)

[2]Materials costs from Nix (1982) assuming:
nitrogen in form of Nitram at 40p $kg^{-1}N$,
phosphorus in form of super triple phosphate at 31p $kg^{-1}P$,
potassium in form of muriate of potash at 15p $kg^{-1}K$.

Application cost taken as £7.50 ha^{-1} (Farm Contractor, June 1983)

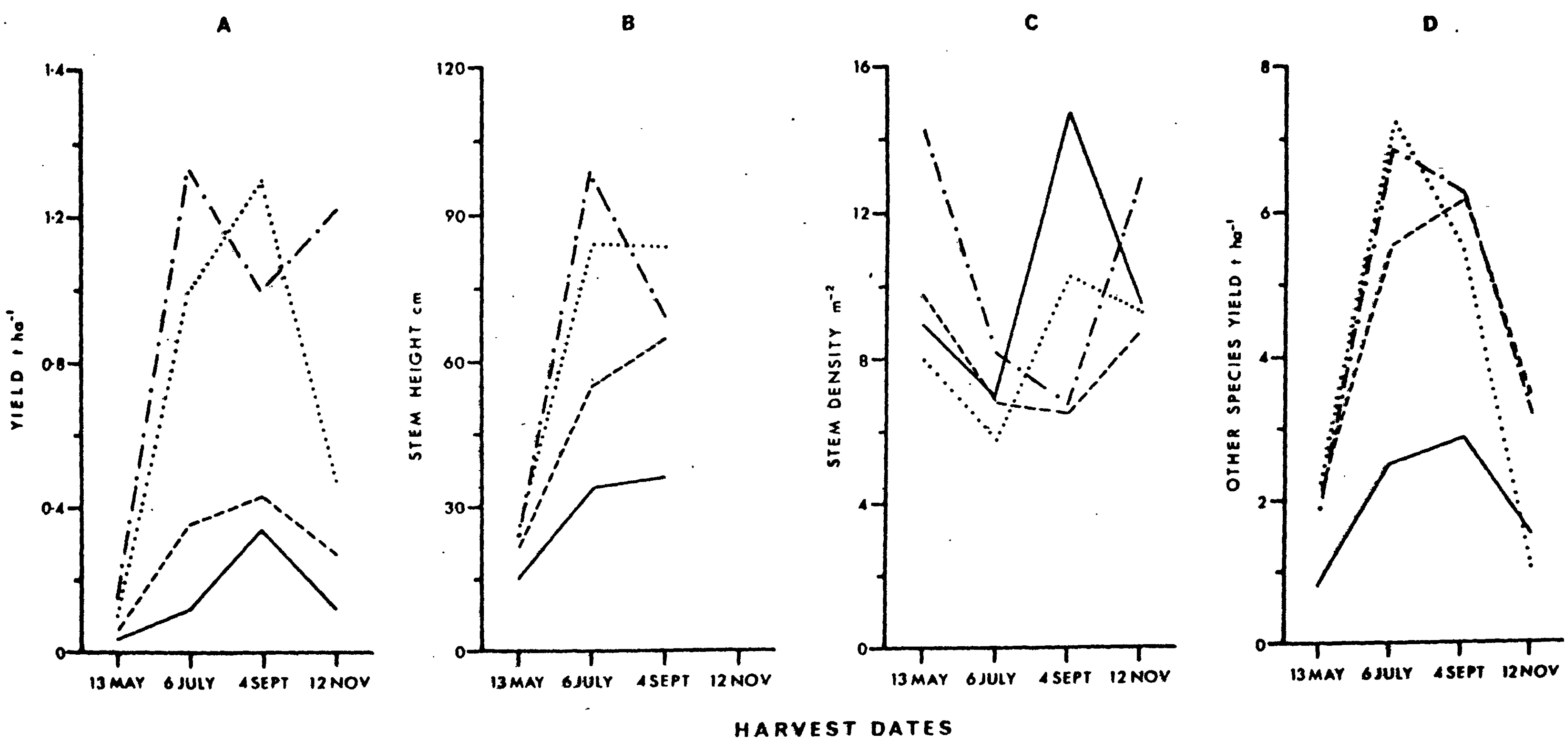


Figure 5 . Effect of the level of fertilizer application on knotweed yield (A), height (B), density (C) and yield of other species (D) after 4 years of harvesting,

——— 0 gm^{-2}
- - - - - 50 gm^{-2}
. . . . . . 100 gm^{-2} (100 gm^{-2} = 1 t ha^{-1})
-.-.-. 200 gm^{-2}

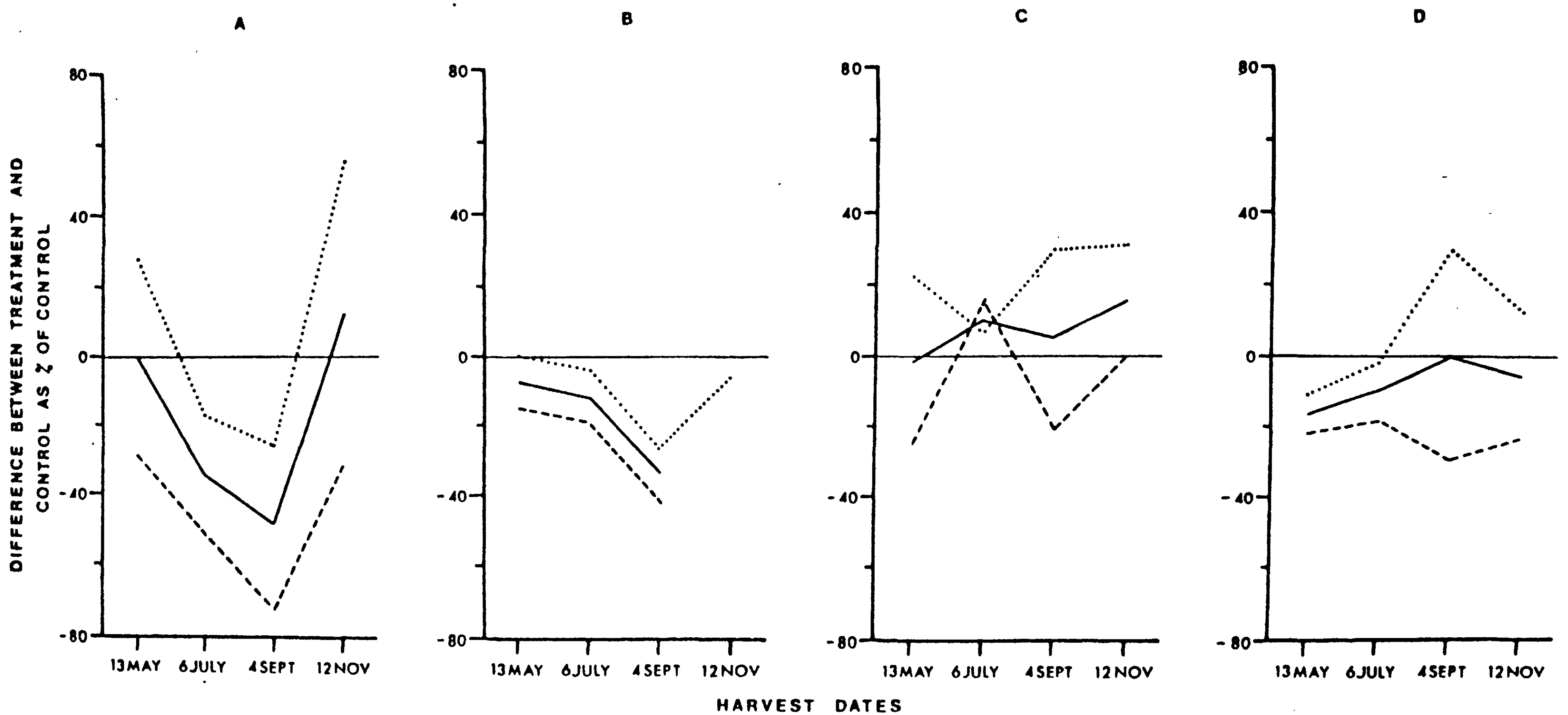


Figure 6. Effect of 1 previous cut on knotweed yield (A), stem height (B), density (C) and yield of other species (D)

--- 1981 cut in 1980 and 1981 on the same date

.... 1982 cut in 1981 and 1982 on the same date

—— mean

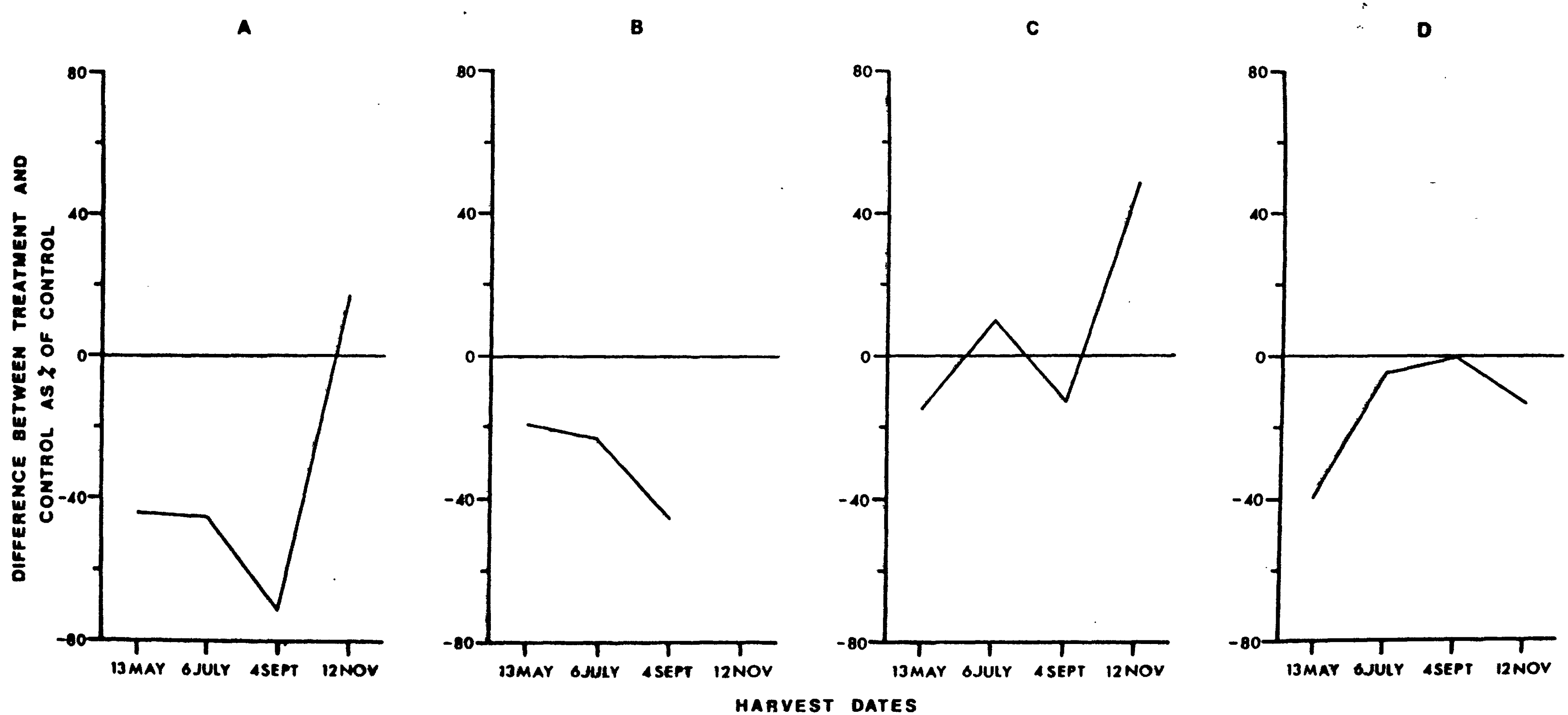


Figure 7. Effect of 2 previous cuts on knotweed yield (A), stem height (B), density (C), and yield of other species (D). Harvests were carried out on the same date in each of the 3 years.

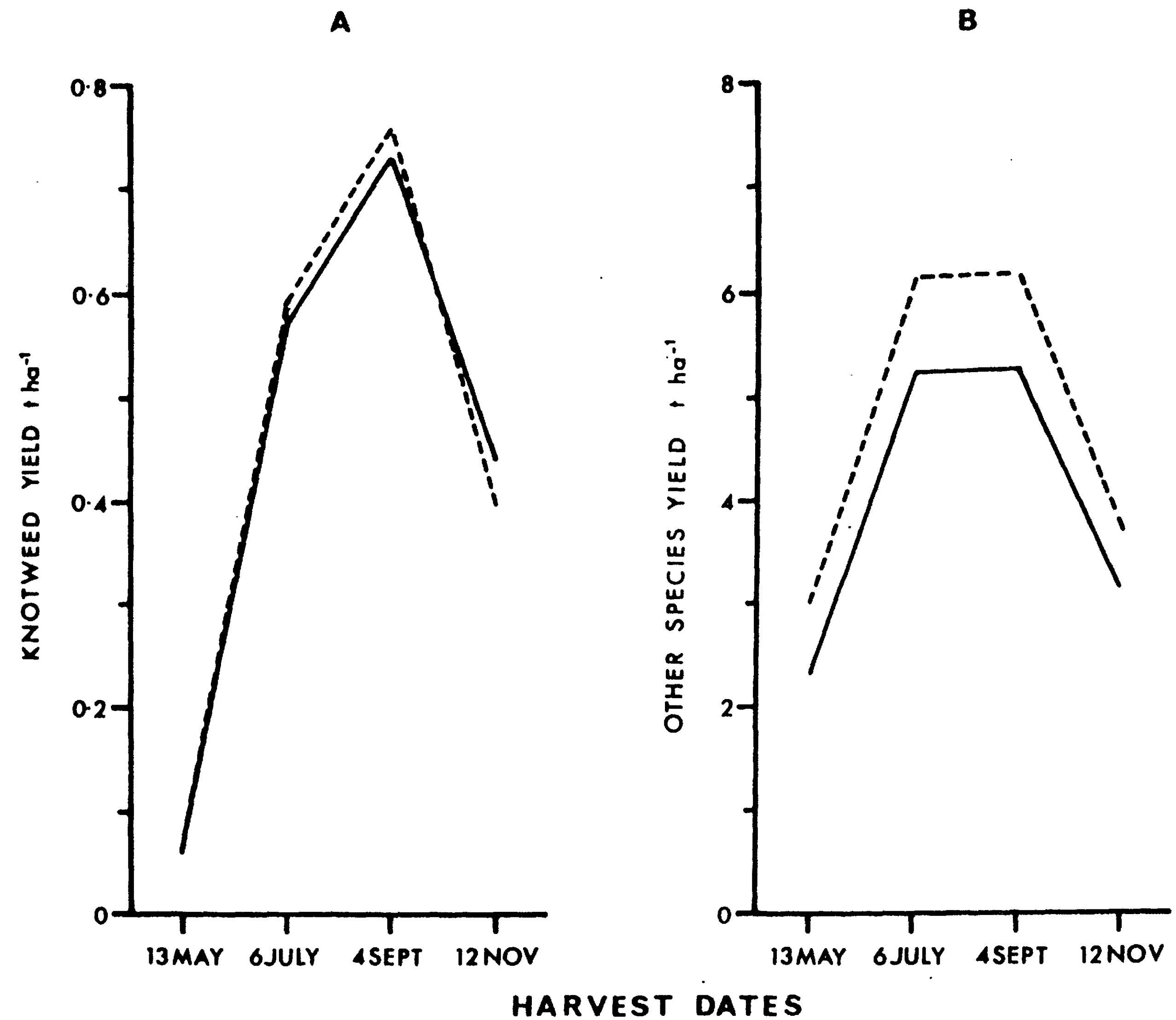


Figure 8. Mean yields of Japanese knotweed (A) and other species (B) in the same sample area after harvesting annually for 2 (---) and 3 (——) years.

4 THE CONVERSION OF JAPANESE KNOTWEED TO FUELS

The ease of conversion of harvested Japanese knotweed will, to a large extent, depend upon the degree of comminution resulting from the harvesting technique. With bracken we suggested that simple reciprocating arm cutters followed by conventional baling would provide a convenient means of transporting senescent bracken fronds to a centralized pelletizing plant. However, unlike bracken, the yields from Japanese knotweed diminish very rapidly after September (Figure 3), and at this time of peak yield the harvested material has a moisture content of 75%. By November, water content has fallen to 66%, but leaf-fall has approximately halved the recoverable yield. Thus, it may be unrealistic to harvest senescent Japanese knotweed in autumn, and forage harvesting techniques designed for silage-making are more appropriate than baling.

Precision chop forage harvesters use a fixed blade rotating on a drum to produce cut and crimped grass of a reasonably standard length, which may be as short as 1 cm. This is ideal for controlled silage-making and will also favour anaerobic digestion, which, for efficient gas production, requires that herbaceous material be reduced to the smallest economically attainable particle size. However, such harvesters require comparatively flat and stone-free land, and would have difficulty chopping the slightly woody stems of mature Japanese knotweed. Japanese knotweed energy plantations are proposed, initially at least, for poor quality or derelict land, and, as it is likely that these areas will be uneven and stony, the fineness of chop gained by precision harvesters will have to be foregone in favour of the robustness provided by simple flail foragers or flail mowers (Lawson et al. 1980). These can be used either to blow the cut material into a trailed forage wagon, or adapted to pile the material in long windrows on the ground. The choice between such alternatives depends partly upon whether maximum drying in the field is required. If and when good quality agricutural land is diverted to biofuel production from producing food surpluses, there will be fewer problems for the harvesting equipment.

Although thermal conversion methods are seldom applied to plant materials with a high moisture content, these processes do become much more viable if Japanese knotweed can be fractionated between energy and food components. Such multiple crop use may radically change the economic attractiveness of energy plantations of non-woody species.

4.1 Crop fractionation

Through a combination of pulping and pressing it is possible to extract a protein-rich juice from many herbaceous plants, leaving a fibrous cake which may still be suitable as a food for ruminants or may be used as an energy feedstock. The fibre remaining after intense pressure may have a moisture content of 35% or less, and the mechanical energy required for this dewatering is theoretically around 30 times less than that required for an identical amount of thermal evaporation. Practical experience of large scale fractionation is limited (Morrison & Pirie 1961), but considerable interest has been expressed in the high feed value of expressed leaf proteins (Pirie 1971; Wilkins et al. 1977; Carlsson et al. 1981), and recent success has been reported (Reines 1984) in the gasification of carrot residues from which the juices has been extracted and sold. However, Plaskett (1981) managed to extract in the form of juice only 4.6% and 5.8% of the solids contained in the leaves of Japanese and giant knotweed, and this extract had an exceptionally low protein content. He finds that the production of leaf protein concentrate (LPC) is not justified on technical grounds with either of the knotweed species, and concludes that recent movements in food and cereal costs have caused this process to become uneconomic even with plant material from which LPC can be efficiently separated.

Plaskett (1981) does, however, consider that it could be economically justified to use knotweed leaves as a ruminant feed and employ the stems for energy. Technically it should not be difficult to separate leaves from the stems, and machinery has been developed in the Soviet Union to do just this with tree leaves (Young 1976). The possible integration of bio-energy production with other land uses is further examined in Volume V.

4.2 The anaerobic digestion of Japanese knotweed

Japanese knotweed cut on 6th July 1981 was processed as reported by Stafford and Hughes (1981). Its digestion efficiency, at 57.3% (Table 3), was the highest of the 3 major species in this programme, and its gas yield compares favourably with those obtained from a variety of herbaceous species as reviewed by Loll (1976).

4.3 Thermal conversion

Work in Denmark (Have 1982) has shown that low grade heat (up to 80°C) can be produced from manure or crop wastes, with a moisture content of up to 82%, at an overall thermal efficiency of 60-65%. The combustion unit uses waste heat to pre-dry the crop and recovers heat from the flue gases using a scrubber and heat exchanger. Since 35% of all energy used in Britain is required for heating at less than 80°C, there does seem to be considerable opportunity to use herbaceous energy crops, like Japanese knotweed, in this type of low grade heat boiler.

The latent heat of vaporization of water (2.26 kJ g^{-1}) suggests that it is energetically inefficient to combust those feedstocks with a moisture content in excess of 30%. With combustion for heat energy, moisture contents should be as low as possible, but with gasification the yield of hydrogen and carbon monoxide is increased by allowing 10-20% moisture to remain in the feed. Many designs are available to utilize waste heat in the pre-drying of biomass (Strehler 1983; Coxe & Aylor 1980), and an interesting package is being manufactured by Pawert-SPM AG to produce densified briquettes from grass, peat, garbage and manure, using a compression process to express water and simultaneously generate heat for evaporation.

Thus, despite the high moisture content of a mid-summer harvest of Japanese knotweed, it is possible that thermal conversion may be economical through the use of field drying, separation of leaves from stems, leaf fractionation for fibre and protein production, and the use of waste process heat for final drying. Although summer-harvesting of biomass may affect subsequent yields, it is unlikely that this effect will be as great as that in bracken (Callaghan *et al.* 1983a).

Table 3. Energy recovery from Japanese knotweed by anaerobic digestion

1 tonne fresh knotweed	= 260 kg volatile solids
270 kg volatile solids	gives 143 m^3 biogas
143 m^3 biogas	= 3.21 GJ
and 1 tonne fresh knotweed contains	5.60 GJ initial energy
therefore, efficiency of conversion (excluding inputs to run digestor)	= 57.3%

5 METHODS AND COSTS OF JAPANESE KNOTWEED MANAGEMENT

5.1 Establishment

As mentioned earlier, Japanese knotweed has been established from small portions of rhizome with a success rate exceeding 90%. These trials used manual methods but mechanization could be possible using modified bulb or mint planters or techniques similar to those used in Sweden to establish portions of reed rhizomes (Bjork 1972). Although Japanese knotweed does not produce viable seed in an average British summer, it may in the long term be economically attractive to establish energy plantations using seed imported from a slightly warmer country.

Planting densities have been varied in our trials between 4 and 25 rhizomes per square metre, and the latter density is assumed in the establishment costs derived here. However, estimation of the optimum planting density will depend upon further experimentation, where the saving in cost of sparse planting is compared with the financial advantage of earlier sward establishment obtained from higher initial planting densities.

5.2 Harvesting

It is assumed that maize harvesting techniques using heavy-duty double chop harvesters (eg Massey Ferguson 200) will be appropriate for both species of knotweed provided they can be harvested before autumn when the stems become woody. Difficulties may arise however because knotweed, unlike maize, does not grow in convenient rows, and many plantations may be on steep or stony waste ground which is difficult to harvest. In these circumstances flail harvesters (eg Tarrup DM1500 or S1500) will be more robust, and can be adapted to either deposit the chopped material in a trailed forage wagon or pile it on the ground in windrows to dry. Such finely chopped material cannot be made into the big bales costed in Table 4 but a conservation system similar to the current vogue for bagged silage is suggested whereby large polythene bags are filled direct from the forage harvester and then evacuated using a slurry tanker or milking machine (Chaplin 1976). By arresting fermentation this would preserve the harvest for use in the winter period when biogas is most required, and would considerably reduce the volume of material to be stored.

5.3 Conversion methods and economic implications

Thermal conversion of Japanese knotweed is technically feasible, but it is unlikely to be financially justified because of the high moisture content in leaf material harvested during summer. This verdict coud change however if one or more of the following techniques is proven:

a. feedstock drying using process heat from gasifiers or pyrolysers;

b. separation of the woody stems from fresh leaves during harvesting;

c. expressing protein rich juice whilst simultaneously drying the residual fibre.

Anaerobic digestion is therefore likely to be the most favoured conversion technology, at least in the short term, and Table 4 presents approximate costs for an energy plantation of Japanese knotweed, derived by analogy with conventional agricultural operations.

The many assumptions made in the derivation of these costs are listed in Appendix IV.

The net revenues presented are similar to management and investment income as it might be calculated for an agricultural enterprise. Land rent and rates have not been included however, and fixed costs have been minimized by assuming that all operations are conducted by contractors. Comparisons between the profitability of agricultural crops are usually made using a statistic called the Gross Margin, which includes only variable costs, and assumes that farm buildings, equipment and labour are available free of charge.

A further complication is introduced by the fact that discounting techniques must be used to compare the profitability of a 10-year energy plantation with that of an annual agricultural crop. Thus, the estimated Net Present Value (NPV) of the energy plantation at £783 ha^{-1} (Table 4) is equivalent to the NPV of a crop sustaining a Gross Margin of £127.50 ha^{-1} for 10 years (assuming 10% discount rate).

Typical Gross Margins for agricultural crops will be in excess of £300 ha^{-1} (Nix 1982), and it therefore seems that knotweed energy plantations will not compete with agriculture on good quality land, especially when one considers that unpurified biogas is unlikely to fetch the assumed price equivalent of calor gas. There are however a number of factors which may modify this conclusion.

a. Agricultural Gross Margins are an overestimate of true farming profits, and Barr _et al_. (in press) in their estimate of the availability of land in GB for forest energy plantations estimate that the average Management and Investment Income for British agriculture (excluding rent and rates) is only £58.2 ha^{-1}.

b. Much agriculture profit is guaranteed by EEC subsidies, and it would be informative, although complicated, to remove this element.

c. Digestor residues are assumed in Table 4 to replace bag fertilizers once the plantation is established (Holdom & Winstrom-Olsen 1980). A high cost of £99 ha^{-1} is allocated to slurry spreading, since it is assumed that 10 dry tonnes ha^{-1} will be returned to the plantation after harvesting. This is around 2 to 3 times the normal rate of application of slurry or farmyard manure (White & Brown 1981). Digestion conserves the original nutrients contained in the feedstock and increases nitrogen and phosphorus concentrations in particular, through microbial activity.

d. Digestor residues could also have economic value as a source of feed for ruminants (Smith 1982; Owen 1980). Of themselves they do not provide a balanced diet, but residues have been used as a protein supplement to mixtures of chopped straw and molasses (Summers _et al_. 1980).

Table 4 Costs and revenue from a hypothetical 10 year plantation cycle of Japanese knotweed, harvested in mid summer and anaerobically digested (£/ha)

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Note*
Ploughing	30	-	-	-	-	-	-	-	-	-	1
Planting	87	-	-	-	-	-	-	-	-	-	2
Spraying	29	29	-	-	-	-	-	-	-	-	3
Fertilizer	78	78	78	-	-	-	-	-	-	-	4
Slurry	-	-	-	99	99	99	99	99	99	99	5
Harvesting	-	40	40	40	40	40	40	40	40	40	6
Carting	-	9	17	26	26	26	26	26	26	26	7
Baling	-	39	78	117	117	117	117	117	117	117	8
Storage	-	37	12	18	18	18	18	18	18	18	9
Total feedstock cost	224	232	225	300	300	300	300	300	300	300	
Biogas production cost	0	200	400	600	600	600	600	600	600	600	10
Revenue as calor gas replacement	0	378	756	1135	1135	1135	1135	1135	1135	1135	11
Net present value of operation at 10% discount	−224	−49	108	177	161	146	133	121	110	100	12

Thus, net present value of plantation = £780 with an internal rate of return of 14.7% 13,14

* See Appendix IV

e. As mentioned previously, the extrusion of leaf juices to make a protein concentrate, suitable for monogastric animals like man, leaves a protein depleted pulp for energy conversion. Wilkins et al. (1977) conducted a thorough economic analysis of green crop fractionation in which a variety of machines were costed in the production of a dried or fresh pressed crop and a fresh juice, which may be further separated into a protein-concentrate and a deproteinized residue. The return on investment from the best of these schemes was only marginally greater than that from a modern grass-drying plant, but methane generation was not considered as a possible source of additional revenue. Anaerobic digestion, or indeed gasification, of part of a wet crop like Japanese knotweed could provide crucial support energy for the fractionating and drying of protein concentrates (McDougall 1980). Plaskett (1981) however, considers that falls in the price of protein in recent years do not currently justify these procedures.

f. Knotweed leaves can be mechanically separated from the stems, allowing the former to be used for ruminant feed and the latter as an energy feedstock. Plaskett (1981) considers that dual-purpose plantations of knotweed could be economically viable and certainly demand further investigation.

Despite these factors it may prove that knotweed plantations will remain uncompetitive with agriculture on good quality land. However, both Japanese and giant knotweed species perform well on waste ground, and there are many areas of derelict land, motorway verges, railway embankments etc which coud in this manner be turned to profitable use.

It must be stressed that the assumptions in this section are based on a yield of an established knotweed plantation of 15 t ha^{-1} yr^{-1}. The experimental trial has fallen far short of this, and further commercial development must await biological and agronomic studies which permit the promising yields observed in the wild to be duplicated in plantations.

6 ENVIRONMENTAL IMPACT

6.1 The use of invasive weed species

Japanese knotweed is a troublesome weed species which is spreading so rapidly throughout Great Britain that legal restraints have recently been imposed on its planting. Small fractions of rhizome have exceptional abilities to survive and the establishment of monocultures or hedgerows of this species would certainly lead to unwanted spread. This spread would be obtrusive in natural habitats and road verges etc (where Japanese knotweed already often occurs). However, experiments on the herbicidal control of Japanese knotweed have largely solved this problem (Harper & Stott 1966). The spread of Japanese knotweed on to pastoral land surrounding its plantations is not likely to be serious, as Japanese knotweed is itself grazed and can be damaged by trampling.

Giant knotweed has far less potential for regeneration and invasive spread. Existing natural stands are generally small and the species is comparatively rare. The dissemination of this weed species through cultivation is not, therefore, envisaged as a problem.

6.2 Soil improvement

Japanese knotweed is a highly successful colonizer of derelict land such as demolished areas of buildings, and can penetrate brick, rubble, concrete, etc. In these situations a fertile soil is quickly established from the great quantities of biomass senescing each autumn. It is feasible that Japanese knotweed could be planted as an energy crop on poor waste land. During the period of establishment, when biomass would not be removed from the site, an organic soil will be produced, and this would soon be augmented by the return of residues from alcoholic or anaerobic fermentation processes.

6.3 Land use change

Each scenario for the use of the species of knotweed presents land use implications. The planting of Japanese knotweed on waste land would have the positive impact of soil conditioning discussed above, together with the amenity and conservation values of plant cover and associated wildlife on otherwise derelict land. The use of either species in hedgerows or strips of vegetation along motorway and railway embankments, etc, would result in a reduction of the diversity of vegetation and wildlife in existing hedgerows and along transport routes. Plantations of Japanese and giant knotweed, if proved to be exceptionally productive, could result in significant displacement of agricultural land. The extraction of protein for fodder and the use of residues for fuel could conceivably reduce the area under grazing,and would strengthen the trend from field grazing to yarded or housed stock. Such a system would lead to a greater production of collectable animal slurry which would be mixed with plant material and used for anaerobic digestion.

6.4 Genetic diversity

The establishment of extensive monocultures results in lack of genetic diversity and generally poor resistance to pathogens, pests and abnormal weather conditions. Natural populations of Japanese knotweed are extremely successful in combating such adversities, however, despite having a depauperate gene pool, resuting from the fact that sexual reproduction is almost unknown in Britain. The potential for developing new genotypes with specific attributes, including increased yield, should therefore be appreciable.

6.5 Harvesting and conversion

Environmental risks and health hazards from the harvesting of Japanese and giant knotweed should not be greater than those currently pertaining to conventional agricultural crops, as conventional equipment would be used.

Similarly, the anaerobic digestion of the crops would incur no greater risks than the digestion of animal slurry etc. If the 2 species of knotweed were to be combusted, then the same considerations would apply as those discussed for the combustion of bracken (Callaghan et al. 1983a) ie possible release of particulates and polycyclic hydrocarbons, low production of sulphur dioxide, low ash production and little smoke.

7 CONCLUSION

The exceptional yield of Japanese and giant knotweed experienced in the field has not been realized in artificial plantations established over a period of 3 years. Almost total lack of data on these wild species, one of which occurs only infrequently in the UK, led to many problems relating to planting density, method of propagation, requirements for weed control, etc. A small experiment comparing planting densities suggests that higher yields can be obtained more rapidly with higher initial densities. However, much greater attention must be devoted to the control of weed species in the phase before the knotweed canopy is established. Also, it is becoming apparent that knotweed is more sensitive to wind exposure than expected, and it could be valuable to establish a trial where it is inter-cropped with tree species.

If the potential of Japanese and giant knotweed shown under natural conditions can be realized under controlled conditions, then these species should form ideal energy crops because they digest more efficiently than other native species, and they are resistant to annual harvesting. Also, the separation of leaf and stem components would allow the protein and metabolic energy requirements of grazing animals to be met, whilst providing a useful source of energy, which will in turn generate residues for use as a fertilizer.

These remarkable, but under-studied species certainly merit further investigations, but the feasibility of their exploitation remains a mid or long term proposition.

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APPENDIX I

METHODS

Field site

Japanese knotweed was transplanted from an established stand in Manchester (map ref SD 854012) to a flat ploughed field near Lindale, Cumbria (map ref SD 433816) in February 1980. Rhizome fragments with a mean weight of 62.6 $\pm$ 8.8g, and a mean bud number of 4.03 $\pm$ -.45 were planted at a density of 4 m^{-2}.

Experimental design

Based on a 3 x 3m quadrat (Figure 1.1) which included a 1 x 1m sample square surrounded by a 1m buffer zone, the total size of the plot was 24 x 72m. The 4-replicated year treatment blocks were randomly placed and each contained 4 fertilizer treatment blocks. Within ech of these 6 x 6m blocks were 4 randomly arranged quadrats for harvest at different times within the year (Figure 1.2).

Harvest dates	H1	H2	H3	H4
	13 May	6 July	4 Sept	12 Nov

Standing vegetation was cut on the specified dates as close as possible to ground level. The knotweed and the associated species were gathered in the 1 m^2 sample area and returned to the laboratory in separate polythene sacks, the stems of the knotweed being kept intact for later measurements. The outer area of the 3 x 3m quadrat was cleared and the cuttings discarded off-site. This zone acted as access within the site and as a buffer between adjacent treatments.

Fertilizer levels	F1	F2	F3	F4
	No application	0.5 t ha^{-1}	1 t ha^{-1}	2 t ha^{-2}

Fisons "regular" 20:10:10 NPK granules were applied by hand during available dry days in late April or early May. Care was taken not to trample the sample areas and to ensure an even spread of granules over the 3 x 3m quadrats.

Year treatments	Y1	Y2	Y3
	Cropped in 1980,81,82	Cropped in 1981,82	Cropped in 1982 only

Differences in frequency of harvest were designed to assess the effect of cutting on subsequent yields.

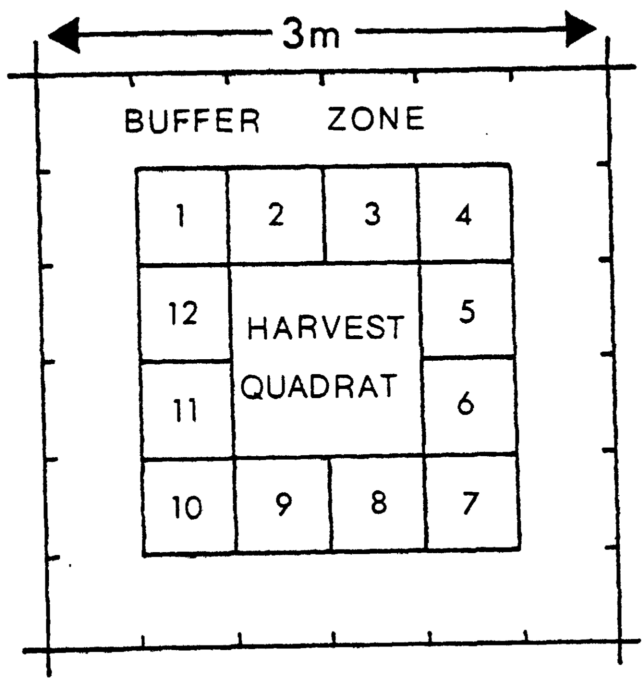

Fig. I.1 Basic sampling unit at the field site.

Laboratory analyses

Fresh weights of the whole samples of Japanese knotweed were recorded soon after sampling and a short period of storage at 4°C was usually necessary before the samples could be analysed. The knotweed stems were counted, and the diameter (at ground level) and heights (from cut to tip of newest leaf) of each stem were measured. The samples of Japanese knotweed and associated species were then dried separately in a well ventilated oven at 80°C to constant weight.

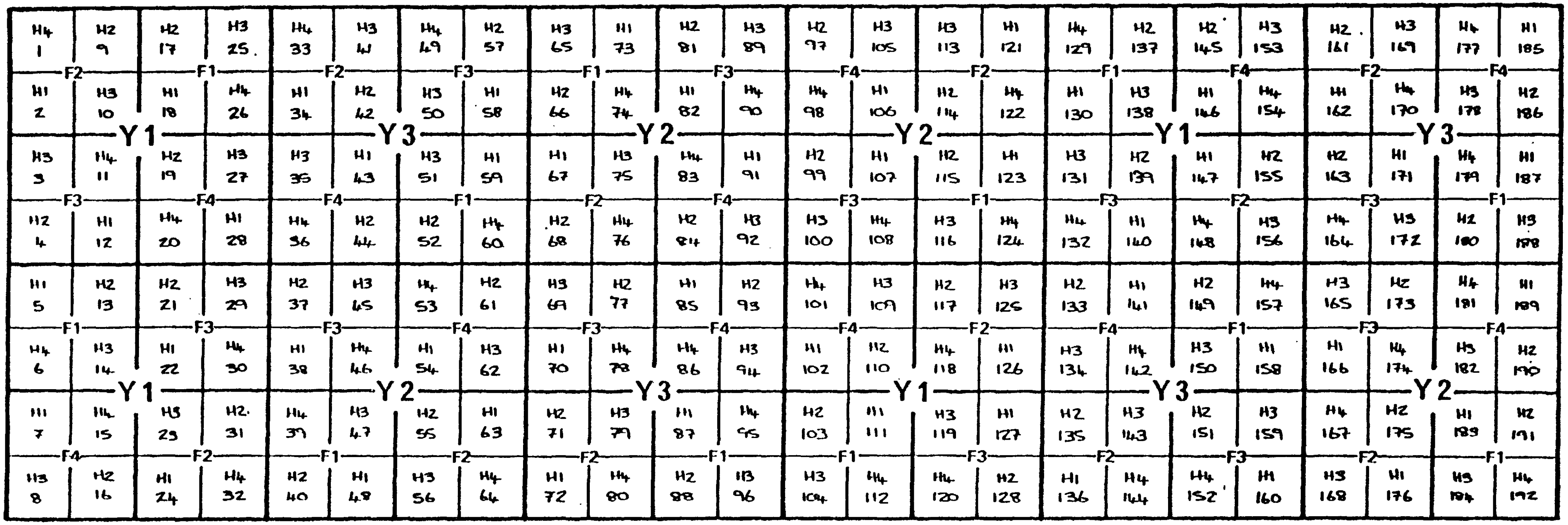

Figure I.2. Layout of Japanese knotweed field site

Appendix II

Statistical Results: overall split-split-plot analysis of variance

knotweed yield

	df	ss	ms	F	Results
Years	2	224 364	112 182	2.25	P>0.05
Error (1)	9	449 381	49 931	4.65	
Fertilizers	3	196 331	65 444	3.15	P<0.05
Years x Fertilizers	6	156 139	26 023	1.25	P>0.05
Error (2)	27	560 657	20 765	1.93	
Harvest dates	3	366 556	122 185	11.37	P<0.001
Years x Dates	6	276 436	46 073	4.29	P<0.001
Fertilizers x Dates	9	112 892	12 544	1.17	P>0.05
Years x Fertilizers x Dates	18	134 436	7 469	0.69	
Error (3)	108	1 159 953	10 740		
Total	191	3 637 147			

other species yield

	df	ss	ms	F	Results
Years	2	219 380	109 690	0.88	P>0.05
Error (1)	9	1 125 578	125 064	5.41	
Fertilizers	3	1 051 254	350 418	9.79	P<0.001
Years x Fertilizers	6	659 629	109 938	3.07	P<0.05
Error (2)	27	966 881	35 810	1.55	
Harvest dates	3	3 879 769	1 293 256	55.91	P<0.001
Years x Dates	6	131 250	21 875	0.95	P>0.05
Fertilizers x Dates	9	409 333	45 481	1.97	P>0.05
Years x Fertilizers x Dates	18	402 296	22 350	0.97	
Error (3)	108	2 497 957	23 129		
Total	191	11 343 328			

knotweed stem density

	df	ss	ms	F	Results
Years	2	34.16	17.08	0.09	P>0.05
Error (1)	9	1621.98	180.22	6.03	
Fertilizers	3	149.64	49.88	0.76	P>0.05
Years x Fertilizers	6	420.59	70.10	1.01	P>0.05
Error (2)	27	1775.33	65.75	2.2	
Harvest dates	3	184.27	61.42	2.06	P>0.05
Years x Dates	6	252.59	42.10	1.41	P>0.05
Fertilizers x Dates	9	266.46	29.61	0.99	P>0.05
Years x Fertilizers x Dates	18	1220.99	67.83	2.27	
Error (3)	103	3226.44	29.87		
Total	191	9152.45			

knotweed stem height

	df		ss	ms	F	Results
Years	2		15569.4	7784.7	11.05	P<0.01
Error (1)	9		6337.3	704.1	3.63	
Fertilizers	3		15605.0	5201.7	15.68	P<0.001
Years x Fertilizers	6		659.5	109.9	0.33	P>0.05
Error (2)	27		8955.6	331.7	1.71	
Harvest dates	2		77687.3	38843.7	200.14	P<0.001
Years x Dates	4		6372.1	1593.0	8.21	P<0.001
Fertilizers x Dates	6		4755.0	792.5	4.08	P<0.01
Years x Fertilizers	12		4017.1	334.8	1.72	
x Dates	70	(2)	13585.5	194.1		
Error (3)						
Total	141		153543.6			

APPENDIX III

STATISTICAL RESULTS

Results of statistical analyses on data presented in the figures

Data source	Comparison	Statistical test	Results
knotweed yield	a) between harvest times		$P<0.001$ ($F=14.18$ with 3 and 11 degrees of freedom)
Figure 3A	b) between years (previously uncut)	two way anovar	$P<0.01$ ($F=7.35$ with 2 and 11 degrees of freedom)
	c) interaction		$P<.05$ ($F=3.28$ with 6 and 11 degrees of freedom)
other species yield			
Figure 3B	a) between harvest times		$P<0.001$ ($F=22.85$ with 2 and 8 degrees of freedom)
	b) between years (previously uncut)	two way anovar	$P<0.001$ ($F=38.9$ with 2 and 8 degrees of freedom)
	c) interaction		$P<0.05$ ($F=6.83$ with 4 and 8 degrees of freedom)
knotweed stem height	a) between harvest times		$P<0.001$ ($F=280.99$ with 2 and 8 degrees of freedom)
Figure 4A	b) between years (previously uncut)	two way anovar	$P<0.001$ ($F=36.52$ with 2 and 8 degrees of freedom)
	c) interaction		$P<0.01$ ($F=8.0$ with 4 and 8 degrees of freedom)

Data source	Comparison	Statistical test	Results
knotweed stem density	a) between harvest times		P>0.05 (F=2.28 with 3 and 11 degrees of freedom)
Figure 4B	b) between years (previously uncut)	two way anovar	P<0.01 (F=7.3 with 2 and 11 degrees of freedom)
	c) interaction		P>0.05 (F=2.69 with 6 and 11 degrees of freedom)
knotweed yield	a) between harvest times		P>0.05 (F=2.72 with 3 and 15 degrees of freedom)
Figure 5A	b) between fertilizer treatments	two way anovar	P<0.05 (F=3.69 with 3 and 15 degrees of freedom)
	c) interaction		P>0.05 (F=0.55 with 9 and 15 degrees of freedom)
knotweed stem height	a) between harvest times		P<0.001 (F= 329.1 with 2 and 11 degrees of freedom)
Figure 5B	b) between fertilizer treatments	two way anovar	P<0.001 (F= 84.15 with 3 and 11 degrees of freedom)
	c) interaction		P<0.001 (F=35.26 with 6 and 11 degrees of freedom)
knotweed stem density	a) between harvest times		P>0.05 (F=0.81 with 3 and 15 degrees of freedom)
Figure 5C	b) between fertilizer treatments		P>0.05 (F=0.56 with 3 and 15 degrees of freedom)
	c) interaction		P>0.05 (F=0.58 with 9 and 15 degrees of freedom)

Data source	Comparison	Statistical test	Results
other species yield	a) between harvest times		P<0.001 (F=20.58 with 3 and 15 degrees of freedom)
Figure 5D	b) between years (previously uncut)	two way anovar	P<0.001 (F=10.23 with 3 and 15 degrees of freedom)
	c) interaction		P>0.05 (F=0.93 with 9 and 15 degrees of freedom)
knotweed yield	a) between harvest times		P<0.01 (F=9.83 with 3 and 7 degrees of freedom)
Figure 6A	b) between 1982 uncut and 1982 cut in 1981	two way anovar	P<0.05 (F=9.06 with 1 and 7 degrees of freedom)
	c) interaction		P>0.05 (F=3.99 with 3 and 7 degrees of freedom)
Figure 6A	a) between harvest times		P=<0.01 (F=8.77 with 3 and 7 degrees of freedom)
	b) between 1981 uncut and 1981 cut in 1980	two way anovar	P=>0.05 (F=0.49 with 1 and 7 degrees of freedom)
	c) interaction		P=>0.05 (F=0.4 with 3 and 7 degrees of freedom)
knotweed stem height	a) between harvest times		P=<0.001 (F=465.61 with 2 and 5 degrees of freedom)
Figure 6B	b) between 1982 uncut and 1982 cut in 1981	two way anovar	P=<0.001 (F=112.85 with 1 and 5 degrees of freedom)
	c) interaction		P=<0.001 (F=58.56 with 2 and 5 degrees of freedom)
knotweed stem height	a) between harvest times		P=<0.01 (F=13.59 wtih 3 and 7 degrees of freedom)
Figure 6B	b) between 1981 uncut and 1981 cut in 1980	two way anovar	P=>0.05 (F=1.24 with 1 and 7 degrees of freedom)
	c) interaction		P=>0.05 (F=0.53 with 3 and 7 degrees of freedom)

Data source	Comparison	Statistical test	Results
knotweed stem density	a) between harvest times		P=>0.05 (F=2.37 with 3 and 7 degrees of freedom)
Figure 6C	b) between 1982 uncut and 1982 cut in 1981	two way anovar	P=>0.05 (F=0.9 with 1 and 7 degrees of freedom)
	c) interaction		P=>0.05 (F=0.74 with 3 and 7 degrees of freedom)
Figure 6C	a) between harvest times		P=>0.05 (F=2.21 with 3 and 7 degrees of freedom)
	b) between 1981 uncut and 1981 cut in 1980	two way anovar	P=>0.05 (F=2.39 with 1 and 7 degrees of freedom)
	c) interaction		P=>0.005 (F=0.99 with 3 and 7 degrees of freedom)
other species yield	a) between harvest times		P=<0.01 (F=20.42 with 3 and 7 degrees of freedom)
Figure 6D	b) between 1982 uncut and 1982 cut in 1981	two way anovar	P=>0.05 (F=0.77 with 1 and 7 degrees of freedom)
	c) interaction		P=>0.05 (F=1.01 with 3 and 7 degrees of freedom)
Figure 6D	a) between harvest times		P=<0.001 (F=54.9 with 3 and 7 degrees of freedom)
	b) between 1981 uncut and 1981 cut in 1980		P=<0.01 (F=20.75 with 1 and 7 degrees of freedom)
	c) interaction		P=>0.05 (F=1.09 with 3 and 7 degrees of freedom)
knotweed yield	a) between harvest times		P=<0.01 (F=8.92 with 3 and 7 degrees of freedom)
Figure 6A	b) between 1982 uncut and 1982 cut in 1981 + 1980	two way anovar	P=<0.05 (F=6.45 with 1 and 7 degrees of freedom)
	c) interaction		P=>0.05 (F=3.71 with 3 and 7 degrees of freedom)

Data source	Comparison	Statistical test	Results
knotweed stem height Figure 7A	a) between harvest times	two way anovar	P=<0.01 (F=8.92 with 3 and 7 degrees of freedom)
	b) between 1982 uncut and 1982 cut in 1981 + 1980		P=<0.05 (F=6.45 with 1 and 7 degrees of freedom)
	c) interaction		P=>0.05 (F=3.71 with 3 and 7 degrees of freedom)
knotweed stem height Figure 7B	a) between harvest times	two way anovar	P=<0.001 (F=479.11 with 2 and 5 degrees of freedom)
	b) between 1982 uncut and 1982 cut in 1981 + 1980		P=<0.001 (F=193.1 with 1 and 5 degrees of freedom)
	c) interaction		P=<0.001 (F=52.16 with 2 and 5 degrees of freedom)
knotweed stem density Figure 7C	a) between harvest times	two way anovar	P=>0.05 (F=2.22 with 3 and 7 degrees of freedom)
	b) between 1982 uncut and 1982 cut in 1981 + 1980		P=>0.05 (F=0.04 with 1 and 7 degrees of freedom)
	c) interaction		P=>0.05 (F=1.02 with 3 and 7 degrees of freedom)
other species yield Figure 7D	a) between harvest time	two way anovar	P=<0.01 (F=22.03 wtih 3 and 7 degrees of freedom)
	b) between 1982 uncut and 1982 cut in 1981 + 1980		P=>0.05 (F=1.71 with 1 and 7 degrees of freedom)
	c) interaction		P=>0.05 (F=0.46 with 3 and 7 degrees of freedom)

APPENDIX IV

Explanation of methods used to derive Table 4 (costs and revenue from a hypothetical 10 year plantation cycle of Japanese knotweed)

1. Contract ploughing (Nix, 1982).

2. Potato planting including labour and seed (Nix, 1982).

3. Contract spraying for maize, including materials (Nix, 1982).

4. Contract fertilizer application for maize, including materials (Nix, 1982).

5. Assuming 10 tonnes dm/ha application, 10% solids content in slurry, 20 min turnaround for 4 500 litre tanker (ADAS 1983), and £13.35/hr for contract tanker, tractor, driver (Farm Contractor 1983).

6. Contract maize harvesting (Farm Contractor 1983).

7. Assuming 5t/ha (dry) in year 2, 10t/ha in year 3 and 15t/ha in years 4 and subsequent. One, 2 and 3 hours work respectively for tractor and trailer at £8.70/hr (Farmers Weekly 1/5/83).

8. Assuming 135 kg/Big round bale and £1.05 contract baling charge (Farmers Weekly 1/5/83). This is probably an overestimate since harvesting and baling have been costed separately. The local storage would be vacuum packing of chopped material at the time of harvest, but vacuum packed silage has not been the trend for 20 years and no costings are available.

9. Assuming hardcore storage bay construction at £9.10/ha (Farmers Weekly 6/5/83) and £1.20 per polythene bag including netting for wind protection.

10. Assuming cost of digestion as 7.5p/m^3 and 450 m^3 Biogas produced from 1 tonne herbaceous material in 100 m^3 digestor (Wheatley & Ader 1979). Updated to 1983 at £40/dry tonne.

11. Assuming 8.5 GJ Biogas produced/dry tonne (Wheatley & Ader 1979) and taking price of Calor gas as £8.90/GJ (47 kg cylinder).

12. These net present values are not true 'Profits' since land rent has not been accounted for. Nevertheless the average net present value over the lifetime of the plantation can usefully be compared with gross margin figures calculated for agricultural crops, remembering that costs to a farmer would be perhaps 30% lower than the contractor costs used above.

13. It is difficult to compare the profitability of annual crops with that of perennial species where cash receipts are delayed for several years. The discount rate selected considerably affects these comparisons, with higher rates favouring annual crops. Another statistic which is useful to present, therefore, is the international rate of return, being the discount rate at which discounted revenue equals discounted expenditure.

14. Similar accounting has been applied with remarkably comprehensive detail in a recent report to the UK DEn (Mitchell *et al.* 1983) which compares the economic returns achieved by conventional agriculture, conventional forestry and energy forestry.

PART IV : Energy crop nutrition

C O N T E N T S

SUMMARY

1. Nutrient applications to energy crops of natural vegetation will be necessary to replace nutrients lost in harvested biomass. However, existing yields of bracken and cord-grass have not been increased by adding NPK fertilizer.

2. If stands of cord-grass and bracken, and plantations of Japanese knotweed, are harvested continuously without nutrient replacement, then consequent yield reductions are associated with decreasing tissue concentration of nutrients in the order Mg,Ca,P,N,K. It may be assumed, therefore, that applications of K are not required, at least over a 3 year harvesting period, but that Mg and Ca, which were not applied in the present experiment, may start to limit yield.

3. The addition of an NPK fertilizer on existing stands of bracken and cord-grass does not affect the decreases in yield due to annual harvesting. Much of the added nutrient is absorbed by the plant, however, since 'luxury' tissue concentrations are observed in those areas receiving high fertilizer applications. Yield must, therefore, be limited by factors other than these 3 macro-nutrients.

4. Luxury levels of nutrients are wasted in that they are not translated into improvements of yield, and translocation into below ground organs during senescence is inhibited.

5. Levels of NPK fertilizer required to replace the nutrients removed in repeated harvesting are between 50% and 100% of those currently applied to UK root crops.

6. Of the 3 species investigated, yields of Japanese knotweed are the most dependent on fertilizer applications. Cord-grass, presumably because of the comparatively high supply of nutrients in its natural environment, appears to be unaffected by such applications.

7. Tissue concentrations of N, P and K in unfertilized bracken are reduced after 3 successive years of harvesting, but this reduction appears to be insufficient to limit yield. It is not known how many years of harvesting are required to induce yield-limiting levels of these macro-nutrients.

8. The soils on which bracken and cord-grass naturally occur are generally fertile, although, on the saltmarsh, nitrogen levels are low and the levels of P are reduced by harvesting. Japanese knotweed was planted on a comparatively infertile site.

9. There is generally no decrease in soil fertility due to 3 successive annual harvests. This is probably because, in the case of bracken and cord-grass, large underground storage organs act as buffers for nutrients between soil and shoots, whereas, at the Japanese knotweed site, the yields harvested were so small as to have little effect on the nutrient status of the soil.

RECOMMENDATIONS

1. This research has shown that the 3 main macro-nutrients do not limit the yield of areas of annually harvested bracken and cord-grass in their natural habitats. More comprehensive experiments should therefore continue into the factors that do restrict yield.

2. It has been demonstrated that tissue concentrations of N, P and to some extent K are decreased by annual harvesting of unfertilized plots. Between 0.5 and 1.0 t ha^{-1} of 20:10:10 NPK fertilizer are required to maintain tissue concentrations of these macro-elements, but, in order to calculate an economic application rate, it is important to determine the number of harvests which can be taken before nutrient replacement becomes essential.

3. In the present experiment, conventional fertilizer has been used. It would be valuable to explore the suitability of residues from fermentation, anaerobic digestion and thermal conversion as replacements for, or supplements to, traditional fertilizers.

1. INTRODUCTION

Previous volumes in this series have described the biology and means of utilizing 3 species which seem particularly suited for conversion to biofuels. (Callaghan et al. 1984a,b,c). One important aspect of management includes the addition of fertilizers to areas of existing natural vegetation and plantations of native species. Such fertilizer additions are expected to be required for 2 reasons: a) existing areas of natural vegetation have not previously had fertilizer additions and current yields may be increased by adding fertilizer, b) the removal of biomass from areas of natural vegetation and new plantations will remove nutrients from the site and decrease soil fertility. Consequently, the long-term experiments on bracken (Pteridium aquilinum), cord-grass (Spartina anglica) and Japanese knotweed (Reynoutria japonica), described in earlier volumes of this series, contained a fertilizer component, including a control and 3 different levels of NPK fertilizer.

The selected levels of fertilizer application were based on the average given to potato crops, and 50% and 200% of this level. The potato crop was chosen as a standard because it is similar to the 3 study species in being perennial, with a large below-ground biomass.

Surprisingly, the yields of bracken and cord-grass (Volumes 1 and 2) showed no significant increase in response to fertilizer applications, but the new plantation of Japanese knotweed did show a highly significant effect of fertilizer upon yield, particularly in those plots which had been harvested each year for a period of 3 years.

Chemical analyses were performed on a variety of soils and plant tissues in order to understand the lack of fertilizer response in bracken and cord-grass, and to assess the effects of harvesting on soil fertility and tissue nutrient concentration.

2. METHODS

2.1 Experimental design

Plant tissues and soils to be analysed for nutrients were collected during each year of the 3 year experiment. The experimental site for bracken was at Lindale Fell, Cumbria (SD 418813), for cord-grass a coastal mud flat at Southport, Merseyside (SD 354206), and for knotweed a flat ploughed field near Lindale, Cumbria (SD 433816), where 4 cuttings m^{-2} were planted.

The experimental design was the same for each of the 3 species and is described in detail in Callaghan et al. (1984a,b,c). The sampling unit was 1 m^2, surrounded by an 8 m^2 buffer zone. Technically the design was a split-split plot, divided first into 3 distinct year treatment blocks (4 replicates), each of which was subdivided between 4 levels of fertilizer application. Finally, each fertilizer sub-block was divided into 4 x 9 m^2 quadrats which were harvested at 4 dates during the season.

Fison's "regular" 20:10:10 NPK granules were applied by hand on available dry days in late April or early May. Application rates were 0.5, 1, and 2 t/ha for treatments F2, F3 and F4 respectively. No fertilizer was applied in the F1 treatment.

The 3 year treatments were harvested on the same date each year as follows:

a) Y1 - cropped in 1980, 81 and 82
b) Y2 - cropped in 1981 and 82
c) Y3 - cropped in 1982 only

The 4 harvest dates were chosen to represent the seasonal development cycle of the plant growth and they varied from species to species. Harvest 3 coincided approximately with maximum yield, whereas harvest 4 represented an early senescent phase when the shoots were dry but still standing intact.

The 1 m wide buffer zone was also cut and cleared. This zone acted as access within the site to minimise the trampling of the sample area, and as a buffer between adjacent treatments.

2.2 Chemical analysis of plant material

Plant material of bracken and cord-grass collected at harvest 3 (10 September and 23 November respectively), and Japanese knotweed collected at harvest 3 and harvest 4 (6 September and 11 November respectively) was oven dried and ground in a 2 mm mesh hammer mill. Determination of K, Ca, Mg and P were made on extracts in 2.5 v/v acetic acid, and total nitrogen was determined by the Kjeldahl digestion method. (Further details of the analyses are presented in Allen *et al.* 1974.)

Statistical comparisons of the effects of harvesting and fertilizer treatments on the nutrient concentrations of the plant tissues were made using the "split-split-plot analysis of variance" contained in GENSTAT, and the results are presented in Appendix I

2.3 Chemical analysis of soil samples

Sections of soil 5 cm deep were taken using a stainless steel corer from unfertilized plots. Samples were taken in 1980 from Y1 H3 F1 plots in July and December to obtain a seasonal comparison between the soils (although one harvest was removed between the 2 sampling periods). Samples were also taken from Y3 H3 F1 plots in July 1982 to give a comparison between years with the Y1 H3 F1 sample of July 1980. Estimates of the effects of harvesting on soil fertility were obtained by comparing samples taken in December 1982 from Y1 H3 F1 (plots from which 3 successive annual harvests had been removed) with those taken from Y1 H3 F1 plots in 1980 before the harvesting regime started.

Surface litter, stones and live plant matter were removed from each sample which was dried at 40^0 C and ground through a 2 mm mesh roller mill. Analyses of N, P, K, Ca and Mg were determined as described above for plant matter. Loss on Ignition (LoI) was determined by weighing the residue after 4 hours, ignition at 450^0 C and pH was determined electrometrically on water slurry allowed to stand for 15 minutes. Statistical comparisons were made using simple Student's t-tests and the results are presented in Appendix II.

3. RESULTS

3.1 Bracken

3.1.1 Yield and tissue concentration of nutrients.

The yield of bracken does not significantly respond to fertilizer additions (Appendix 1), although there is a sl decrease in yield associated with the highest fertilizer level (Figure 1a) (some damage to young fronds was observed in the field for this treatment, probably resulting from direct contact with caustic nutrients). There is, however, a highly significant decrease in yield due to harvesting over the 3 years (Figure 1a).

Although there is no increase in yield due to fertilizers, tissue concentrations of N, P and K increase in relation to the levels of these nutrients added in the fertilizer (Figures 1b,c,d). Concentrations of N, P, and K are higher than those at the start of the experiment, indicating 'luxury' levels which are not translated into yields. Tissue concentrations of P do not respond to fertilizers until the second year, whereas there is a fast response in concentration of N.

On control plots, without any fertilizer treatment, tissue concentrations of N and K remained stable even though biomass rich in N and K was removed for 2 successive years (Figures 1b, d). In contrast, tissue concentrations of P decreased markedly on control plots and only the highest applications of fertilizer were sufficient to maintain, or increase, initial tissue concentrations (Figure 1c). It would appear, therefore, that P is a critical element which must be supplied to areas of bracken managed for biofuel production. However, the lack of yield response to P applied as fertilizer suggests that other factors are limiting growth in this annual harvesting regime.

There is no significant effect of mixed NPK fertilizer on levels of Ca and Mg, but repeated harvesting appears to approximately halve the tissue concentration of Mg. It seems, therefore, that fertilizer treatments including Mg should be used to maintain long-term yields, although soil concentrations of Mg suggest that at this particular site it may not be limiting to growth (qv).

Concentrations of ash remained stable and did not respond to

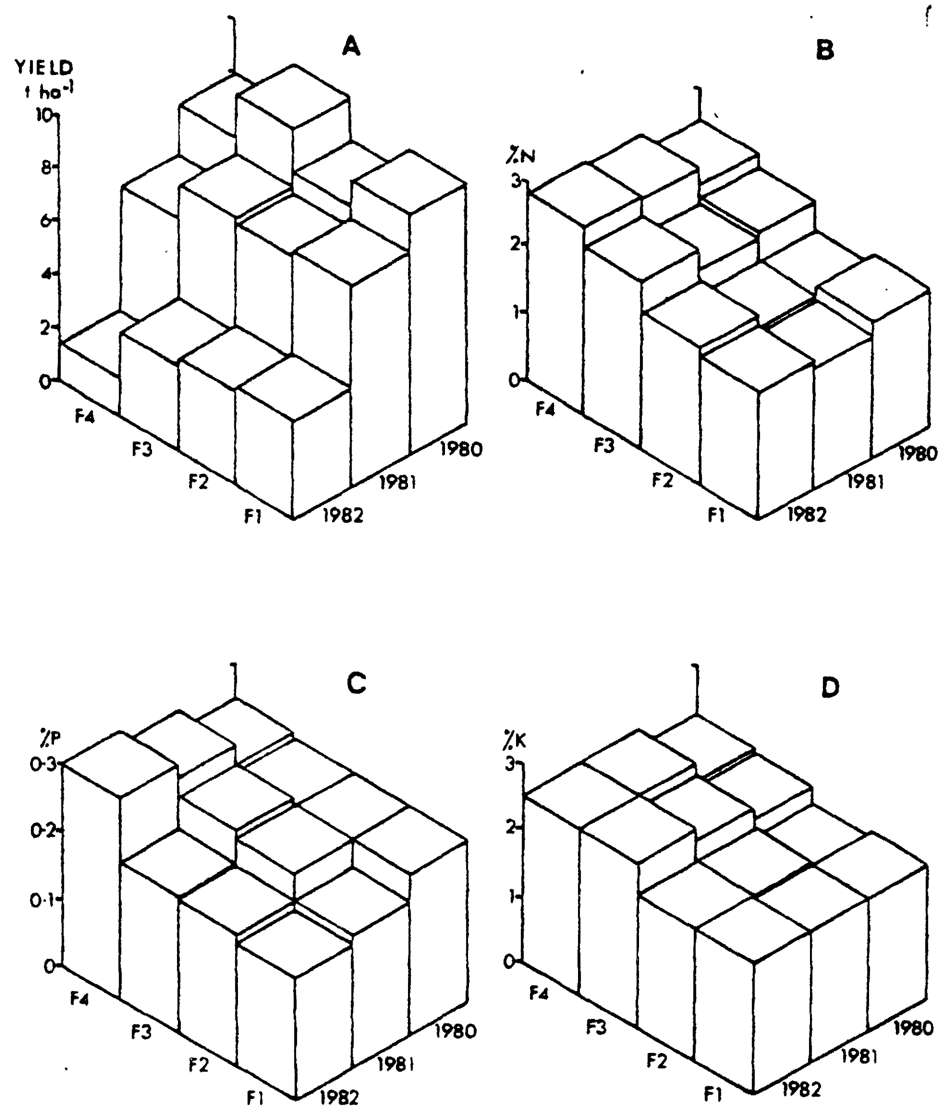

Figure 1

The yield (A) and concentrations (% dry weight) of N(B), P(C) and K(D) in the tissues of bracken harvested at peak yield for 3 years in relation to 4 levels of fertilizer. (F1 to F4 = 0, 0.5, 1.0 and 2.0 t ha^{-1} respectively of Fison's regular 20:10:10 NPK fertilizer). Statistical analyses are presented in Appendix I.

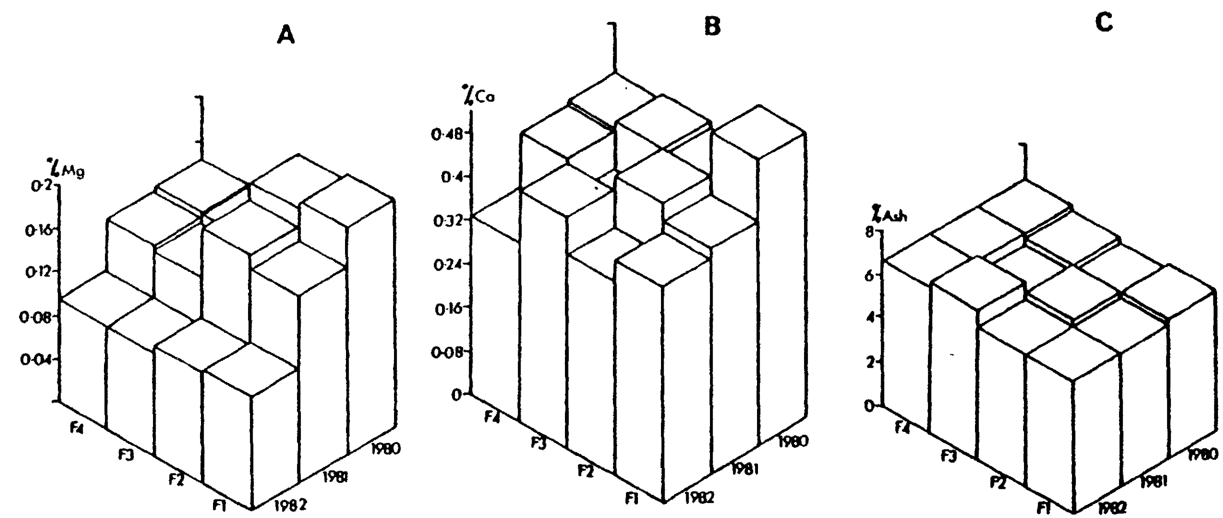

Figure 2

The concentrations (% dry weight) of Mg (A), Ca (B) and ash (C) in the tissues of bracken harvested at peak yield for 3 years in relation to 4 levels of fertilizer. (F1 to F4 = 0, 0.5, 1.0 and 2.0 t ha^{-1} respectively of Fison's regular 20:10:10 NPK fertilizer).
Statistical analyses are presented in Appendix I.

fertilizer or harvesting treatments (Figure 2c). As N,P,K,Ca and Mg either decreased or remained stable in relation to harvesting on the unfertilized plots, other elements not measured here may have increased proportionately. However, silica is such a large and stable component of ash that it generally obscures any trends.

3.1.2 Soil fertility

The soil at the bracken site (Table 1) is quite fertile when compared with a range of soils found in Great Britain (Table 2). Levels of N,P and K are particularly high, but those of Mg and Ca are comparatively low. Bracken can grow on a wide range of soils, but it thrives in moderately acid conditions, and the low pH at the study site is typical. The organic content of the soil, measured as Loss on Ignition (LoI), is considerable and is equivalent to a percentage carbon content of 25 (% carbon = LoI-2.0/1.87, Howard 1966), which is characteristic of peaty soils.

The variation in soil chemistry at the bracken site between July and December is insignificant, and there is only a slightly significant variation in N levels between years (Table 1). More importantly, there is no significant reduction of soil fertility resulting from the removal of 3 annual harvests of biomass. Thus, the reduction in tissue concentrations of P, and particularly Mg, must be associated with the processes of nutrient uptake, storage in the rhizome and allocation, rather than a depletion in the soil pool.

3.2 Cord-grass

3.2.1 Yield and tissue concentration of nutrients

Like bracken, cord-grass shows no response of yield to fertilizer application but a highly significant decrease of yield in relation to annual harvesting (Figure 3a).

Although somewhat variable, the tissue concentrations of N and P show no significant response to fertilizers or harvesting (Figure 3b,c). Significant increases of K are apparent in response to harvesting (Figure 3d), and there is a suggestion of an increase in P. This is clearly in contrast to the depletion of both elements induced by the harvesting of bracken and Japanese knotweed, and the explanation must be found in the naturally nutrient-rich estuarine environment in which cord-grass grows.

In contrast to the behaviour of N, P, and K, the tissue concentrations of Mg and Ca show marked decreases associated with harvesting (Figure 4a,b).

Concentrations of Mg and Ca in the tissues are not related to fertilizer treatments as the fertilizer did not contain these elements. Unlike the trend in bracken, concentrations of ash in the tissues of cord-grass show a decrease in relation to harvesting but no overall effect due to fertilizer treatment (Fig 4c).

Table 1. Variation in soil fertility of unfertilised plots at the bracken site. (See Appendix II for details of the statistical analyses).

	Seasonal variation 1			Annual variation 2		Variation due to Harvesting 3	
	July 1980	Dec. 1980	Significance (July 80-Dec 80)	July 1982	Significance (July 80-July 82)	Dec. 1982	Significance (July 80-Dec. 82)
N(%)	1.63	1.85	NS	1.03	*	1.52	NS
P(mg/100g) *	1.86	1.17	NS	1.68	NS	1.82	NS
K(mg/100g) *	30.5	50.0	NS	24.3	NS	32.3	NS
Mg(mg/100g) *	22.8	19.8	NS	21.0	NS	29.8	NS
Ca(mg/100g) *	80.5	51.5	NS	76.0	NS	93.5	NS
LoI(%)	47.8	46.5	NS	38.0	NS	55.0	NS
pH	4.2	4.2	NS	4.1	NS	4.1	NS

* (mg $100g^{-1}$)

1. This compares plots sampled at the beginning and end of season, with a harvest in between.

2. This compares samples taken from plots which had not been harvested.

3. This compares plots sampled before and after 3 successive years of harvesting.

Table 2. Chemical characteristics of some contrasting soil types. Sampling depth 0-15 cm. All results (except pH) given on dry weight basis. Extractions carried out using M ammonium acetate, pH 7.0. (Copied from Allen et al. 1974).

		mg 100 g^{-1}				%	
	pH	K	Ca	Mg	P	C	N
Upland limestone soil, Ingleborough	8.0	15	310	17	0.2	6	0.3
Lowland chalk soil, Sussex Downs	8.2	16	720	40	0.7	9	0.7
Brown-earth (Serpentine), Cornwall	7.5	47	92	52	0.4	6	0.4
Iron humus podzol (Moine schists), Sutherland	5.5	10	12	8	0.4	5	0.2
Gleyed podzol (Basalt), Ben Harris, Argyll	6.3	13	170	130	1.0	12	0.3
Iron podzol (Granite), Kerloch, Kincardineshire	4.8	15	14	7	0.8	9	0.3
Upland blanket peat, Moor House, Westmorland	3.5	32	70	27	1.0	50	1.0
Upland gley (Silurian slates), Furness	4.4	18	22	3	0.3	8	0.2
Lowland podzol (Bunter sst). Delamere	4.9	3	6	2	0.3	7	0.3
"Thin" light podzol (Kellaways rock) N. Yorks. moors	4.7	4	14	4	0.2	6	0.2
Brown forest soil (O.R.S.), Shropshire	5.4	19	25	17	0.9	8	0.4
Alluvial warp, Trent Valley	5.9	24	70	31	0.7	4	0.5
Peaty-gley (Torridonian) Beinn Eighe, W. Ross	4.7	14	42	21	0.8	19	0.7
Shallow podzol (Extrusive lavas), Borrowdale, Cumberland	4.3	23	20	11	0.5	10	0.5
Sketal montane soil (Cairngorms)	6.2	2	3	1	0.1	1	0.1
Blown sand regosol, Ainsdale, Lancashire	6.3	2	6	6	0.1	2	0.1
Chalk heath, Hampshire	4.7	23	84	25	0.3	11	0.7
Peaty-podzol (Calc sst), Northumberland	4.3	8	5	2	0.7	8	0.5

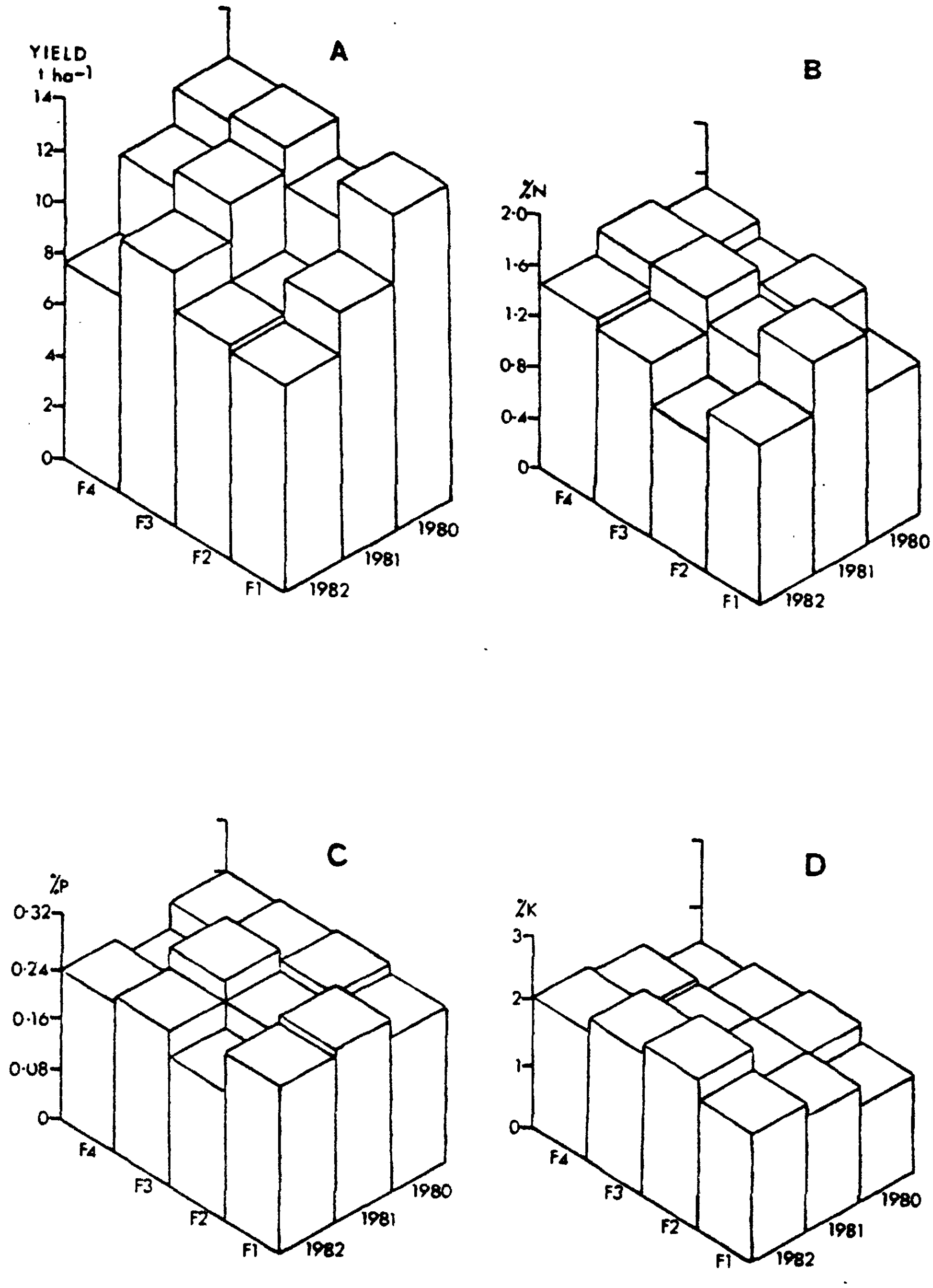

Figure 3

The yield (A) and concentrations (% dry weight) of N(B), P(C) and K(D) in the tissues of cord grass harvested at peak yield for 3 years in relation to 4 levels of fertilizer. (F1 to F4 = 0, 0.5, 1.0 and 2.0 t ha^{-1} respectively of Fison's regular 20:10:10 NPK fertilizer.). Statistical analyses are presented in Appendix I.

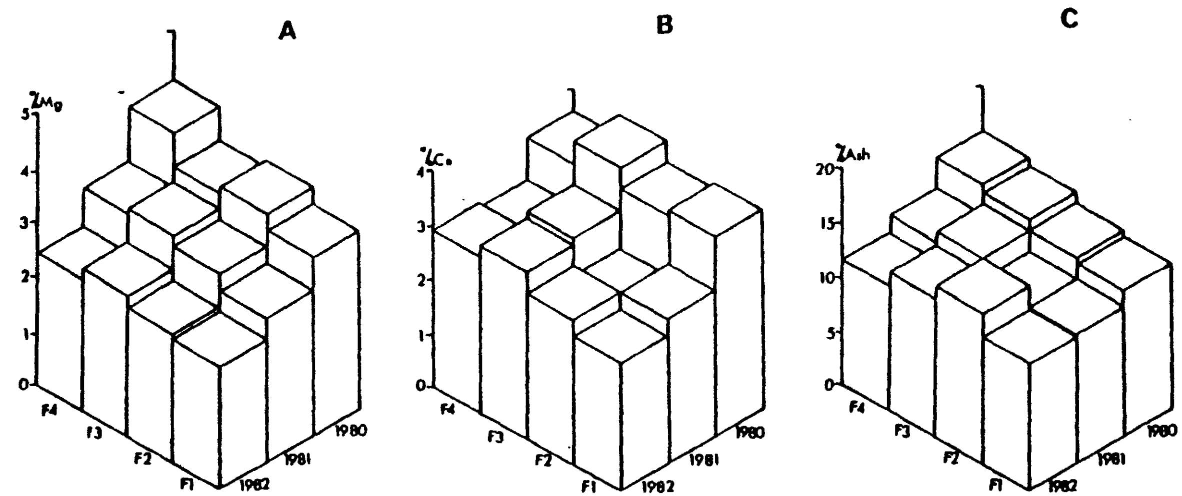

Figure 4

The concentrations (% dry weight) of Mg(A), Ca(B) and ash(C) in the tissues of cord grass harvested at peak yield for 3 years in relation to 4 levels of fertilizer. (F1 to F4 = 0, 0.5, 1.0 and 2.0 t ha^{-1} respectively of Fison's regular 20:10:10 NPK fertilizer).
Statistical analyses are presented in Appendix I.

3.2.2 Soil fertility

The estuarine silt of the cord-grass site is characterised by having low levels of N and organic matter, but a high pH and high levels of P, K, Mg and Ca (Table 3). Some significant seasonal and annual variation occurs in levels of Ca and P, while K varies between years (Table 3). Although the levels of Ca and K are so high that this variation will probably be irrelevant to growth, the variation in P content could be important, particularly when removal of P is envisaged through bio-energy harvesting.

It is somewhat surprising that the low levels of N are not further depleted by 3 successive annual harvests of biomass, but it is probable that the storage rhizomes act as a buffer between above-ground yield and soil fertility. This effect can be seen by considering the decreasing tissue concentrations of Mg and Ca in the shoots of cord-grass, whereas the external concentrations in the soil are far from limiting.

3.3 Japanese knotweed

3.3.1 Yield and tissue concentration of nutrients

Unlike bracken and cord-grass, Japanese knotweed was planted on cultivated agricultural land, and the 3 year experiment started with freshly planted rhizome fragments. There was therefore no established pool of nutrients in an extensive underground perenniating system. Perhaps for this reason, applications of fertilizers increased yields during the second and third years of harvesting, whereas unfertilized plots showed reduced yield as a result of harvesting (Figure 5a).

Tissue concentrations of N and P appear to limit growth, as control plots show significant decreases in tissue concentrations associated with harvesting, but fertilized plots show increases even after harvesting, resulting in high concentrations (Figure 5b,c).

As in the case of bracken, depletion of phosphorus in plant tissues is particularly marked after harvesting unfertilized plots. In contrast, tissue concentrations of K show no decrease due to harvesting and with fertilizing this element increases to high levels, even in the first year (Figure 5d). The slight increase in tissue concentrations after the harvesting of unfertilized plots is not statistically significant (Figure 5d).

Tissue concentrations of calcium decrease due to harvesting (Figure 6b) but those of Mg are variable, with a clear decrease only occurring on the control plots (Figure 6a). Total ash concentrations in the tissues are relatively stable, with perhaps a small increase related to the increased nutrient levels in fertilized plots (Figure 6c).

Table 3: Variation in soil fertility of unfertilized plots at the cord grass site. (See Appendix II for details of the statistical analyses).

	Seasonal variation 1			Annual variation 2		Variation due to harvesting 3	
	July 1980	Dec. 1980	Significance (July 80-Dec. 80)	July 1982	Significance (July 80-July 82)	Dec. 1982	Significance (July 80-Dec 82)
N(%)	0.31	0.33	NS	0.35	NS	0.32	NS
P(mg/100g)*	7.37	5.12	**	5.52	**	2.67	***
K(mg/100g)*	75.0	77.75	NS	60.0	**	80.3	NS
Mg(mg/100g)*	220	208	NS	185	NS	243	NS
Ca(mg/100g)*	2800	2675	*	2700	*	3025	NS
LoI(%)	10.7	10.6	NS	11.3	NS	10.8	NS
pH	7.8	8.1	NS	7.8	NS	8.2	**

* (mg $100g^{-1}$)

1. This compares plots sampled at the beginning and end of season, with a harvest in between.

2. This compares samples taken from plots which had not been harvested.

3. This compares plots sampled before and after 3 successive years of harvesting.

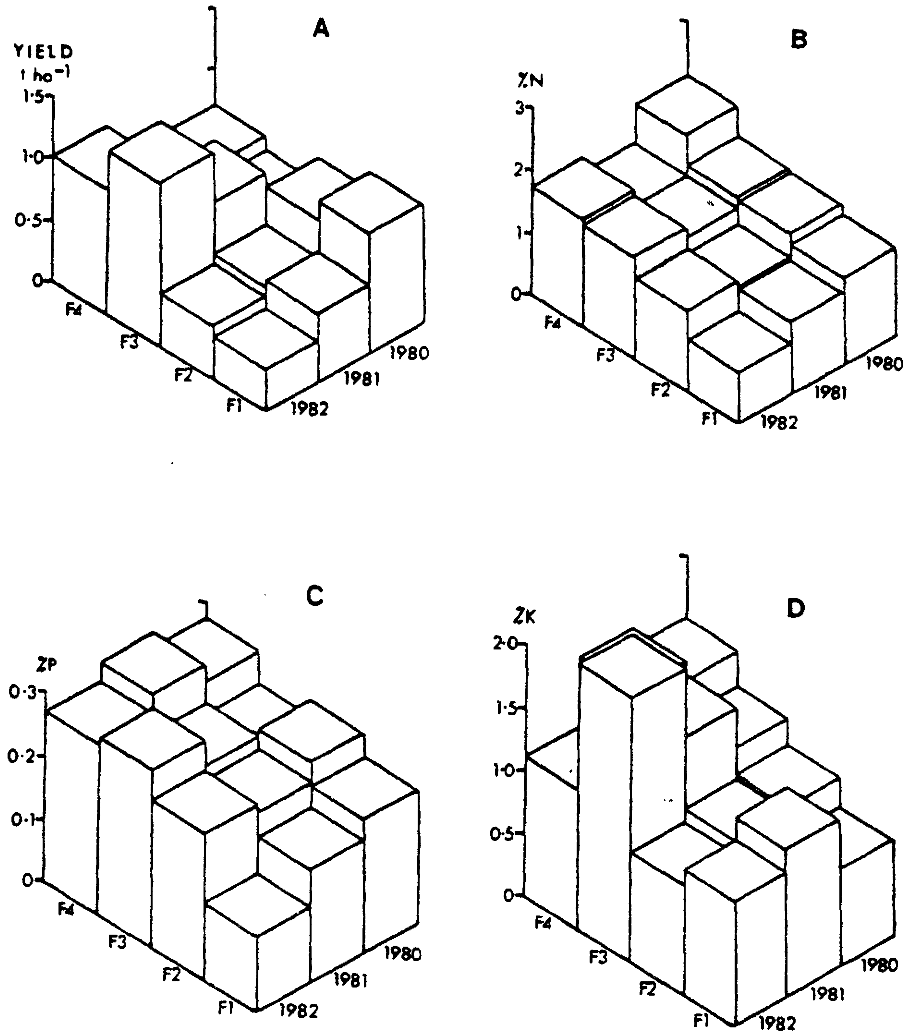

Figure 5

The yield (A) and concentrations (% dry weight) of N(B), P(C) and K(D) in the tissues of Japanese knotweed harvested at peak yield for 3 years in relation to 4 levels of fertilizer. (F1 to F4 = 0, 0.5, 1.0 and 2.0 t ha^{-1} respectively of Fison's regular 20:10:10 NPK fertilizer). Statistical analyses are presented in Appendix I.

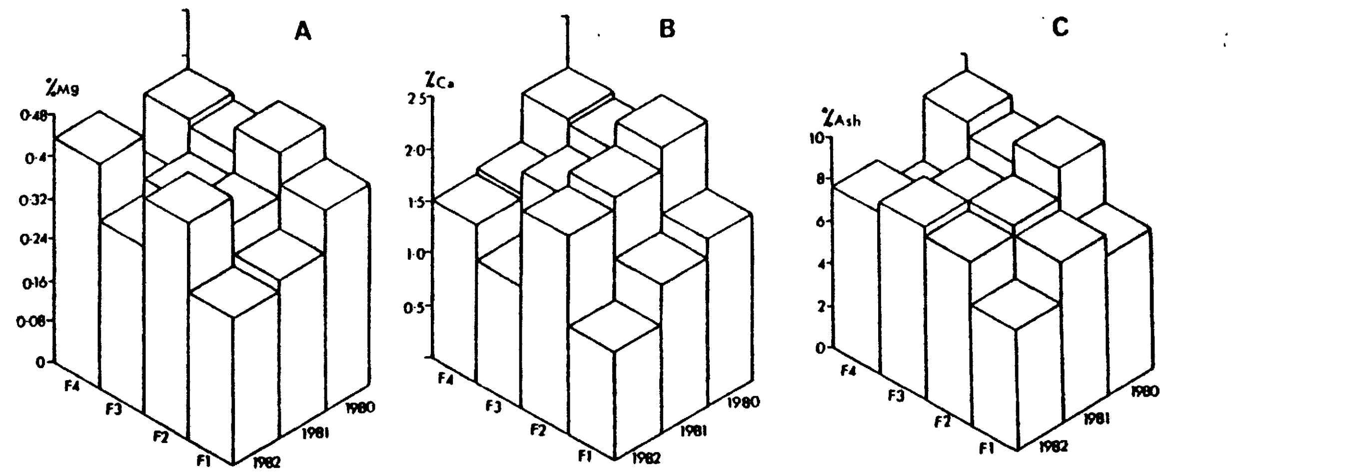

Figure 6

The concentrations (% dry weight) of Mg(A), Ca(B) and ash(C) in the tissues of Japanese knotweed harvested at peak yield for 3 years in relation to 4 levels of fertilizer. (F1 to F4 = 0, 0.5, 1.0 and 2.0 t ha^{-1} respectively of Fison's regular 20:10:10 NPK fertilizer).
Statistical analyses are presented in Appendix I.

In the case of Japanese knotweed, it is possible to compare concentrations of the nutrients in senescent tissues at the end of the growing season with those in the healthy tissues discussed above. The tissue concentrations of nitrogen show similar trends in response to harvesting and fertilizer applications, although actual concentrations in senescent tissues are approximately 50% of those in younger tissues (Figures 5b and 7b). Similarly, tissue concentrations of phosphorus are lower in senescent tissues due to translocation, as would be expected (Callaghan et al. 1981), but the trends in relation to harvesting and fertilizing are far more pronounced at this late harvest (Figs 5c and 7c).

This finding suggests that, when tissue concentrations reach high levels during the growing season, relatively little phosphorus is translocated below ground: there is a decrease from 0.27% to 0.23% at the highest fertilizer level, compared with a decrease from 0.21% to 0.11% at the zero fertilizer level (Figures 5c and 7c). A similar trend is shown by potassium, where there is also a large seasonal decrease in concentration between harvests 3 and 4 (0.78% to 0.34%), whereas the decrease at the highest fertilizer treatment is only from 1.5% to 1.0% (Figures 5d and 7d). In the case of potassium, although no decrease in tissue concentration was apparent at harvest 3 in relation to cutting, there was a large reduction in all but the highest fertilizer levels at harvest 4 (Figure 7d). Similarly, tissue concentration of Mg showed a clear decrease due to cutting at harvest 4 (Figure 8a) but not at harvest 3 (Figure 6a).

Tissue concentrations of Ca at harvest 4 show no clear trend and levels of this relatively non-mobile element are fairly similar at both harvests 3 and 4 (Figures 6b and 8b).

The ash concentrations of tissues harvested during senescence (Figure 8c) show a clear reduction due to annual harvesting, reflecting the trends described above for the nutrients P, K and Mg in particular.

3.3.2 Soil fertility

The marginal agricultural soil on which Japanese knotweed was planted is relatively infertile when compared with the other soils. Ca and K levels are especially low. With the exception of K, which is a particularly mobile element, there is no variation in soil fertility associated with seasonal, annual or harvesting effects.

Harvesting, and the removal of nutrients contained in harvested vegetation, did not significantly effect the yields of Japanese knotweed, or associated weed species, measured in subsequent years. This is somewhat surprising in view of the fact that the highly-significant effect of artificial fertilizers on yields shows that this is a infertile site. However, Japanese knotweed is not normally the main component of yield, and many of the other weed species are those able to sustain high yields in low fertility conditions (eg. thistles). When these species are cut they may be replaced by species with higher nutrient requirements, thereby confusing the results which would be displayed by a monoculture of Japanese knotweed.

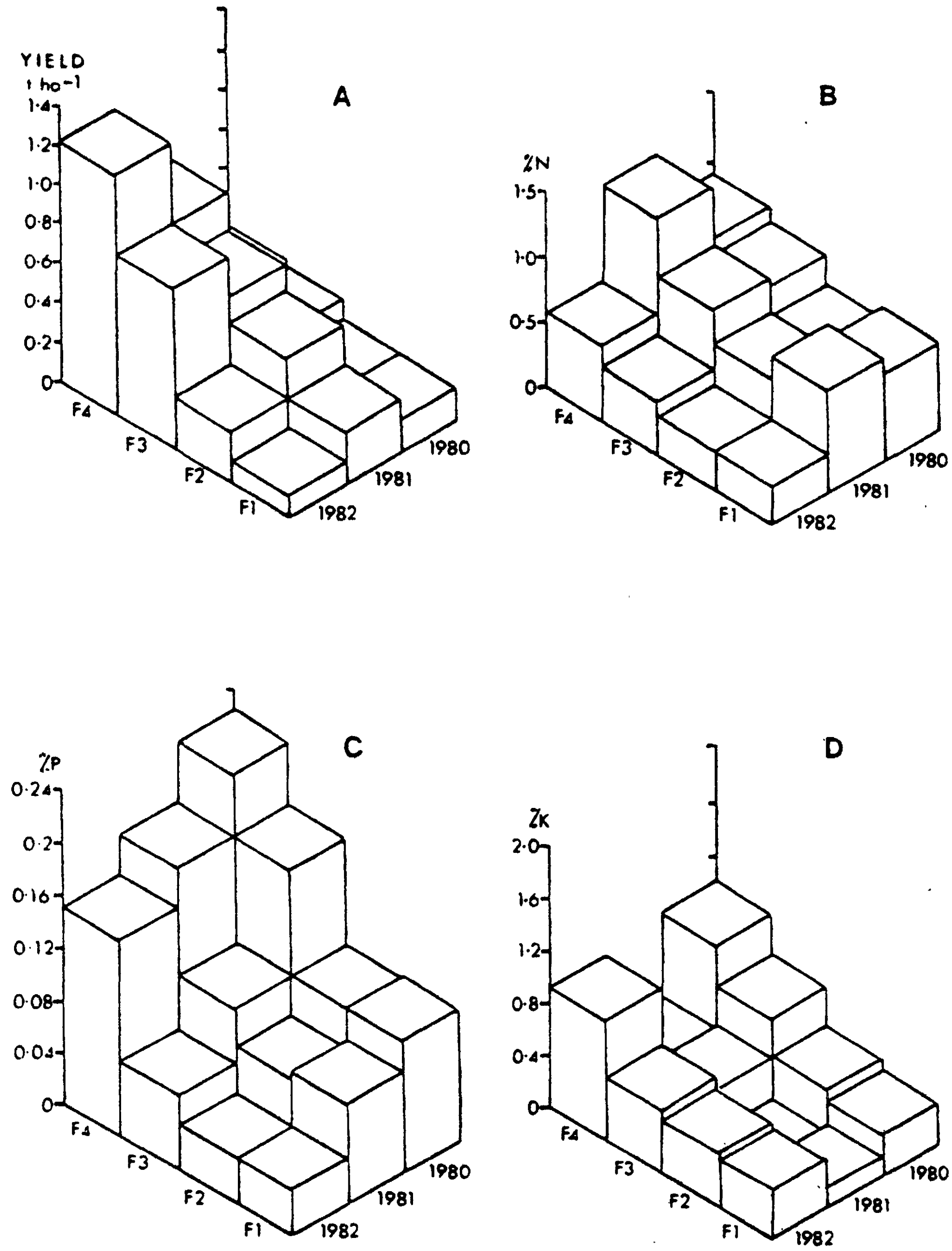

Figure 7

The yield (A) and concentrations (% dry weight) of N(B), P(C) and K(D) in the tissues of Japanese knotweed harvested during senescence for 3 years in relation to 4 levels of fertilizer. (F1 to F4 = 0, 0.5, 1.0 and 2.0 t ha^{-1} respectively of Fison's regular 20:10:10 NPK fertilizer). Statistical analyses are presented in Appendix I.

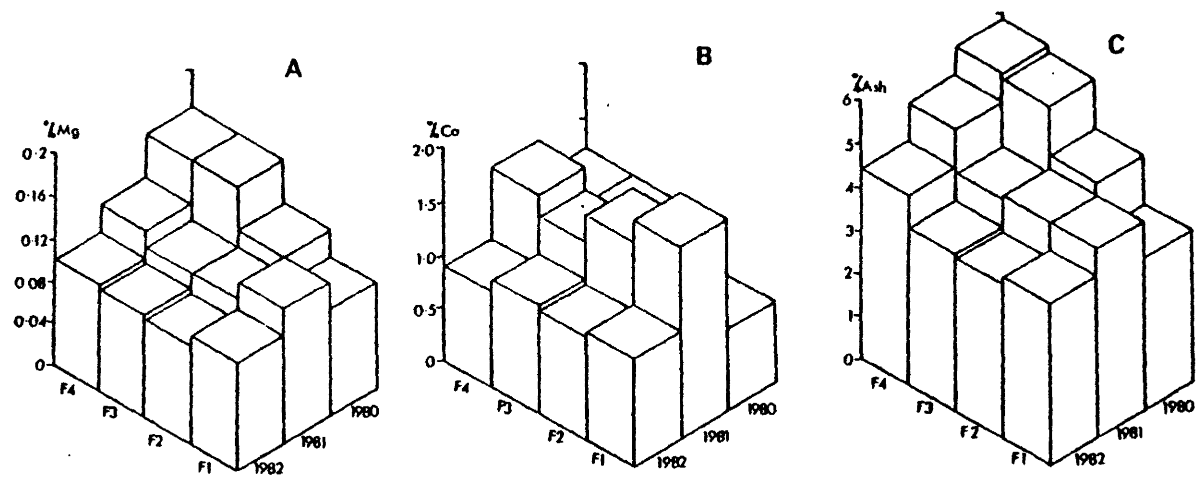

Figure 8

The concentrations (% dry weight) of Mg(A), Ca(B) and ash(C) in the tissues of Japanese knotweed harvested during senescence for 3 years in relation to 4 levels of fertilizer. (F1 to F4 = 0, 0.5, 1.0 and 2.0 t ha^{-1} respectively of Fison's regular 20:10:10 NPK fertilizer).
Statistical analyses are presented in Appendix I.

Table 4. Variation in soil fertility of unfertilised plots at the Japanese knotweed site. (See Appendix II for details of the statistical analyses).

	Seasonal variation 1			Annual variation 2		Variation due to harvesting 3	
	July 1980	Dec. 1980	Significance (July 80-Dec. 80)	July 1982	Significance (July 80-July 82)	Dec. 1982	Significance (July 80-Dec. 82)
N(%)	0.24	0.40	NS	0.32	NS	0.19	NS
P(mg/100g)*	5.05	4.77	NS	5.02	NS	3.05	NS
K(mg/100g)*	3.90	9.82	*	7.70	**	6.17	NS
Mg(mg/100g)*	26.3	29.3	NS	38.0	NS	21.9	NS
Ca(mg/100g)*	338	394	NS	348	NS	303	NS
LoI(%)	6.5	10.8	NS	9.7	NS	5.6	NS
pH	7.5	7.1	*	7.1	**	7.5	NS

*(mg $100g^{-1}$)

1. This compares plots sampled at the beginning and end of season, with a harvest in between.

2. This compares samples taken from plots which had not been harvested.

3. This compares plots sampled before and after 3 successive years of harvesting.

4. CONCLUSION

Fertilizer applications of N, P and K to existing stands of bracken and cord-grass neither increase yields, nor prevent loss of yield under sustained annual harvesting. However, annual harvesting results in decreases in tissue concentrations of P and N if fertilizers are not added. Fertilizer applications can maintain or even increase tissue concentrations. It must be concluded, therefore, that N, P and K are not limiting the yield of bracken and cord-grass, either in existing stands or after biomass removal during harvesting. As bracken tissue concentrations of Mg and, to a lesser extent, Ca decrease with harvesting, these elements may eventually cause a yield limitation. However, their abundance in the soil of the bracken and cord-grass sites suggests that it may be simply uptake rates that are limited.

At the Japanese knotweed site, the addition of N, P and K is essential to maintain yields with continuous annual harvesting, and yields of this species respond to fertilizers even when no harvesting takes place. This is undoubtedly due to the infertility of the soil at this site, and the absence of a large buffering nutrient pool in below-ground rhizomes.

It may be concluded that natural stands of bracken and cord-grass can be harvested for at least 3 years without the addition of NPK fertilizer, and that yields and soil fertility will remain unaffected. If, however, tissue concentrations of these elements are to be maintained (although there is no evidence that low concentrations affect yield), then application rates between 50% and 100% of the average application to a potato crop will be required. On the other hand, high application rates of fertilizer will be necessary to maintain yields of Japanese knotweed planted from cuttings on infertile soils.

This work has shown that some nutrients other than N, P or K may limit the yield of bracken or cord-grass: the identification of these nutrients could lead to higher yields from already productive crops.

5. ACKNOWLEDGEMENTS

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APPENDIX I

Statistical results of a split-split-plot analysis of variance (GENSTAT) on data presented graphically in the text.

DATA SOURCE	COMPARISON		RESULTS
Figure 1A	(a) between fertilizer treatments	$p>0.05$	($F=1.62$ with 3 and 27 degrees of freedom)
	(b) between successive years of harvesting	$p<0.001$	($F=13.88$ with 2 and 6 degrees of freedom)
	(c) interaction	$p>0.05$	($F=1.08$ with 6 and 27 degrees of freedom)
Figure 1B	(a) between fertilizer treatments	$p<0.001$	($F=10.79$ with 3 and 27 degrees of freedom)
	(b) between successive years of harvesting	$p>0.05$	($F=0.93$ with 2 and 9 degrees of freedom)
	(c) interaction	$p>0.05$	($F=0.62$ with 6 and 27 degrees of fredom)
Figure 1C	(a) between fertilizer treatments	$p<0.001$	($F=8.57$ with 3 and 27 degrees of freedom)
	(b) between successive years of harvesting	$p>0.05$	($F=0.78$ with 2 and 9 degrees of freedom)
	(c) interaction	$p>0.05$	($F=1.78$ with 6 and 27 degrees of freedom)
Figure 1D	(a) between fertilizer treatments	$p<0.001$	($F=8.64$ with 3 and 27 degrees of freedom)
	(b) between successive years of harvesting	$p>0.05$	($F=3.58$ with 2 and 9 degrees of freedom)
	(c) interaction	$p>0.05$	($F=0.21$ with 6 and 27 degrees of freedom)
Figure 2A	(a) between fertilizer treatments	$p<0.001$	($F=22.69$ with 3 and 27 degrees of freedom)
	(b) between successive years of harvesting	$p<0.001$	($F=16.45$ with 2 and 9 degrees of freedom)
	(c) interaction	$P<0.05$	($F=2.85$ with 6 and 27 degrees of freedom)

Figure 2B	(a) between fertilizer treatments	$p > 0.05$	($F=1.14$ with 3 and 27 degrees of freedom)
	(b) between successive years of harvesting	$p < 0.05$	($F=3.53$ with 2 and 9 degrees of freedom)
	(c) interaction	$p < 0.01$	($F=2.18$ with 6 and 27 degrees of freedom)
Figure 2C	(a) between fertilizer treatments	$p > 0.05$	($F=1.52$ with 3 and 27 degrees of freedom)
	(b) between successive years of harvesting	$p > 0.05$	($F=0.11$ with 2 and 9 degrees of freedom)
	(c) interaction	$p > 0.05$	($F=0.61$ with 6 and 27 degrees of freedom)
Figure 3A	(a) between fertilizer treatments	$p > 0.05$	($F=0.75$ with 3 and 27 degrees of freedom)
	(b) between successive years of harvesting	$p > 0.05$	($F=0.42$ with 2 and 11 degrees of freedom)
	(c) interaction	$p > 0.03$	($F=0.41$ with 6 and 27 degrees of freedom)
Figure 3B	(a) between fertilizer treatments	$p < 0.05$	($F=3.67$ with 3 and 23 degrees of freedom)
	(b) between successive years of harvesting	$p > 0.05$	($F=4.0$ with 2 and 9 degrees of freedom)
	(c) interaction	$p > 0.05$	($F=2.07$ with 6 and 23 degrees of freedom)
Figure 3C	(a) between fertilizer treatments	$p > 0.05$	($F=1.74$ with 3 and 23 degrees of freedom)
	(b) between successive years of harvesting	$p > 0.05$	($F=1.73$ with 2 and 9 degrees of freedom)
	(c) interaction	$p > 0.05$	($F=2.68$ with 6 and 23 degrees of freedom)
Figure 3D	(a) between fertilizer treatments	$p > 0.05$	($F=2.42$ with 3 and 23 degrees of freedom)
	(b) between successive years of harvesting	$p < 0.001$	($F=19.32$ with 2 and 11 degrees of freedom)
	(c) interaction	$p < 0.05$	($F=2.98$ with 6 and 23 degrees of freedom)

Figure 4A	(a) between fertilizer treatments	$p>0.05$	($F=2.05$ with 3 and 23 degrees of freedom)
	(b) between successive years of harvesting	$p<0.001$	($F=43.72$ with 2 and 9 degrees of freedom)
	(c) interaction	$p>0.05$	($F=1.11$ with 6 and 23 degrees freedom)
Figure 4B	(a) between fertilizer treatments	$p>0.05$	($F=1.79$ with 3 and 23 degrees of freedom)
	(b) between successive years of harvesting	$p<0.05$	($F=7.68$ with 2 and 9 degrees of freedom)
	(c) interaction	$p>0.05$	($F=0.68$ with 6 and 23 degrees of freedom)
Figure 4C	(a) between fertilizer treatments	$p>0.05$	($F=1.54$ with 3 and 23 degrees of freedom)
	(b) between successive years of harvesting	$p<0.05$	($F=7.14$ with 2 and 9 degrees of freedom)
	(c) interaction	$p>0.05$	($F=1.57$ with 6 and 23 degrees of freedom)
Figure 5A	(a) between fertilizer treatments	$p>0.05$	($F=2.02$ with 3 and 27 degrees of freedom)
	(b) between successive years of harvesting	$p>0.05$	($F=2.89$ with 2 and 11 degrees of freedom)
	(c) interaction	$p>0.05$	($F=1.02$ with 6 and 27 degrees of freedom)
Figure 5B	(a) between fertilizer treatments	$p<0.01$	($F=4.89$ with 3 and 25 degrees of freedom)
	(b) between successive years of harvesting	$p<0.01$	($F=4.71$ with 2 and 9 degrees of freedom)
	(c) interaction	$p>0.05$	($F=0.67$ with 6 and 25 degrees of freedom)
Figure 5C	(a) between fertilizer treatments	$p>0.05$	($F=0.40$ with 3 and 25 degrees of freedom)
	(b) between successive years of harvesting	$p>0.05$	($F=1.18$ with 2 and 9 degrees of freedom)
	(c) interaction	$p>0.05$	($F=0.65$ with 6 and 25 degrees of freedom)

Figure 5D	(a) between fertilizer treatments	$p<0.01$	($F=6.54$ with 3 and 25 degrees of freedom)
	(b) between successive years of harvesting	$p>0.05$	($F=2.36$ with 2 and 9 degrees of freedom)
	(c) interaction	$p>0.05$	($F=2.31$ with 6 and 25 degrees of freedom)
Figure 6A	(a) between fertilizer treatments	$p>0.05$	($F=1.00$ with 3 and 25 degrees of freedom)
	(b) between successive years of harvesting	$p<0.05$	($F=4.96$ with 2 and 9 degrees of freedom)
	(c) interaction	$p>0.05$	($F=0.82$ with 6 and 25 degrees of freedom)
Figure 6B	(a) between fertilizer treatments	$p<0.01$	($F=5.51$ with 3 and 25 degrees of freedom)
	(b) between successive years of harvesting	$p<0.05$	($F=7.20$ with 2 and 9 degrees of freedom)
	(c) interaction	$p>0.05$	($F=0.30$ with 6 and 25 degrees of freedom)
Figure 6C	(a) between fertilizer treatments	$p<0.05$	($F=4.09$ with 3 and 25 degrees of freedom)
	(b) between successive years of harvesting	$p>0.05$	($F=2.92$ with 2 and 9 degrees of freedom)
	(c) interaction	$p>0.05$	($F=0.81$ with 6 and 25 degrees of freedom)
Figure 7a	(a) between fertilizer treatments	$p<0.01$	($F=4.6$ with 3 and 27 degrees of freedom)
	(b) between successive years of harvesting	$p>0.05$	($F=0.6$ with 2 and 11 degrees of freedom)
	(c) interaction	$p>0.05$	($F=1.75$ with 6 and 27 degrees of freedom)
Figure 7B	(a) between fertilizer treatments	$p<0.001$	($F=11.4$ with 3 and 21 degrees of freedom)
	(b) between successive years of harvesting	$p<0.001$	($F=54.2$ with 2 and 9 degrees of freedom)
	(c) interaction	$p>0.05$	($F=1.49$ with 6 and 21 degrees of freedom)

Figure 7C	(a) between fertilizer treatments	$p<0.001$	($F=21.4$ with 3 and 20 degrees of freedom)
	(b) between successive years of harvesting	$p<0.01$	($F=11.5$ with 2 and 9 degrees of freedom)
	(c) interaction	$p>0.05$	($F=1.03$ with 6 and 20 degrees of freedom)
Figure 7D	(a) between fertilizer treatments	$p<0.001$	($F=20.2$ with 3 and 20 degrees of freedom)
	(b) between successive years of harvesting	$p<0.01$	($F=9.63$ with 2 and 9 degrees of freedom)
	(c) interaction	$p>0.05$	($F=1.48$ with 6 and 20 degrees of freedom)
Figure 8A	(a) between fertilizer treatments	$p>0.05$	($F=1.13$ with 3 and 20 degrees of freedom)
	(b) between successive years of harvesting	$p>0.05$	($F=1.37$ with 2 and 9 degrees of freedom)
	(c) interaction	$p>0.05$	($F=0.99$ with 6 and 20 degrees of freedom)
Figure 8B	(a) between fertilizer treatments	$p>0.05$	($F=1.08$ with 3 and 20 degrees of freedom)
	(b) between successive years of harvesting	$p<0.01$	($F=1.08$ with 2 and 9 degres of freedom)
	(c) interaction	$p>0.05$	($F=6.20$ with 6 and 20 degrees of freedom)
Figure 8c	(a) between fertilizer treatments	$p<0.01$	($F=6.0$ with 3 and 20 degrees of freedom)
	(b) between successive years of harvesting	$p>0.05$	($F=2.16$ with 2 and 9 degrees of freedom)
	(c) interaction	$p>0.05$	($F=1.07$ with 6 and 20 degrees of freedom)

APPENDIX II

Statistical results of Student's t-test on data presented in the tables.
(degrees of freedom = 6 in all cases)

DATA SOURCE	COMPARISON		RESULTS	
Table 1	(a) between July and Dec. 1980			
		N(%)	$p>0.05$	$t = 0.69$
		P(mg/100g)	$p>0.05$	$t = 0.57$
		K(mg/100g)	$p>0.05$	$t = 1.95$
		Mg(mg/100g)	$p>0.05$	$t = 0.54$
		Ca(mg/100g)	$p>0.05$	$t = 1.67$
		LOI(%)	$p>0.05$	$t = 0.01$
		pH	$p>0.05$	$t = 0.01$
	(b) between July 1980 and July 1982			
		N(%)	$p<0.05$	$t = 2.61$
		P(mg/100g)	$p>0.05$	$t = 0.17$
		K(mg/100g)	$p>0.05$	$t = 0.48$
		Mg(mg/100g)	$p>0.05$	$t = 0.31$
		Ca(mg/100g)	$p>0.05$	$t = 0.25$
		LOI(%)	$p>0.05$	$t = 1.10$
		pH	$p>0.05$	$t = 0.21$
	(c) between July 1980 and Dec. 1982			
		N(%)	$p>0.05$	$t = 0.32$
		P(mg/100g)	$p>0.05$	$t = 0.03$
		K(mg/100g)	$p>0.05$	$t = 0.18$
		Mg(mg/100g)	$p>0.05$	$t = 0.84$
		Ca(mg/100g)	$p>0.05$	$t = 0.56$
		LOI(%)	$p>0.05$	$t = 0.56$
		pH	$p>0.05$	$t = 0.17$
Table 3	(a) between July 1980 and Dec. 1980			
		N(%)	$p>0.05$	$t = 0.61$
		P(mg/100g)	$p<0.01$	$t = 4.70$
		K(mg/100g)	$p>0.05$	$t = 0.40$
		Mg(mg/100g)	$p>0.05$	$t = 0.56$
		Ca(mg/100g)	$p<0.05$	$t = 2.61$
		LOI(%)	$p>0.05$	$t = 0.10$
		pH	$p>0.05$	$t = 1.18$
	(b) between July 1980 and July 1982			
		N(%)	$p>0.05$	$t = 0.04$
		P(mg/100g)	$p<0.01$	$t = 4.20$
		K(mg/100g)	$p<0.01$	$t = 3.25$
		Mg(mg/100g)	$p>0.05$	$t = 1.70$
		Ca(mg/100g)	$p<0.05$	$t = 2.45$
		LOI(%)	$p>0.05$	$t = 0.97$
		pH	$p>0.05$	$t = 0.24$

(c) between July 1980 and Dec. 1982

N(%)	$p>0.05$	$t = 0.37$
P(mg/100g)	$p<0.001$	$t = 9.02$
K(mg/100g)	$p>0.05$	$t = 1.35$
Mg(mg/100g)	$p>0.05$	$t = 1.02$
Ca(mg/100g)	$p>0.05$	$t = 2.03$
LOI(%)	$p>0.05$	$t = 0.09$
pH	$p<0.01$	$t = 5.34$

Table 4

(a) between July 1980 and Dec. 1980

N(%)	$p>0.05$	$t = 0.97$
P(mg/100g)	$p>0.05$	$t = 0.21$
K(mg/100g)	$p<0.05$	$t = 2.75$
Mg(mg/100g)	$p>0.05$	$t = 0.30$
Ca(mg/100g)	$p>0.05$	$t = 0.31$
LOI(%)	$p>0.05$	$t = 1.14$
pH	$p<0.05$	$t = 3.25$

(b) between July 1980 and July 1982

N(%)	$p>0.05$	$t = 0.68$
P(mg/100g)	$p>0.05$	$t = 0.04$
K(mg/100g)	$p<0.01$	$t = 3.30$
Mg(mg/100g)	$p>0.05$	$t = 1.38$
Ca(mg/100g)	$p>0.05$	$t = 0.07$
LOI(%)	$p>0.05$	$t = 1.14$
pH	$p<0.01$	$t = 3.53$

(c) between July 1980 and Dec. 1982

N(%)	$p>0.05$	$t = 0.82$
P(mg/100g)	$p>0.05$	$t = 2.15$
K(mg/100g)	$p>0.05$	$t = 1.84$
Mg(mg/100g)	$p>0.05$	$t = 0.68$
Ca(mg/100g)	$p>0.05$	$t = 1.61$
LOI(%)	$p>0.05$	$t = 0.43$
pH	$p>0.05$	$t = 0.11$

PART V : Overview

CONTENTS

SUMMARY

1. Natural and semi-natural vegetation occupies 85 200 km^2 and has a mean above-ground production of 4.5 t ha^{-1} yr^{-1}. Bracken and cordgrass cover 3 000 and 120 km^2 respectively of Britain, and could be harvested from where they currently occur. Japanese knotweed is comparatively scarce and could be planted as a dedicated energy crop.

2. Prior to this study, estimates of the productivity of natural vegetation were available in the scientific literature, but little was known about the effects of continued management or repeated cropping. A 3-year experimental programme was, therefore, initiated to determine the responses of 3 productive species (bracken, cordgrass and Japanese knotweed) to various management treatments and to interpret these responses in the context of local, regional and national biofuel production.

3. In nature, the productivity of the 3 species ranges from 10 to 30 t ha^{-1} yr^{-1}. Yields of bracken in the experimental plots have been maintained at up to 9 t ha^{-1} yr^{-1} after 4 years of annual harvesting and without the benefit of fertilizers. Yields of cordgrass have remained even higher at 16 t ha^{-1} yr^{-1} under the same treatment. The experimental plantation of Japanese knotweed, however, yielded less than 4 t ha^{-1} yr^{-1}, even 4 years after it was established. This poor performance was largely due to infertility and weed competition, and several improvements in cultivation techniques are therefore suggested.

4. Weather conditions can affect yields, and in the case of bracken, late frosts can dramatically reduce yields. Fertilizer treatments were found not to increase the yields of bracken or cordgrass, although tissue concentrations of N, P and K were reduced in biomass from annually harvested plots which had not received fertilizer. As tissue concentrations of N, P and K increased when fertilizer was added, yield must be limited by other factors. Knotweed showed a strong requirement for fertilizer.

5. Bracken and cordgrass could be exploited from where they already occur, although both species could be planted if required. Species like cordgrass have already been successfully established and have led to the reclamation of estuarine land. Japanese knotweed and its close relative, giant knotweed, could initialy be planted on land with low agricultrual value and few ecological problems are envisaged. Bracken would be harvested using reciprocating cutter-bars, flail-mowers or rotary slashers, depending upon slope. Tractors and self-loading forage wagons developed for alpine slopes could be used to collect the biomass. Cordgrass would be harvested using equipment developed in Sweden to harvest reeds. Japanese knotweed would be harvested using standard heavy-duty forage harvesting equipment.

6. Bracken could be collected in summer for anaerobic digestion or in autumn for thermal conversion. Summer harvests would lead to eventual eradication but would save the cost of herbicides. Cordgrass and knotweed have been anaerobically digested with efficiencies between 39 and 57%. The extraction of protein-rich juices or other products from these species before conversion to biofuel could enhance the economics of the cropping when cheap protein sources from the 3rd world are no longer available.

7. The energy equivalent of the above ground production of natural vegetation is 700 PJ. The upland nature of most of this vegetation reduces the mean yield to 4.5 t ha^{-1} yr^{-1} but greatly improved yields are possible, in particular in some categories of permanent grazing and on unutilized land like salt marshes, heather moors and mires. Estimates of regional resources have been made using the ITE land classification and the technique can be used to explore possible changes in traditional land use when, and if, a clear market advantage is demonstrated for biofuels.

8. A range of planting, fertilizing, harvesting, processing and conversion systems were applied to the study species by analogy with agriculture or energy crops abroad. Chopped Japanese knotweed and cordgrass could be delivered to nerby anaerobic digesters for £23.20 t^{-1} or £15.35 t^{-1}. The knotweed costs were derived in greater detail, assuming a 10 year plantation cycle and allowing a 4-year establishment period. The Internal Rate of Return on investment over this period will be around 14.7%. Bracken briquettes could be produced with portable machinery for £53.40 t^{-1}, assuming harvesting, storage and local transport costs of £18.20 t^{-1}, drying costs of £9 t^{-1}, and briquetting costs of £26.20 t^{-1}. A generous estimate of expenditure on fertilizer, packaging and marketing could raise the total cost of production to £74.50 t^{-1}, but it is not thought that these latter expenditures would be necessary with a small scale operation.

   Such costs should be balanced against possible savings in: government food subsidies, government weed control grants, the use of residues as a fertilizer or animal feed, the co-production of food through leaffractionation or multiple cropping, and the extraction of enzymes or insecticides - particularly from bracken.

9. The environmental impact of biofuels, particularly those developed at a small scale, will be slight. However, institutional boundaries will be a major barrier to the development of larger scale harvesting. The lack of planning control over the use of land and the absence of a national integrated land use policy will also make the organisation of crop areas and markets very difficult. However, particularly away from large towns, there could be wide range of benefits from the development of biofuels. Prolonging the energy self-sufficiency of Britain, preserving petroleum and coal as chemical feedstock, making waste land productive, reducing air pollution and providing a stimulus for rural development could all be listed as benefits.

RECOMMENDATIONS

1. Detailed estimates are required of the actual and potential extent of the 3 energy crops. These estimates should consider factors determining the harvestability of bracken, eg steepness of slope and stoniness, and variations in yield of all 3 species due to location.

2. Although the yield from the experimental plantations of Japanese knotweed was disappointing, subsequent trials on this and giant knotweed showed that increased planting density could quickly lead to higher yields. Bearing in mind the exceptionally high yields obtained from small natural stands, methods of establishing the 2 knotweed species should be investigated further.

3. The methods of exploiting all 3 species have been developed by analogy with similar crops, although bracken is regularly harvested for animal bedding using conventional equipment. It is essential to conduct field trials with available equipment to assess its performance, and to investigate the feasibility of any modifications which may be required.

4. Costings of managing the 3 species and producing biofuels from them have also been based on comparisons with similar crops. It is, therefore, equally essential to substantiate the extension of these figures to the economics of the natural biofuel systems.

5. Data on the response of these species to management now exist for a 5 year period and are quite optimistic. It is important to continue to monitor these responses, and to study the effect of rest years should yields become depressed.

6. Further liaison is required with workers developing pilot scale anaerobic digesters and thermal convertors, to test the technical suitability of natural vegetation feedstocks, and to determine the economics of various degrees of feedstock preparation.

   More detailed recommendations are included in the previous technical reports.

1 INTRODUCTION

As the price of fossil fuels increased during the mid 1970s, the vulnerability of this non-renewable and often politically manipulated source of energy became particularly apparent. Considerable emphasis was therefore attached to investigations of additional - often called "alternative" - forms of energy which were renewable. One of these sources was biomass, ie the chemical energy captured from the sun by the process of photosynthesis in green plants. In an attempt to estimate the potential of all types of plants growing in the UK as renewable sources of energy, the UK Department of Energy, via the Energy Technology Support Unit, commissioned a series of one year desk studies into plant yields and the technologies required to convert biomass into useful forms of energy.

Results of comparisons between different types of plants such as agricultural crops, forest trees, coppice and natural vegetation (Callaghan *et al*. 1978), together with a specific desk study of natural vegetation (Lawson *et al*. 1980), showed that plants occurring naturally in the UK occupied 40% of its land area and could be an important source of energy.

This potential for exploitation occurred either because the natural vegetation was already extensive, thereby obviating the need for land use change and planting costs, etc, or because it could be at least as productive in poor habitats as conventional crops were under intensive cultivation. However, the existing literature was biased towards the plants on poor or waterlogged habitats and little information was available on the yields or general biology of the more productive species, such as invasive weeds. Consequently, a one year field programme was commissioned by ETSU to investigate yield, chemical composition in relation to nutrient replacement from areas of harvested natural vegetation, and the general production ecology of 13 plant species which showed particular potential as sources of biofuels.

All but one of the species investigated in the field (*Impatiens glandulifera*) were perennials and their management would be analogous to the practice of coppicing, ie continual harvesting without the necessity for replanting. It was found that most species could yield more than 7 t ha^{-1} of above-ground biomass in one growing season and some invasive weed species could yield more than 20 t ha^{-1} (Callaghan *et al*. 1981).

Two basic systems of management were recommended in relation to the different types of species: extensive species such as bracken (*Pteridium aquilinum*) would be harvested from where they already occur, whereas the particularly productive species such as Japanese and giant knotweed (*Reynoutria japonica* and *R sachalinensis*) would be planted on better quality land dedicated to the production of biofuels.

The yields measured by Callaghan *et al*. (1981) related to one season's growth of species which had become naturally established over many years: nothing was known about how these species would react to harvesting and the removal of nutrients from site in harvested biomass. Predictions of these reactions could be made, however, from observations on the seasonal trends of nutrients in the shoots and from the basic biology of the species. It was found, for example, that some species such as bracken showed a strong seasonal trend of nutrient content in the shoots, whereby, during senescence, 80%, 92% and 65% of nitrogen, phosphorus and potassium respectively were translocated to the rhizomes for use by the following year's growth. Consequently, it could be predicted that by harvesting after this downward movement of nutrients, subsequent regrowth would be only minimally reduced and replacement rates of artificial fertilizers would be low. Other plants, such as species of knotweed and butterbur (Petasites hybridus), showed senescence suddenly, and harvesting would be confined to a pre-senescence phase when yields were maximal.

The timing of the harvest also had implications for the conversion of the biomass to usable fuel: biomass harvested before senescence would have a high nutrient and water content, suggesting anaerobic digestion as a suitable conversion process, whereas species harvested after senescence would be comparatively dry and low in nutrients and would suited to thermal conversion technologies.

It was obvious from the results of the field programme that more detailed experiments were required to test these predictions of plant growth in relation to harvesting, and to establish optimum management practices for natural energy crops. However, because of the detailed and long term nature of these experiments, only 3 plant species could be considered in detail. Consequently a 3-year experimental programme was commissioned by the UK DEn via ETSU, and the EEC to:

1. establish experimental sites;
2. measure yield in relation to applications of conventional fertilizer;
3. assess the effects of time and frequency of harvesting on yields and regrowth;
4. monitor the effects of climatic variables on yield;
5. assess the digestibility of fresh biomass in an experimental anaerobic digester;
6. develop strategies for harvesting integrated with conventional farming:
7. extend these results to a national level.

This report presents a summary of the detailed results of the 3-year experiments presented in the accompanying volumes, and also includes some additional data for the year following the commissioned research. The results of the multivariate experiments are also discussed within a national and regional context.

2 THE EXTENT AND DISTRIBUTION OF NATURAL VEGETATION IN THE UK

2.1 Estimates available from the literature

Previous reports (Callaghan et al. 1978; Lawson et al. 1980) have stressed the fragmented and overlapping nature of the available information on land use in the United Kingdom. Nevertheless, it has been necessary in these reports to collate tables such as Table 1 which mix official and other estimates of land use and relate these to estimates of plant production which will be discussed in Chapter 3.

Intensive agriculture occupies 50% of the country's land surface but natural or semi-natural vegetation, together with vegetation in urban areas, comprises a further 40%, and it is this area which is suggested to have the most immediate scope for utilizing biomass energy.

2.2 Estimates from the ITE land classification system

Further information on the distribution of vegetation in Great Britian is available from the ITE land classification system (Bunce et al. 1983). This method uses a total of 282 physiographic map attributes (climatic, topographic, human and geological) and a multivariate statistical method to allocate each kilometre square in Britain to one of 32 'land classes'. These land classes can then be used as strata for field sampling to determine land use, soil type, farming type or, indeed, any other spatially distributed characteristic of the landscape.

Eight sample kilometre squares per land class (256 in total) were used for intensive field sampling and the areas of different land use were then transferred to maps and quantified using a computerised digitizer. Close concurrence has been demonstrated between estimates derived from the land classification method and corresponding official statistics for the areas of several major crops and woodlands, and also for lengths of rail and road networks (Bunce et al. 1983). This lends confidence to the land classification estimates of the extent of major species of natural vegetation, for which no alternative statistics exist. Table 2 indicates the extent of the 10 most common native species, which together cover 23% of the GB land area, and also appends the predicted current extent of a number of weed species which have been considered as dedicated energy crops (Callaghan et al. 1981).

Maps of plant production derived from the land classification system have been used to site catchment areas for theoretical chemical conversion units (Chapter 5), and Bunce et al. (1983) have used the system to quantify the area of land available for wood energy production, having principal regard to financial profitability.

2.3 Distribution of species in current study

The first 3 volumes of this report deal in detail with species which are examples of different types of energy crop. Bracken is a widespread species, covering around 3 000 km^2 of Britain (Figure 1) - although Taylor (1983) estimates that there may be almost double this figure. It is also very widely distributed in Europe (Figure 2) and in the world (Figure 3). It grows in this country on land which was once used for agriculture because, although it is a hill species, it is limited by exposure to a zone below 600 m. It is an example of an opportunity energy crop which occurs sufficiently widely to be harvested from where it grows naturally. This may involve technical difficulty (Chapter 4), but financial profit is possible (Chapter 6).

Table 1. Land use within the UK: extents derived mainly from official (Lawson & Callaghan 1983)

	Extent (km^2)	Above-ground production ('000t yr^{-1})	% of total area	% of total production
Cereals and fallow	41 910	42 455	17.4	25.7
Root crops and horticulture	7 740	3 190	3.2	1.9
Leys and pasture	70 170	56 791	29.1	34.4
Total intensive agriculture	119 820	102 436	49.7	62.0
Conifers	13 377	12 985	5.6	7.9
Broadleaves	4 056	2 783	1.7	1.7
Total productive woodland	17 433	15 768	7.2	9.5
Rough grazing	63 370	27 279	26.3	16.5
Scrub woodland	2 983	2 028	1.2	1.2
Miscellaneous non-urban	18 880	9 191	7.8	5.6
Total natural/semi-natural	85 233	38 498	35.4	23.3
Derelict land	3 310	2 714	1.4	1.6
Amenity and gardens	4 311	3 640	1.8	2.2
Transport	2 340	2 090	1.0	1.3
Miscellaneous	8 489	0	3.6	0
Total urban	18 450	8 444	7.8	5.1
TOTAL	237 870	165 146		

In contrast to bracken, Japanese knotweed is estimated by the ITE land classification method to cover only 3.1 km^2. However, it can be locally abundant and has been gradually spreading from an original introduction to Britain in 1825 (Figure 1). Japanese knotweed occurs principally on disturbed areas like waste ground, roadsides and streambanks. It colonizes bare ground easily and, once established, is difficult to eradicate. Giantknotweed (Reynoutria sachalinensis) is larger, but its current distribution is more restricted in both Britain (Figure 1) and Europe (Figure 2). Both species seem well suited to establishment as dedicated energy plantations on waste ground, or, when economic constraints permit, on higher quality agricultural land. The comparatively slow spread of these species to date is largely due to their apparent inability to set viable seed during a normal British summer.

Cordgrass (Spartina anglica) was estimated to cover 120 km^2 around the coast of Britain (Ranwell 1967 and Figure 1). It is a new hybrid species which was first recorded in 1870 and subsequently acquired pollen fertility. It could be exploited as an opportunity energy crop in those areas where it occurs naturally, but there is also considerable potential for it to be established in new areas. Well established planting techniques can be used (Chapter 4) but conflicts are possible with recreational use of beaches (Chapter 6).

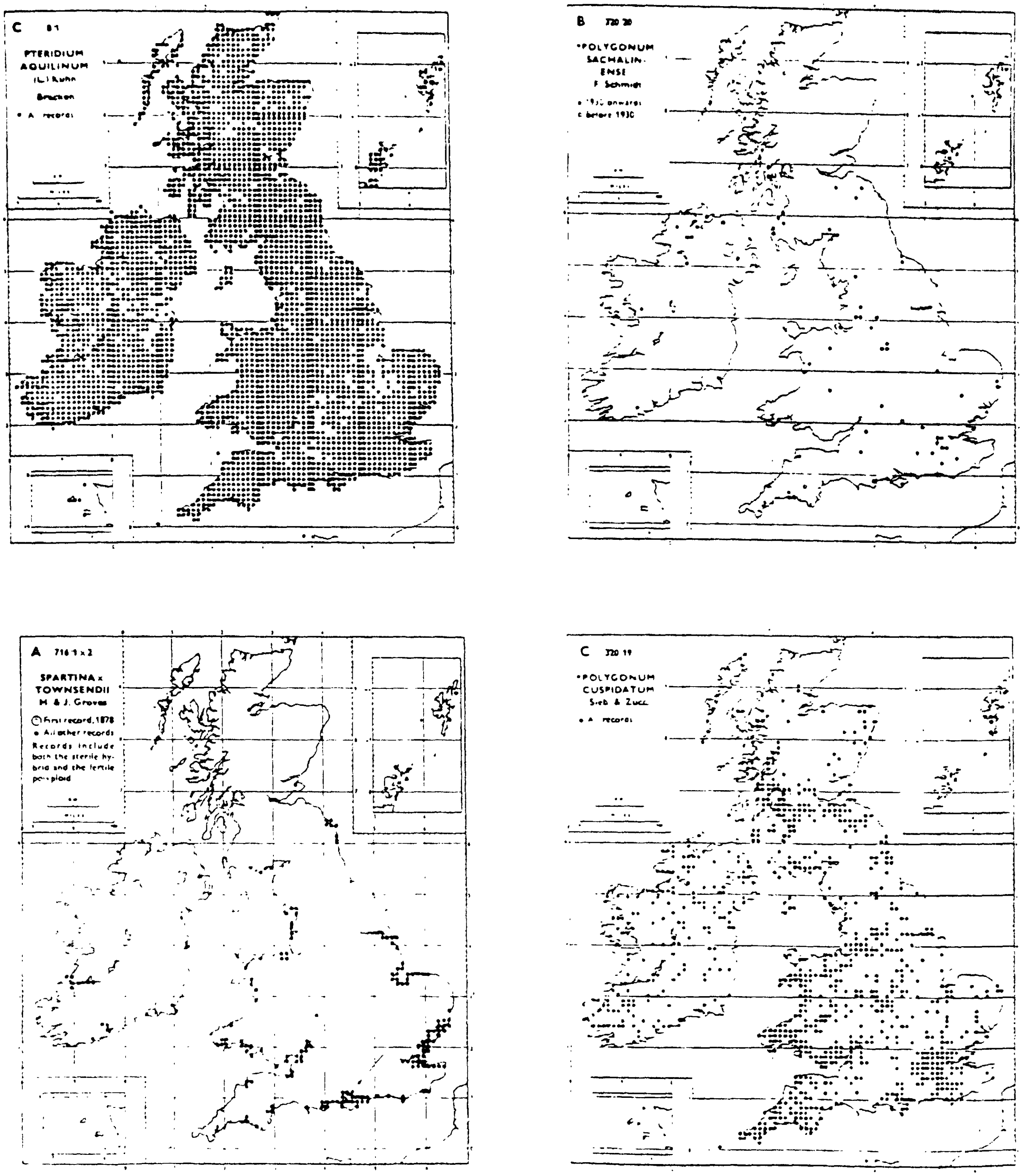


Figure 1. The distribution of bracken (A) cordgrass (B), giant knotweed (C) and Japanese knotweed (D) in Great Britain. Taken from Perring and Walters (1962).

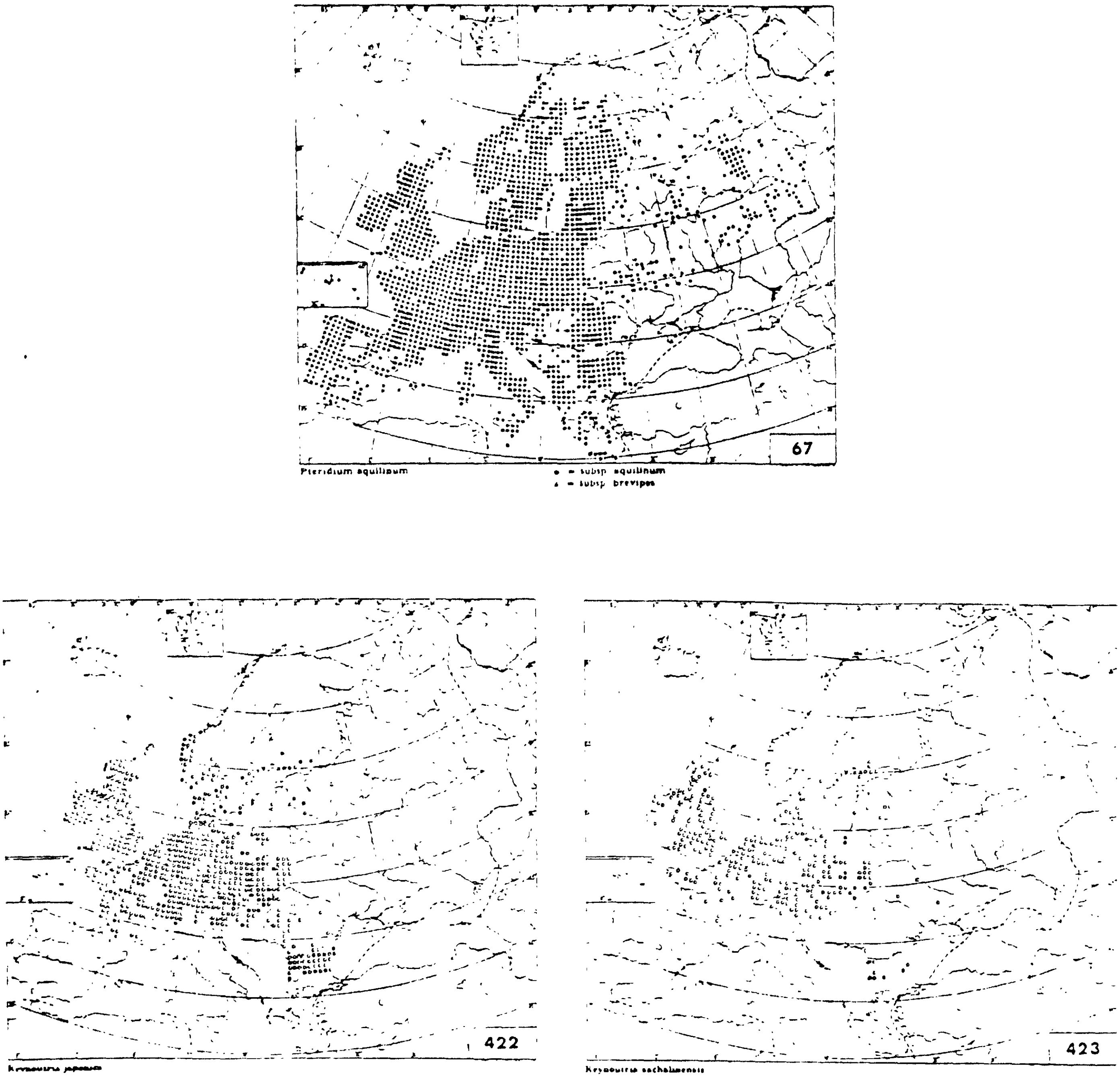


Figure 2. The distribution of bracken (A), Japanese knotweed (B) and giant knotweed (C) in Europe Jalas & Suominon 1972).

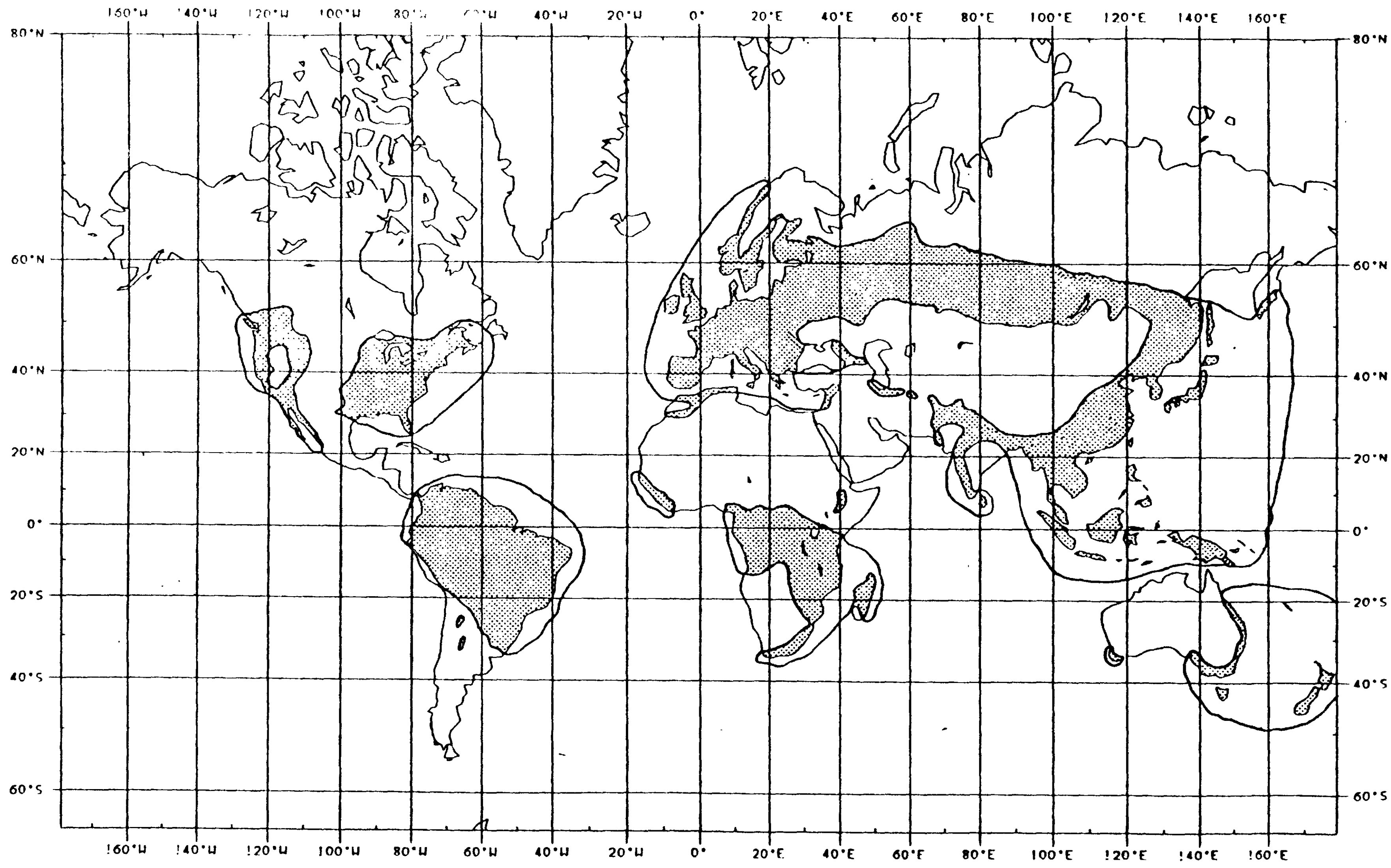


Figure 3. World distribution of bracken (taken from Meusel, *et al.* 1965).

3 PRODUCTIVITY

3.1 Background

The theoretical maximum productivity of plants in the UK ranges from 89 to 134 t ha^{-1} yr^{-1} (Callaghan et al. 1978). This figure is based entirely on the annual receipt of solar radiation and observed productivity is much lower, with yields for closed natural vegetation ranging from 2 to 40 t ha^{-1} yr^{-1} for heather (Calluna vulgaris) and reed (Phragmites australis) respectively (Lawson et al. 1981). However, compared with trees and agricultural crops, natural vegetation is often productive: yields of 8-11 t ha^{-1} yr^{-1} are common, whereas Japanese and giant knotweed may achieve over 30 t ha^{-1} yr^{-1} (Callaghan et al. 1981). Land use and overall plant production in the UK is summarized in Table 2 from detailed data listed by Lawson and Callaghan (1983). Bracken and cordgrass also give high yields (around 10-15 t ha^{-1} yr^{-1}). Until the present experiments were completed, however, little information was available on the fluctuations in yield of these species resulting from various weather conditions, or the ways in which yield would respond to management.

3.2 The 3-year experimental programme

3.2.1 Methods

The species investigated in the detailed 3-year experimental programme were bracken (Peteridium aquilinum), cordgrass (Spartina anglica) and Japanese knotweed (Reynoutria japonica).

The experimental site for bracken was at Lindale Fell, Cumbria (SD 418813), for cordgrass a coastal mudflat at Southport, Merseyside (SD 354206), and for knotweed a flat ploughed field near Lindale, Cumbria (SD 433816) where 4 cuttings, per sq metre, were planted.

The experimental design was the same for each of the 3 species and is described in detail in Callaghan et al. (1983a, b, c). It was based on a 3 x 3 m quadrat which included a 1 x 1 m sample square surrounded by a 1 m buffer zone. The 4-replicated 3-year treatment blocks were randomly placed, and each contained 4 fertilizer blocks. Within each of these 6 x 6 m fertilizer blocks were 4 randomly arranged quadrats for each harvest at different times within the year.

The fertilizer was applied by hand on available dry days in late April or early May. Fisons "regular" 20:10:10 NPK granules were used, and applied at the rates of 0.5, 1 and 2 t ha^{-1} for treatments F2, F3 and F4 respectively. No fertilizer was applied to the F1 treatments.

The 3-year treatments were harvested on the same date each year as follows:

a) Y1 - cropped in 1980, 81 and 82
b) Y2 - cropped in 1981 and 82
c) Y3 - cropped in 1982 only

On the specified harvesting dates for each species, standing vegetation was cut from the central 1 m^2 sample area of each treatment and returned to the laboratory where stem density, dry weight, water content and mean stem height were determined (as described in Callaghan et al. 1983a, b, c). The 1 m buffer zone was also cut and cleared. This zone acted as access within the site to minimize the trampling of the sample area, and as a buffer between adjacent treatments.

Table 2. The distribution of selected species in Britain (Lawson *et al.* 1980)

	% cover	area (km^2)
The 10 most widespread species or groups		
Calluna vulgaris (heather)	7.22	13 896
Agrostis tenuis (common bent-grass)	(3.95)	(7 602)
Agrostis stolonifera (creeping bent)	(1.22)	(2 356)
combined *Agrostis*	5.17	9 958
Molinia caerulea (purple moor grass)	2.81	5 413
Eriophorum angustifolium (common cotton-grass)	(0.46)	893
Eriophorum vaginatum (cotton-grass)	(0.69)	(1 331)
Trichophorum cespitosum (deer-grass)	(1.24)	(2 385)
boggy moors	2.39	4 609
Pteridium aquilinum (bracken)	1.49	2 876
Nardus stricta (mat-grass)	1.51	2 903
Dactylis glomerata (cock's foot)	1.60	3 072
Phleum pratense (timothy)	1.29	2 480
Festuca ovina (sheep's fescue)	(1.24)	(2 378)
Festuca rubra (red fescue)	(0.75)	(1 442)
combined *Festuca*	1.99	3 820
Poa annua (annual meadow-grass)	(0.53)	(1 017)
Poa pratensis (smooth-stalked meadow-grass)	(0.26)	(495)
Poa trivialis (rough-stalked meadow-grass)	(0.79)	(1 528)
combined *Poa*	(1.58)	(3 040)
TOTAL	27.05	52 067

Possible dedicated energy crops		
Urtica dioicia (nettle)		331
Chamaenerion angustifolium (rose-bay willow-herb)		138
Spartina anglica (cordgrass)		120
Filipendula ulmaria (meadow-sweet)		110
Petasite hybridus (butterbur)		33
Epilobium hirsutum (great-hairy willow-herb)		6
Reynoutria japonica		3
Impatiens glandulifera (policeman's helmet)		0.6

3.2.2 The effect of weather on yield

The main effects of weather on yield are due to temperature, spring drought and late frosts, which have particularly severe effects on non-woody perennial energy crops. Over the 3 years of the experiment, the weather in 1981 resulted in the highest yields of bracken (Figure 4A and cordgrass (Figure 4B), whereas lower yields, particularly in autumn, were obtained in 1982. At peak yield, variations in yield due to weather were 37% for bracken and 29% for cordgrass, and in autumn these variations were 46% and 81% respectively.

It is important, therefore, to consider variations in weather when assessing the yields of such short rotation energy crops. Longer rotation crops, ie trees, integrate the effects of weather on growth over a long period and yields would be expected to be significantly reduced only by exceptional weather conditions.

3.2.3 Effect of establishment on yield

It has not yet been possible to assess the effects of weather on a planted energy crop because variations in yield between the years 1980, 81 and 82 resulted predominantly from factors related to the establishment of the crop. Four rootless rhizome fragments of Japanese knotweed (mean weight 224 g) were planted in spring 1980 and maximum yields of only 0.7 t ha^{-1} were attained in that year. In 1981, however, yields increased to a maximum of 0.9 t ha^{-1} and in 1982 a mean yield of 2.7 t ha yr^{-1} was achieved (Figure 5A). It is unfortunate that the present experimental period has not been long enough, and the management methods insufficiently intensive, to allow the complete establishment of a new perennial energy crop. In September 1983, a maximum Japanese knotweed yield of only 3.16 t ha^{-1} was recorded. However species which naturally invaded the site showed a high yield of 8.75 t ha^{-1} (Figure 5B) during the second year: thus, total site production can reach 9.5 t ha^{-1} yr^{-1} from bare ground by almost completely natural means during a 2-year period.

One reason why initial yields of Japanese knotweed were low was the low density of planting, as little previous experience of planting such a crop existed. However, results from a separate experiment comparing planting densities of 2 species of knotweed - Japanese knotweed and giant knotweed - suggest that higher yields could be obtained more quickly by increasing the density to 16-25 plants m^{-2} (Table 3).

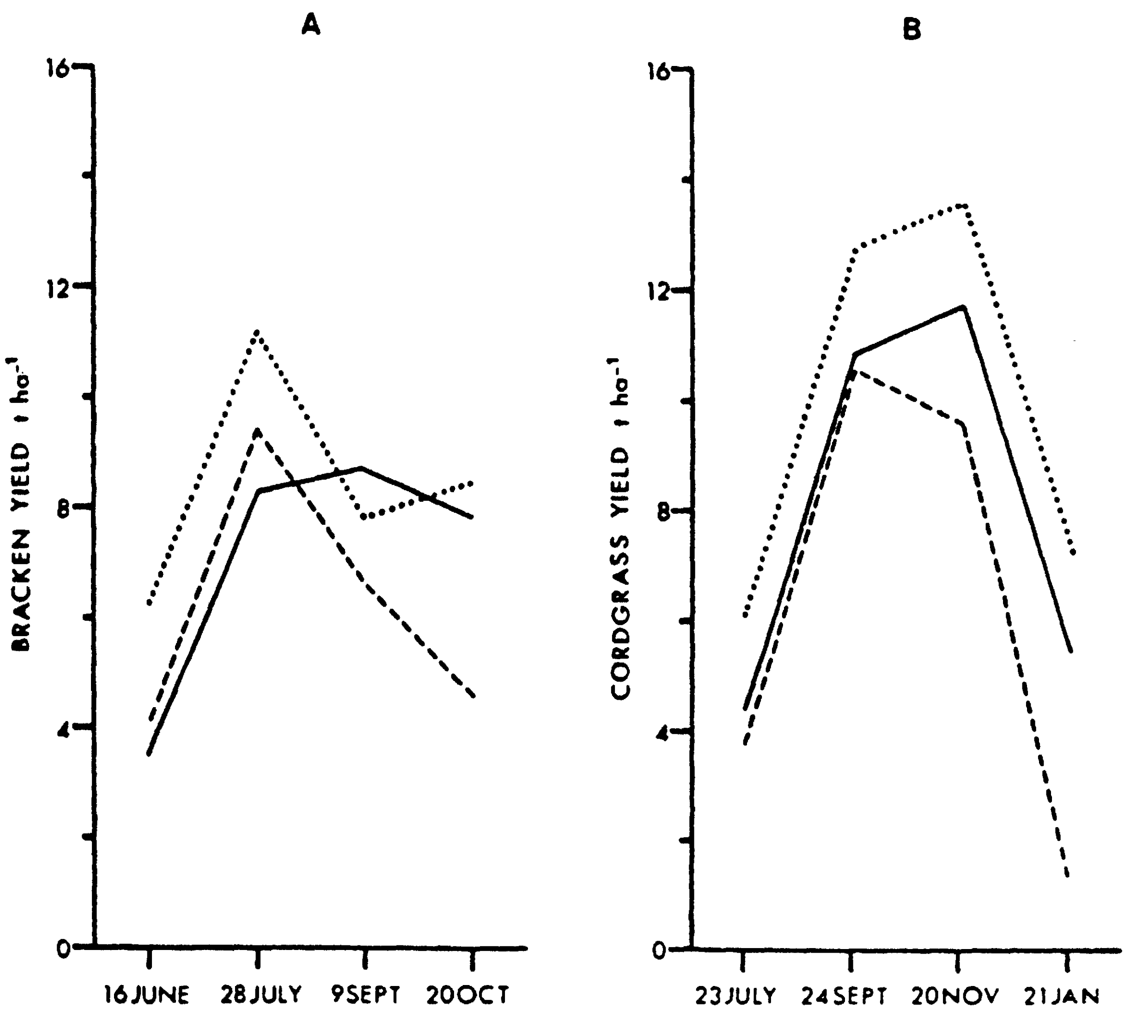


Figure 4. Variations in the yields of bracken (A) and cordgrass (B) in 1980 (——), 1981 (·...) and 1982 (---) due to different weather conditions

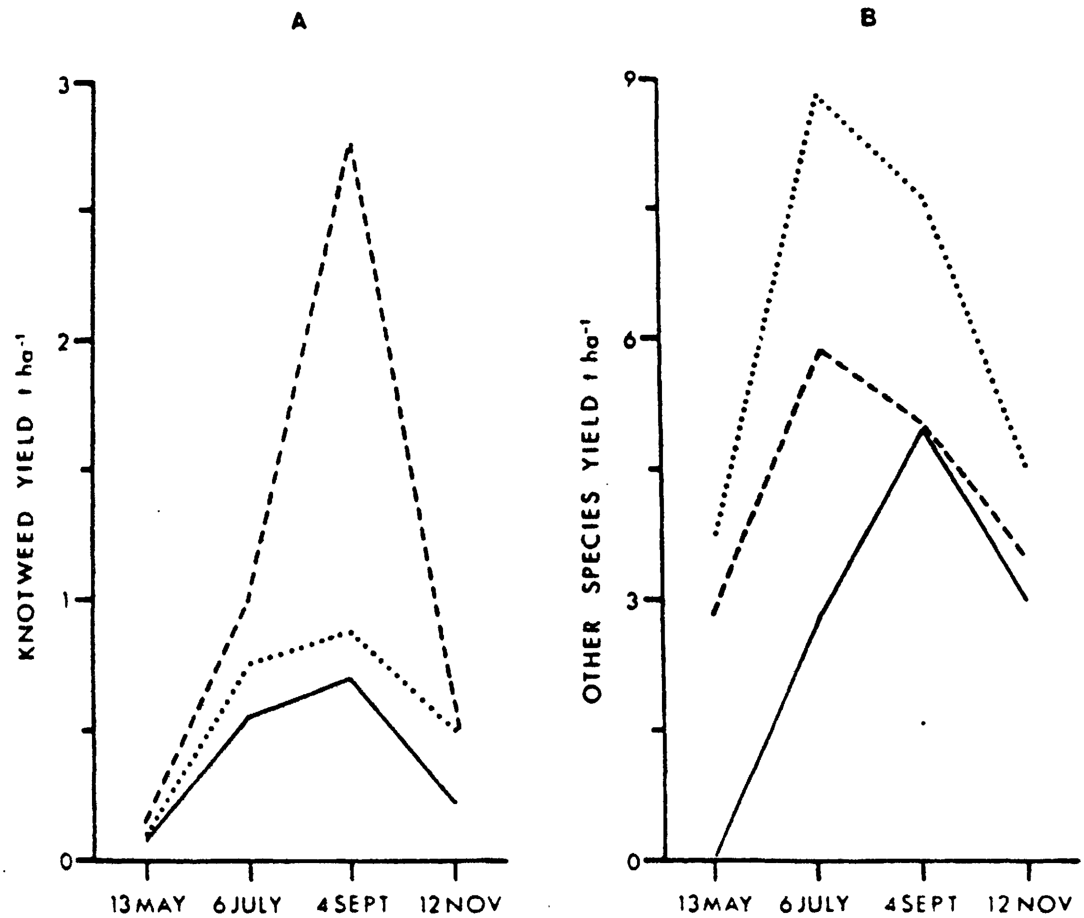


Figure 5. Effect of establishment on the yields of Japanese knotweed planted in spring 1980 (A) and weed species which invaded the site (B). Yields shown were obtained by harvesting for the first time in 1980 (——), 1981 (.....) and 1982 (----)

Table 3. Effects of planting density on the establishment of monocultures of 2 species of knotweed from March 1981 to August 1983

	Planted density (plants m^{-2})	Final density (plants m^{-2})	Plant height (cm)	Yield (t ha^{-1})
Japanese knotweed	4	8	87.7	1.04
	9	10	114.5	2.6
	16	32	136.9	5.96
	25	23	134.9	4.61
Giant knotweed	4	8	239.2	4.89
	9	10	226.3	5.9
	16	10	190.1	3.22
	25	15	236.9	8.46

3.2.4 Effect of fertilizer applications on yield

There are 2 reasons for applying fertilizers to natural energy crops: (i) these crops may have been limited by nutrient supply and increases in yield might be expected; (ii) the harvesting of these crops for the first time will result in the removal of biomass containing nutrients which must be replaced.

Surprisingly, applications of fertilizer did not significantly affect the yield of bracken, cordgrass or Japanese knotweed on plots which had not been harvested previously, even though the highest level of fertilizer application was twice that currently applied to agricultural root crops. Perhaps it is even more surprising that the yields of bracken plots which have been harvested annually for 3 years showed a significant decrease in yield as the level of fertilizer application increased (Figure 6A). Cordgrass (Figure 6B) showed a significant response to fertilizers only after 3 years of harvesting. Japanese knotweed, however, showed a significant response to fertilizer applications with a 6-fold increase in yield with the 2 highest levels of application (Figure 6C). It would appear, therefore, that natural areas of vegetation are quite resistant to the removal of nutrients in harvested biomass, at least initially. New monocultures established from weed species may, however, have significant requirements for additions of fertilizers equivalent to those currently used in agriculture (Table 4).

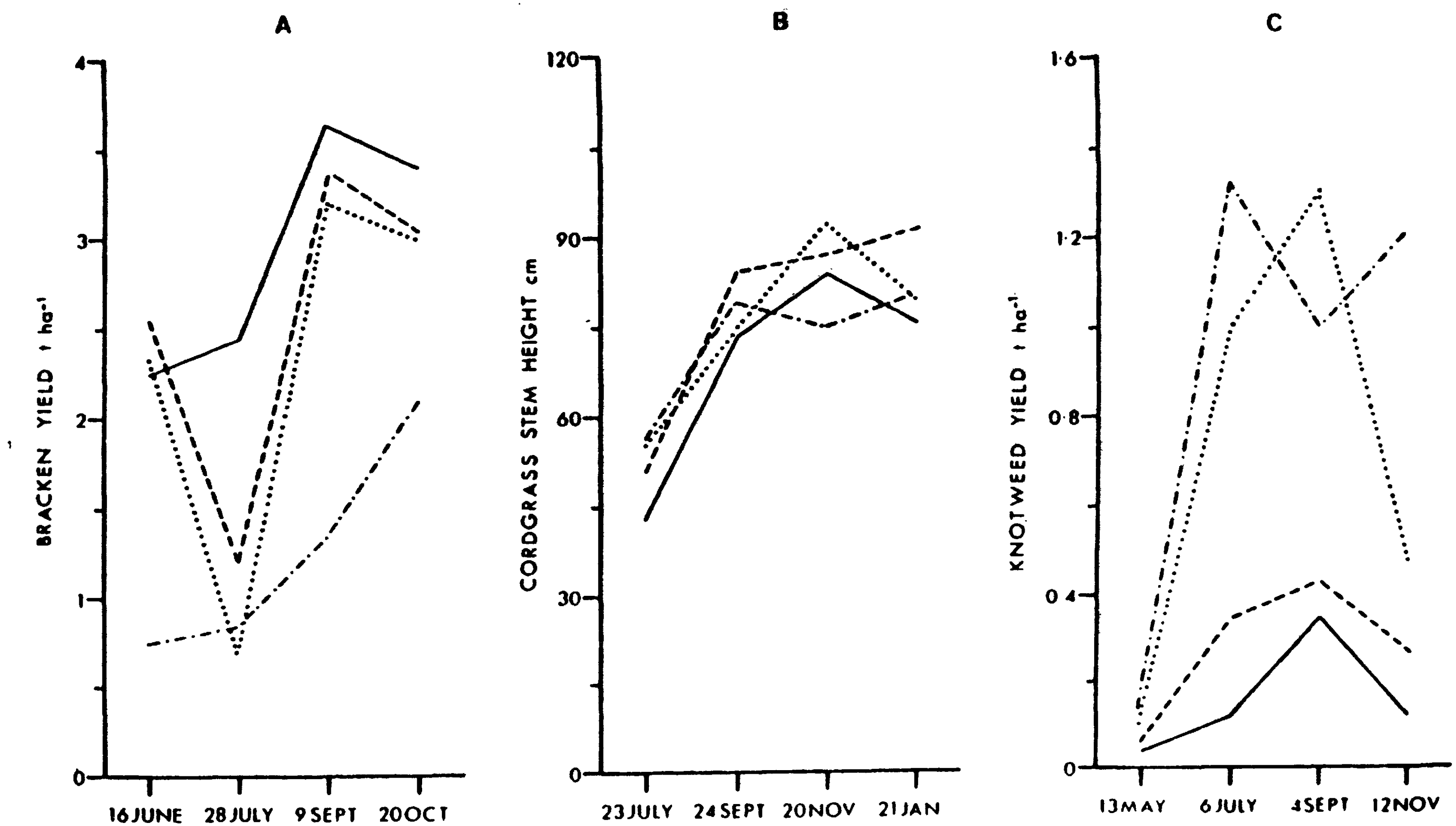


Figure 6. Effect of the level of NPK fertilizer application on bracken yield (A) cordgrass stem height (B) and Japanese knotweed yield (C) after 3 years of harvesting on the same date.
——0 gm^{-2}, ----50 gm^{-2}, ...100 gm^{-2}, -.-.-.200 gm^{-2}
(100 gm^{-2} = 1 + ha^{-1}).

Table 4 Scenarios for fertilizer applications (kg ha^{-1}) to energy crops

	Nutrients removed in biomass				Nutrients currently applied to agriculture[1]
	Bracken		Knotweed		
	Summer cut	Autumn cut	Summer cut	Autumn cut	
N	168.5	33.9	142	25	158
P	16.0	2.32	23	3.6	72
K	239.5	83.52	205	58	183
Total cost[2] of replacement	£116	£34	£102	£27	£120

Notes: [1]Main crop potatoes from Church (1975)
[2]Materials costs from Nix (1982) assuming:

nitrogen in form of Nitram at 40p kg^{-1} N
phosphorus in form of super triple phosphate at 31p kg^{-1} P
Potassium in form of muriate of potash at 15p kg^{-1} K

Application cost taken as £7.50 ha^{-1} (Farm Contractor, June 1983).

Although yields of bracken and cordgrass were not increased by adding fertilizer, concencentrations of N, P and K showed significantly higher levels in the tissues of plants supplied with these elements (Figure 7). For example, P concentrations quickly decline in the fronds of bracken plants experiencing annual cuttings, but they show a marked increase under the same cutting regime when supplied with 30 g m^{-2} of P_2O_5 (Figure 7). The nutrients supplied in fertilizer applications are, therefore, taken up by the plants even though yields are not increased. It seems that growth is either limited by another - possibly trace - element or is already maximal in terms of light interception at the site. However, no information is yet available on the fertilizer-related yields of the rhizomes, although these have a considerable biomass. These surprising results stress the importance of investigating the complete nutrition of perennial species subjected to harvesting.

The decrease in soil fertility due to the continued harvesting of unfertilized natural vegetation (Table 5) further emphasises the importance of studies on mineral nutrition. Concentrations of 3 of the major elements, N, P and K, are reduced in soils from which bracken has been removed and replacement is obviously required. However, this effect is not significant for N and K in soils from the cordgrass site and, as predicted, this naturally fertile area may be managed without adding fertilizer. In contrast, the removal of biomass from the Japanese knotweed site reduces nutrient concentrations by between 31 and 44% and significant additions of fertilizer will be essential at this site.

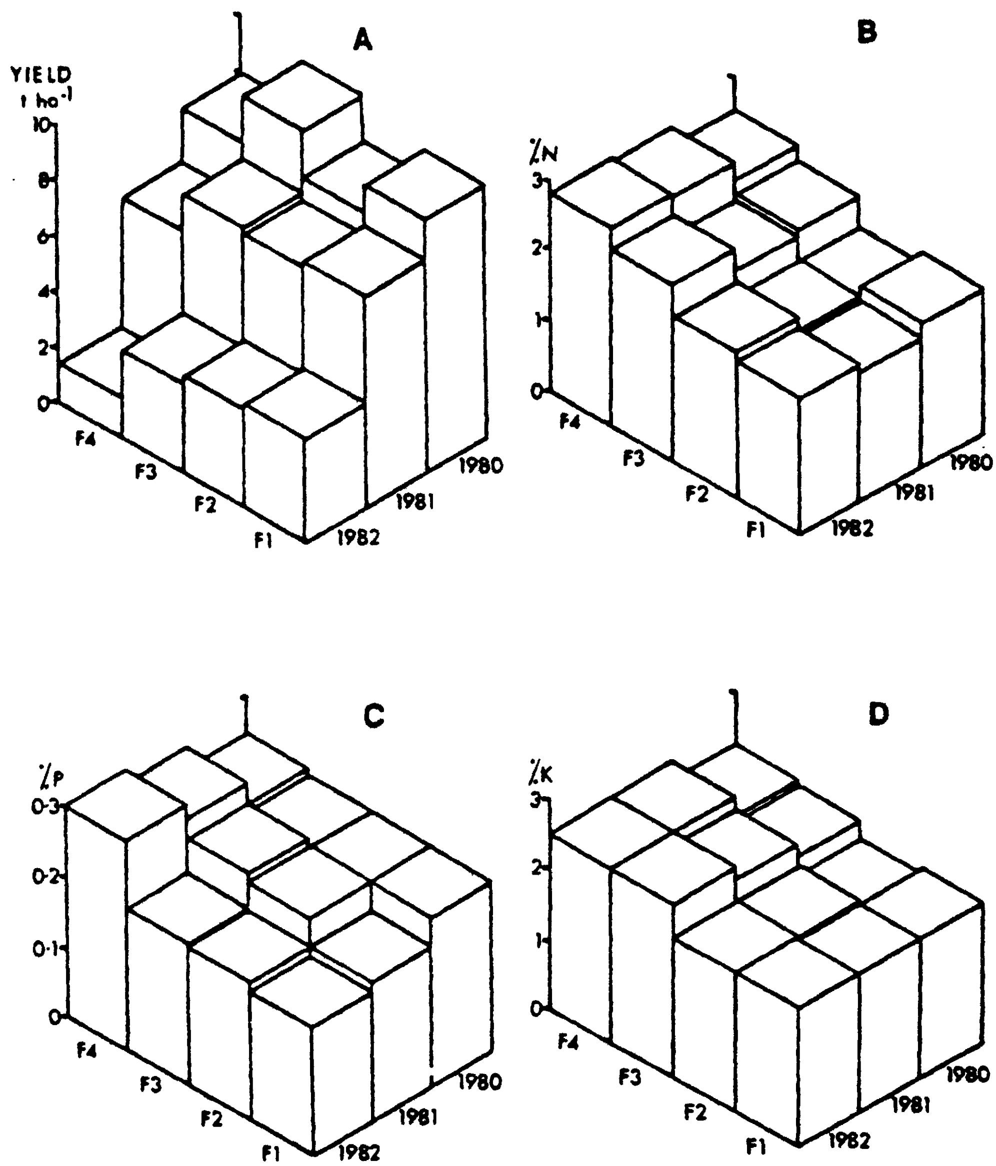


Figure 7. The yield (A) and concentrations (% dry weight) of N (B), P (C) and K (D) in the tissues of bracken harvesting at peak yield for 3 years in relation to 4 levels of fertilizer. (F1 to F4 = 0, 0.5, 1.0 and 2.0 t ha^{-1} respectively of Fison's regular 20:10:10 NPK fertilizer)

Table 5. Percentage change in nutrient concentrations due to harvesting peak biomass for 2 consecutive years (- = decrease, + = increase in concentration)

Element	Bracken	Cordgrass	Japanese knotweed
N	-12	- 3	-34
P	-12	-11	-31
K	- 8	+ 7	-44

3.2.5 Effect of harvesting on yield

Callaghan et al. (1981) predicted that perennial energy crops harvested in autumn, when nutrients had been translocated from shoots to below-ground storage organs, would show better regrowth than those harvested in summer. These predictions were validated in the present 3-year experiment. Yields of bracken harvested for 2 years in summer were reduced by 35% and 15% in autumn, yields of cordgrass were reduced by 60% with annual summer harvesting and 19% with annual autumn harvesting, while yields of Japanese knotweed were reduced by 50% and increased by 10% respectively (Callaghan et al. 1983a, b, c). On the third annual harvesting occasion, the same seasonal patterns were observed, but the magnitude of the decrease in yield was slightly greater. However, even on the third harvesting occasion, significant yields were obtained from the 2 species occurring on under-utilized land. Thus, a total yield of between 26.9 and 30.4 t ha^{-1} of senescent bracken could be harvested over a 4-year period (Figure 8A). At the cordgrass site, a total of 34.3 t ha^{-1} could be obtained over this 4-year period which gives high mean yields of 7.6 to 13.6 t ha^{-1} yr (Figure 8B) for a totally unused area of vegetation. Decreasing yields on the natural sites suggested that occasional rest years would be required to sustain the vegetation as a permanent energy crop. Over the 3 main years of intensive survey, however, observations in the 4th year of harvesting indicate the yields may again be rising. The optimum rotations of harvesting and resting need, therefore, to be determined.

It is difficult to predict how harvesting will affect subsequent yields of a dedicated energy crop established as a monoculture. However, the resilience of Japanese knotweed to harvesting annually for each of 4 years since planting (Figure 8C) suggests optimism, despite the low overall yields.

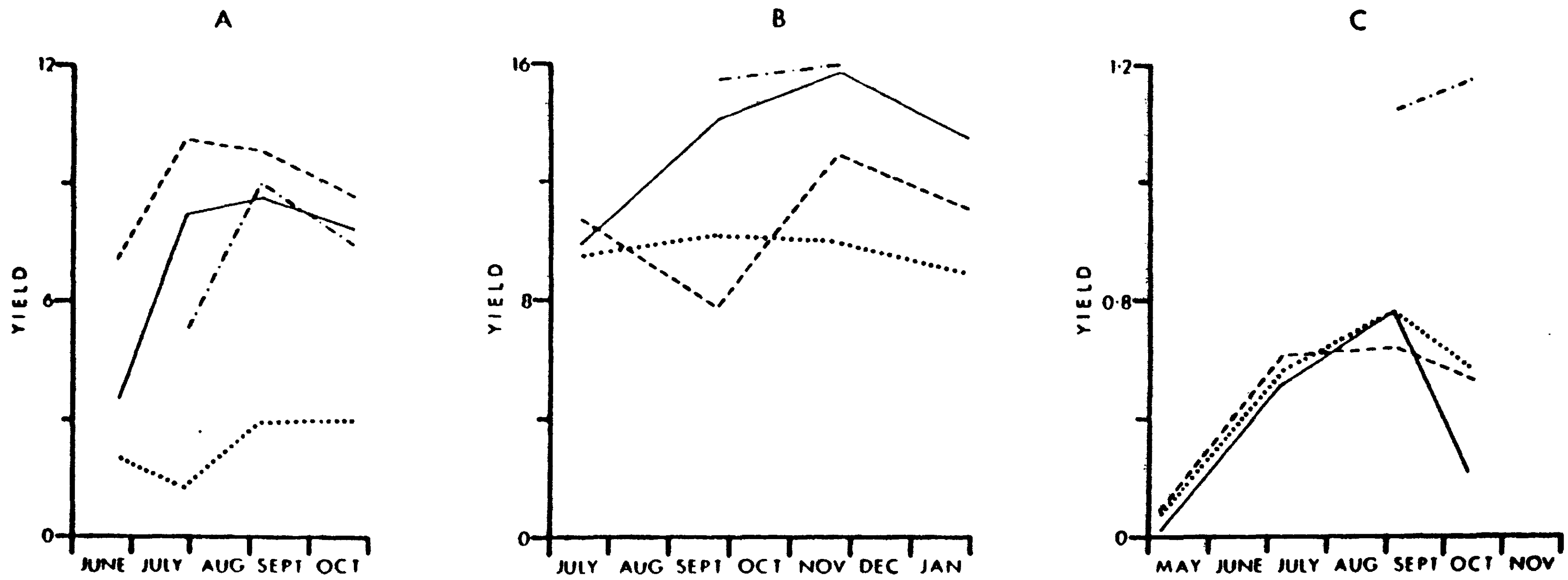


Figure 8. The yield (t ha^{-1}) of Bracken (A), Cordgrass (B) and Japanese knotweed (C) from plots at each year for 4 successive years. (——) 1980, (----) 1981, (....) 1982, (-.-.-.) 1983

4 THE EXPLOITATION OF NATURAL VEGETATION

Natural vegetation may be extensive or highly productive: unfortunately, it is seldom both. Opportunity crops like bracken or reed may be harvested *in situ* but inevitably some mangement is implied in the timing of the harvest, the introduction of rest years or in the replacement of nutrients through fertilizer applications. Even opportunity crops are not a mine of bioenergy. The most productive weed species have a restricted distribution and require to be established in plantations prior to effective exploitation.

The 3 study species illustrate different techniques for the exploitation and management of natural vegetation. Further information is provided in the other volumes of this series.

4.1 Establishment

Bracken already covers such extensive areas that further planting is unnecessary. Planting is also unlikely to be economically justified, and it would cause considerable conflict with other land uses in upland areas. Technically, however, bracken could be planted.

Cordgrass covers only 120 km^2 round the coasts of Britain. Its distribution is limited by its recent emergence as a species, and many coastal areas appear suitable for colonization. Cordgrass spreads by sexual and asexual means and plantations could be established using modified cabbage, bulb or potato planters which accept seedlings or rhizomme fragments, and are fitted with low ground pressure tyres. These methods would ensure rapid colonization but they are only semi-automatic, and large-scale aerial broadcasting of seeds seems likely to be a cheaper, if less reliable, technique.

Japanese knotweed has been established from rhizome fragments in our experiments with a success rate exceeding 90%. Such planting could be automated using machinery similar to that suggested for cordgrass. Japanese knotweed does not set viable seed in Britain, and this somewhat restricts its distribution, but plantations could be established using seed collected from a country with a slightly warmer climate than our own. Yields in our experimental trials have been low, partially because a low initial planting density was employed. The choice between achieving high yields rapidly using high initial planting densities, or allowing the sward to thicken over a number of years will be determined by economics. As indicated in Section 6.4, economic considerations are likely to dictate that Japanese knotweed will not at present be planted on high quality agricultural land. Cultivation techniques suited to heavy or stony land are therefore required.

4.2 Harvesting

Bracken has been cut by hand for many centuries and is still harvested by machine for animal bedding in several parts of the country. Conventional reciprocating cutter-bars, hay-making machinery and 2-wheel drive tractors have been used up till now, and these are quite adequate for the easiest terrain. On steeper and stonier ground, use can be made of either 'flail-mowers', which have hinged knives rotating vertically on a horizontal shaft; or 'rotary slashers', where 2 or 3 knives or chains rotate horizontally from a central hub. Either type of machine could be adapted to load material into a trailed forage wagon, but most farmers and contractors in this country would be forced to rake material down from the steeper slopes for subsequent loading into a forage wagon or stationary baler. In Switzerland and Austria, the need to harvest steep alpine meadows has led several firms to produce versatile and stable self-loading forage wagons which greatly spread the collection of hay on slopes. The same firms manufacture a variety of small, powerful, low centre-of-gravity, 4-wheel drive tractors which are able to mow on inclines of up to 65%. (Lawson et al. 1980).

With cordgrass, harvesting methods are less well established than planting methods. Nevertheless, experience gained with reed in Sweden and reedmace in Minnesota suggests that harvesting is possible with machinery carried on large balloon tyres, having ground pressures as low as 40 g cm^{-2}. Tracked or half-tracked vehicles have also been used to collect reeds, and recent developments include a harvester which chops and blows cut reed portions into a trailed, low ground pressure forage wagon.

Knotweed could be cut and collected by standard heavy-duty forage harvesting machinery. Double-chop harvesters may be sufficiently robust to macerate fresh material in summer, but towards autumn the stems become woody, and single-chop or flail harvesters will be preferable, particularly as they could be used in stony or uneven terrain. The advantage of a fine chop is that it significantly increases the efficiency of anaerobic digestion.

4.3 Conversion to fuel

Four alternatives exist for the converstion of natural vegetation to a useful fuel: anaerobic digestion, thermal conversion, direct combustion or alcoholic fermentation. However, the use of yeasts to produce ethanol is unlikely to be economically attractive (ETSU 1982), particularly from non-sugar crops, and is not considered in these reports.

4.3.1 Anaerobic digestion

Trials of anaerobic digestion on the 3 study species have yielded efficiencies ranging from 39% to 57% (Table 6). Such figures are well above average, although they were achieved after a long retention time using a finely macerated feedstock.

Table 6. The anaerobic digestion of natural energy crops collected close to mid-summer (from Stafford & Hughes 1981)

	Bracken	Cordgrass	Japanese knotweed
Biogas yield (m^3t^{-1} volatile solids)	400	380	550
Energy content per dry tonne (MJ)	8800	5460	5600
Efficiency of conversion (%)	44.3	38.8	57.3

Anaerobic digestion is most suitable for species with a consistently high moisture content. Mid-summer moisture contents over 3 years of harvesting were 81% for cordgrass, 82% for bracken and 79% for Japanese knotweed. In autumn, the water content of all species drops only slightly: cordgrass to 71%, bracken to 78% and knotweed to 74%. Autumn cut bracken could be dried naturally in the field prior to use for thermal conversion, but this will be impossible for cordgrass on tidally inundated salt marshes, and is likely to produce an unacceptable loss of yield with Japanese knotweed. Anaerobic digestion would therefore be the most likely conversion method for 2 of the 3 study species.

4.3.2 Thermal conversion

Whilst senescent bracken is a conveniently dry feedstock for thermal conversion, it is unwise to completely discount the other 2 species, and moist plant material in general. Both cordgrass and knotweed have high feeding value and it is possible that extrusion of protein-rich juices may generate a useful animal feed, whilst drying the residues to the extent that they can be used for thermal conversion. Residues from a variety of de-juiced vegetables have been gasified successfully (Reines 1984), and there is scope for pre-drying the plant material using waste process heat. However, Plaskett (1982) concludes that cheap sources of protein feedstuff, available often from the 3rd world currently preclude the extraction of leaf protein on economic grounds. He does, however, identify the possible economic advantage of mechanically separating leaves for use as an animal feedstuff, whilst retaining the stems for energy.

With present technology, the small-scale gasification of agricultural residues or dried herbaceous energy crops does not appear to be practical. This is because such material often has a very small and variable particle size, which cannot be efficiently combusted other than in expensive and large throughput rotary-kilns or fluidized beds (Beenackers & Van Swaaij 1984). Pelletizing to increase the particle size is not currently economic as a pre-treatment for thermal conversion (Chapter 6).

4.3.3 Direct combustion

For maximum efficiency, combustion obviously requires a fairly dry feedstock. One tonne of perfectly dry bracken, for example, has an energy content of 19 GJ, but this decreases to 8.3 GJ at 50% moisture content and 1.8 GJ at 80% moisture content. Thus, it is vital to use the suns heat to dry the crop before and after harvesting and employ any waste heat which may be available from the combustion process. Have (1982) describes a heat exchange and gas scrubbing system which generates economic low grade heat for space heating from vegetation with a moisture content in excess of 80%.

Either bales or compressed briquettes of dry natural vegetation, like bracken, could be, and have been, used in the domestic sector for space heating or electricity generation, particularly in rural areas. Few technical difficulties are apparent and the increased combustion of herbaceous material depends mainly on economic factors, and the introduction of cheaper and lower technology pelletizing apparatus.

4.4 Integration with existing land uses

Bracken is a poisonous weed of hill land and 50% Government grants are given towards the cost of its eradication. In 1979 average costs for herbicide spraying and follow-up treatments were around £160/hectare (Volume 3, Appendix 6). Yet bracken control by chemical means is currently covering only one third of the area which was controlled by cutting in the early 1950s (McCreath 1982). Low financial returns on bracken spraying explain this decline, and control operations are currently only viable on the best land, in conjunction with intensive management and follow-up treatments. However, control of bracken by cutting appears to be competetive with herbicide application, and bracken harvesting for energy could be timed to minimize regrowth and restore stock-grazing, whilst generating a secondary revenue. Other areas may best be maintained in semi-continuous bracken production by harvesting later in the year.

Cordgrass has been extensively planted as a means of consolidating salt marshes, and by gradually raising the level of the marsh it permits other species to invade and provide valuable grazing for sheep. It is not competitive with agriculture, although some regard it as unsightly.

Japanese knotweed, and to a lesser extent giant knotweed, are continuously colonizing more areas of waste land in Britain. The short term strategy for their use as energy crops would be to establish plantations primarily on derelict areas, thereby imparting financial and environmental value without entering into competition with agriculture. In the longer term, energy plantations of highly productive herbaceous energy species like giant knotweed may be established on agricultural land, particularly pastoral land, as a response to the political imperative to reduce agricultural supluses in the EEC (Dalsager 1983) and as a suitable species for the co-production of animal feed and bioenergy through crop fractionation (Plaskett 1981).

5 CONTRIBUTION TO ENERGY SUPPLY

5.1 Market penetration

Useful projections on the diffusion time for a new technology to gain acceptance and penetrate existing energy markets are made in ETSU R14 (1983). In view of the need to overcome consumer suspicion about reliability of supply, we feel that of the diversity of supply of natural vegetation could give some reassurance. The estimated current yield of natural and semi-natural vegetation is 38.5 Mt yr^{-1} (see Table 1). This total figure could be raised by management and planting different species, but the key question obviously relates to the proportion which can be economically harvested and marketed.

Organizational and technological problems to the implentation of biofuels derived from natural vegetation should not be greater than for crop residue utilization. Given the technical feasibility of using a diversity of feedstock, then it can be assumed that crop residues and harvested natural vegetation could be combined, with a reduction in the size of feedstock catchment for a converter of a particular size.

Our concept of large-scale application would not be the 1 000 t day^{-1} gasifiers envisaged in ETSU R14, but instead the widespread use of small converters at farm, industrial or municipal level. Accepting some loss of the economies of scale, and perhaps a dirtier process overall environmentally, the market diffusion and development should occur more quickly because they will occur in small steps, financed locally, rather than in large unsurmountable leaps. Infrastructural aspects would require less central organization with a diffused system than with a large central processor.

5.2 Local resources

Detailed vegetation maps have been made for sample one km squares used in the ITE land classification (Bunce et al. 1983) and maps of the original squares from different land classes have been examined to estimate their potential for energy cropping (Figure 8). Restricting calculations at this stage to land under what we have defined as natural vegetation, which includes rough grazing, the present projected yield for each one km^2 was estimated for the 4 examples (see Table 7).

TABLE 7. Present and projected yields from natural vegetation in 1 km^2 examples

Land class	13	7	22	8
Square no	684	835	726	459
Nat. veg. area (ha)	67.1	78.8	99.8	47.6
Present production (t yr^{-1})	517	508	266	94
Projected production (t yr^{-1})	552	736	630	567
Projected production (t 100 ha^{-1})	823	934	631	1191

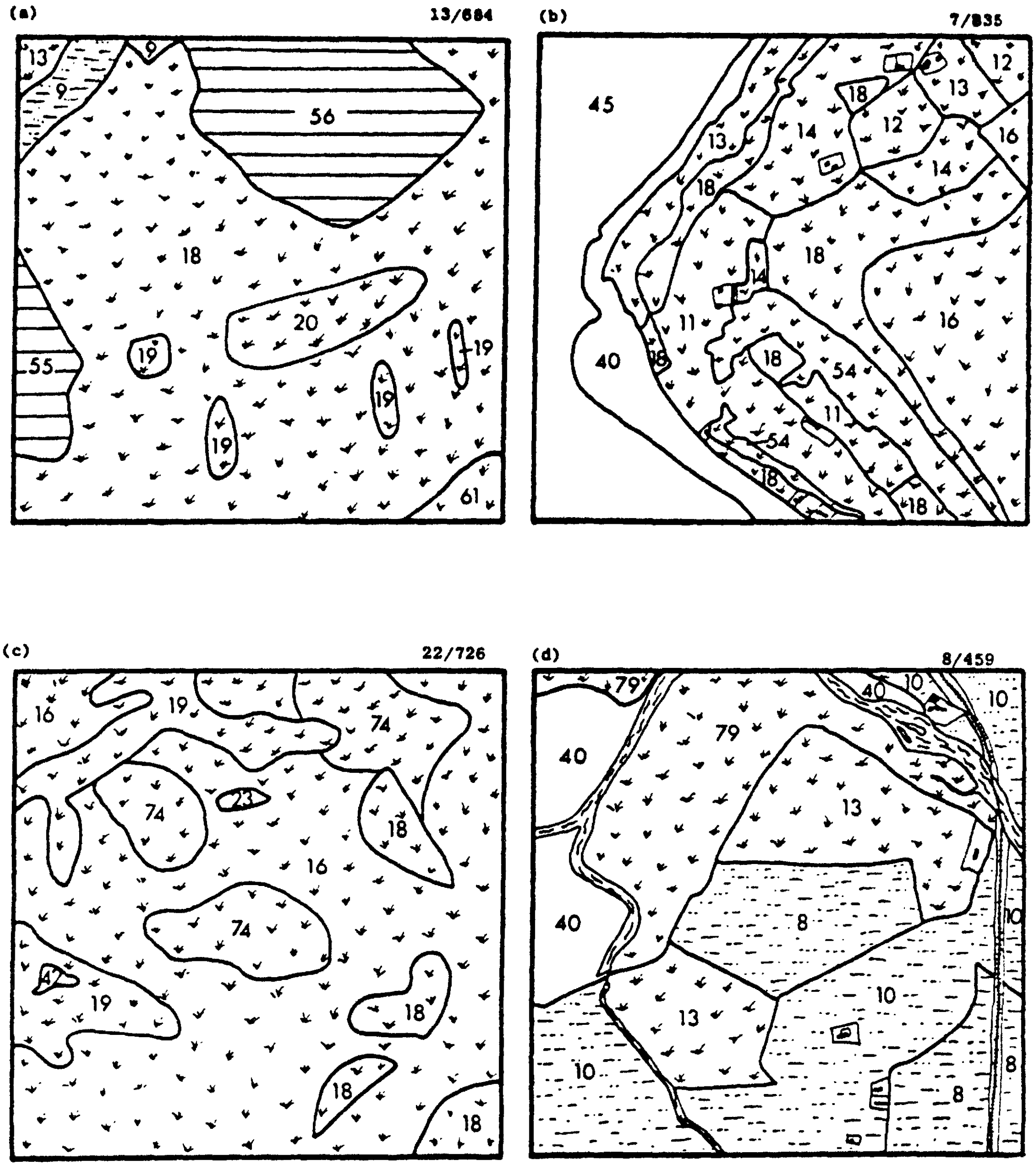


Figure 8. One km squares used as examples of present vegetation cover

8. Ryegrass /Yorkshire fog/meadowgrass/bent grass
9. Unspecified mixtures/generally improved
10. Dogstail/bent/Yorkshire fog (neglected)

Permanent pasture

11. Bent grass/*Fescue* rough pasture
12. Unspecified mixture, rough pasture
13. Rush-infested, rough pasture
14. Bracken infested, rough pasture
16. Heather dominant
18. Bracken dominant
19. Rush dominant/marshland
20. Moorgrass dominant
23. Herb-rich grazed land
54. Scrub
61. Matgrass dominant
74. Burnt heather
79. Saltmarsh

Rough Grazing

55. Broadleaved woodland
56. Conifer woodland

Woodland

40. Cliffs/sand/mud
42. Lake
45. Sea

Other

Square 13/684 (Figure 8 (a)) has little extra scope for increasing yield as it is already mainly occupied by productive natural vegetation, predominantly bracken. Woodland areas were assumed not to be available for use but the rest could be harvested and around 8 t could be expected from each hectare of available land. In square 7/835 (Figure 8 (b)), which was the subject of an earlier analysis (Callaghan et al. 1982, some of the land has the potential to upgrade to higher yield. Steeply sloping land may limit the availability for cropping but we have not been able to provide estimates of the effect of this factor. Land in 22/726 (Figure 8 (c)) shows considerable potential for yield improvement, and there would be few harvesting problems. Instead, to maintain the present land use, the heather could be removed periodically , say at 12 year intervals, at low yield but with correspondingly low management inputs. For land in the category of 8/459 (Figure 8 (d)), the options are many; reduced drainage would allow planting with reed or, alternatively, improved drainage would make the land, suitable for a knotweed plantation. Salt marshes and estuarine flats could be impounded and reed beds established. These habitats would be relatively nutrient-rich. This approach can be used for local site analysis of for incorporation in predictions using the land class method.

5.3 Regional resources

Using the county of Cumbria, a geographically diverse area with virtually all grades of land, a classification into 16 categories allows vegetation distribution and predicted yield to be projected on a grid of one km^2 units (Figure 9). The map can be used to predict the yield potential of Cumbria based on the expected distribution of vegetation. A similar approach was used by Larkin et al. (1981) to assess agricultural waste resources.

The accuracy of this technique depends on the land area occupied and the mean production in each land class. By using this technique, the great heterogeneity of land use can be resolved at finer scale than national data based on census information. The method also allows updating and prediction by changing yield parameters and land use to meet present or anticipated trends. By adding to the data inputs of the sample set, it would also be possible to estimate the effect of such factors as slope and accessibility on the biomass resource.

5.4 National impact

Subject to the various price rise and energy demand scenarios investigated by the Department of Energy (ETSU 1983), biofuels are officially expected to contribute from 43-119 PJ by the year 2000. More optimistic assumptions have been made by Carruthers and Jones (1983), suggesting that waste, residues and unharvested vegetation could provide up to 818 PJ. They also calcuate that a further 842-1344 PJ could be obtained from energy plantations on derelict areas and surplus agricultural land. With drastic changes in the pattern of agriculture and food consumption, a final 1738 PJ could be provided. Larkin et al. estimated that 336 PJ of agricultural wastes are produced annually, although, naturally, not all is collectable.

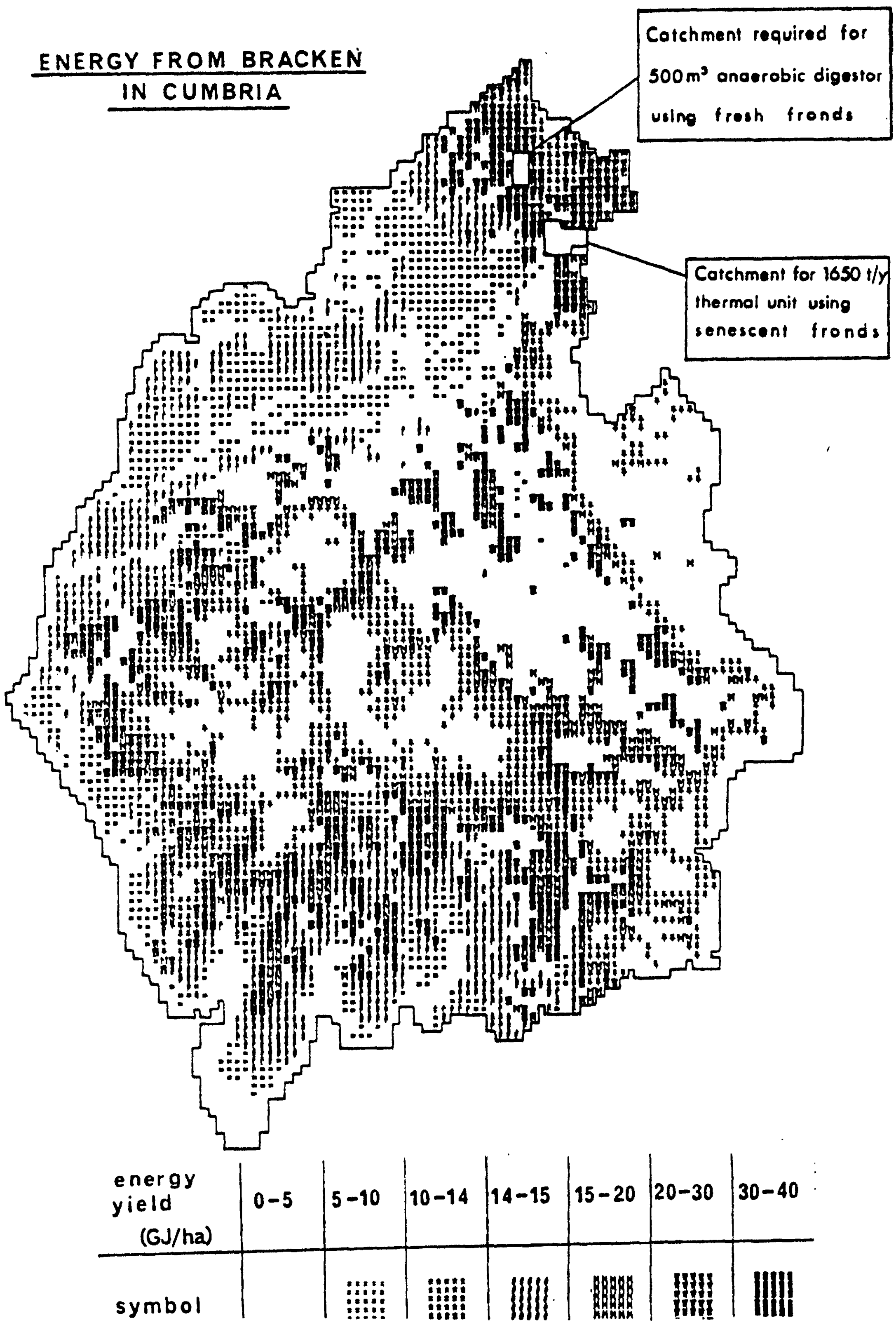


Figure 9. The distribution of bracken in Cumbria in terms of its energy content.

Lawson and Callaghan (1983) collated a variety of estimates on biomass resources available for energy production, and involving minimal competition with agriculture (Table 8), and identified above ground material vegetation production as the largest potential resource (700 PJ).

Table 8. Biofuel sources involving minimal change to existing land uses. (Lawson and Callaghan 1983)

	PJ
Natural Vegetation (UK)	700
Catch Fuel Crops (UK)	382
Crop Residues and Wastes (GB)	234
Industrial and Commercial Refuse (UK)	209
Domestic Refuse (UK)	170
Urban Vegetation (UK)	152
Animal Wastes (GB)	102
Dual-Purpose Crops (UK)	80
Sewage Sludge (UK)	29
Forest Residues (GB)	28
Waste Oil and Tyres (UK)	12
Seaweed (UK)	7.5
Forest Early Thinnings (GB)	6
Weeds in inland water (UK)	0.5
Total	2112

Natural vegetation has a predominantly upland distribution and this results in a low average yield (4.5 t ha^{-1} - Lawson & Callaghan 1983). Nevertheless, opportunity crops like reed, gorse, heather and bracken have yields which could justify the expense of harvesting; and bracken in Scotland, for example, has an energy content equivalent to 4.5% of that country's energy demand (Callaghan et al. 1982).

Dedicated energy crops of perennial natural vegetation could be postulated to replace low value agricultural land, and an impressive potential contribution similar to that of Carruthers and Jones (1983) would ensue. We must advocate caution in this regard, however, until agronomic experience, protein fractionation expertise and reliable costings have been obtained from mechanized and realistic field trials. The high yields observed in natural stands of perennial species have yet to be duplicated in plantations, and considerable experimentation is still required, both in monocultures and in mixtures with agricultural or forestry species.

The proportion of the total resource in Table 8 which can be exploited depends upon technical and economic barriers and the next section considers these economic constraints, as they relate to natural vegetation.

6 ECONOMIC CONSTRAINTS

A recent economic assessment of the renewable energy technologies (ETSU 1982) suggested that the combustion of 'dry' organic materials and the anaerobic digestion of animal wastes were currently economic, or soon would be. Digestion of vegetable material to substitute natural gas (SNG) would be economic by around 2000, even with a low predicted rise in conventional fuel prices. Many unknown factors are highlighted in the ETSU synthesis, however, particularly in the application of new conversion technologies and in the allocation of production costs for novel agronomic systems such as harvesting perennial natural vegetation. Whilst the other volumes in this series deal in more detail with the suggested economics of utilizing each of the study species, this section will attempt to collate the costings, indicate the areas of greatest doubt, and point to savings which can be made if fuel production is integrated with other types of land management.

6.1 Planting

Japanese knotweed is typical of many perennial species which could be established in energy plantations, but, unlike reed or cordgrass, it does not set viable seed in this country. If seed cannot be cheaply obtained from abroad, establishment will be by vegetative means using portions of rhizomes. Survival of these rhizomes has been above 90% in hand planting trials, and it is thought that semi-automatic potato or bulb planting machinery could be employed with little alteration. Estimated contract costs for combined ploughing and mechanical planting are around £120 ha^{-1}.

Seedlings of cordgrass species have been successfully planted in the US using semi-automatic rice planters, but costings are not available. Four-row transplanting machinery is used to move vegetable seedlings in this country, but there is no agricultural analogue from which to derive costs for young cordgrass shoots.

Direct seeding on salt marshes is possible on different scales (and in likely order of cost), using backpack hoppers, mechanical broadcasting or driling, spraying while mixed with a clay slurry, or distribution from the air. Cordgrass, reed and reedmace are known to have been established from seed in the US, Sweden and Holland, but no cost details have been published. Contract charges in this country for cereal and grass drilling range from £16.40 to £31.50 ha^{-1}, and fixed wing or helicopter broadcasting (excluding seed) ranges from £8.40 to £12.36 ha^{-1} (Farm Contractor Magazine, June 1983).

No costs are available for bracken planting and this is unlikely to be required.

6.2 Harvesting

Six theoretical harvesting systems were evaluated for bracken in Volume 1 - Appendix IV, and costs per dry tonne delivered to the farm are estimated to range from £12.80 to £16.60 in summer and from £13.00 to £16.60 in autumn. These recent costings recognize the considerable difficulty of collecting cut bracken on steep fellsides and are greater than previous estimates, eg Callaghan et al. (1982).

The cheapest harvesting system in autumn appears to be a modified Unimog 4-wheel-drive truck/trailer, with side-mounted flail harvester. Around one tonne would be loaded into a rear tipper section for transfer on level ground to high-sided farm trailers which would be relayed to a farm-based high density baler or briquetting press. Field baling has been discounted as too costly in this and all systems. High yields would be achieved as simultaneous cutting and collecting will reduce losses on the ground. However, the opportunity for field drying will also be lost.

A higher yield is assumed in summer (8 t ha^{-1}) than autumn (6 t ha^{-1}), but estimated harvesting costs are similar in the 2 seasons as a faster working rate can be assumed for autumn (0.5 ha h^{-1} as opposed to 0.4 ha h^{-1}). In summer, it may be necessary to use a flail mower followed by a flail harvester to provide a second chop and finer maceration; alternatively, a contracted precision chop unit could be used prior to anaerobic digestion at a total cost of some £13 t^{-1}. This would increase the gas yield but trials are required to establish cost effectiveness.

It must be recognized that the costings derived for bracken harvesting are for an operation which is seldom attempted by machine, and has never been tackled with the systems described. In the absence of a field trial, all quoted prices must remain highly tentative.

Cordgrass poses a similar series of unknowns. Some similarities exist with reed or reedmace in other countries, for which prices of from £25-£35 t^{-1} have been quoted, but such harvesting generally takes place in winter. Contractor costs for harvesting, carting and ensiling maize range up to £130 ha^{-1}. Assuming that low pressure tyres or tracks can be fitted to such equipment, and assuming also that harvesting takes place in periods of neap tides and dry weather, then the figures of £150 ha^{-1} or £15 t^{-1} may be a guide to minimum costs. However, harvesting trials are required to substantiate these costs.

Harvesting costs for Japanese and giant knotweed are easier to estimate by analogy with agriculture. In Volume 3 (Table 4), a series of assumptions (£40 ha^{-1} for a precision chop harvester, £8 h^{-1} for carting, £7.80 t^{-1} for baling in large polythene bags and £1.50 t^{-1} for open hardcore storage) has provided harvesting and storage costs during the first 10 years of a hypothetical Japanese knotweed plantation. These decrease from £25 t^{-1} in year 2 to £13.4 t ha^{-1} in the fourth and subsequent years.

6.3 Conversion

6.3.1 Densification and combustion

The density, particle size and degree of processing of harvested vegetation are important questions. Domestic boilers will operate efficiently using pellets (up to 1100 kg m^{-3}), but such high densification may not be financially justified except in markets where existing appliances must be used. Many makes of straw bale burners are available, but size, expense and the tedium of loading have limited their popularity in this country. Standard straw bales have a specific density of 128 kg m^{-3}, but the specialist Heston bale and NIAE bale have densities of 210 and 240 kg m^{-3} (Volume 1, Table 3). This is around the optimum at which a transporting lorry can be fuly loaded in terms of both weight and volume. Small high-density bales may therefore be an alternative to briquetting for large domestic and farm combustion systems.

The density of hammer milled bracken (135 kg m^{-3}) is greater than that of standard straw bales, because the non-fibrous component of the fronds turns into a compact dust upon chopping. This implies that the transport of unbaled bracken to a central industrial combustion unit may be achieved comparatively cheaply. A rigid 10-ton lorry covering 644 km $week^{-1}$, in 20 trips of average radius 16.9 km, could be contracted at £3.20 t^{-1} (Commercial Motor 1983).

ETSU (1982) indicates that, whilst staw bales and pellets are not yet fully economic in the industrial combustion sector, they will be more than competitive by the year 2000. Similar conclusions should pertain with bracken and other types of dry natural vegetation. Industrial processes normally require the high temperature and more efficient combustion provided by cyclone or fluidized bed burners. Finely chopped straw when combusted in these systems could display an overall efficiency approaching 80% (Martindale 1982).

ETSU (1982) also show that the manufacture and combustion of wood and straw briquettes are presently, at least marginally, economic under all likely fuel replacement strategies in the domestic and rural areas. Martindale (1984), performing a study for ETSU, has examined the possible finances of a 6000 t yr^{-1} briquetting plant, run as a farmer's co-operative in a straw producing area. He included choppers, drying plant, silos and presses to derive an operating and capital cost of £20.20 t^{-1} of briquettes. Feedstock costs (accounting for losses) were estimated as £18.00 t^{-1}, and packaging and sales costs added a further £12.30 t^{-1}.

A smaller briquetting plant is envisaged for bracken areas, based on a portable Danish machine operated by a 100 HP tractor (Plate II and Volume 1, Appendix V). Discounting the capital cost of machinery and buildings over 5 and 10 years respectively indicates a cost of £15.02 t^{-1}, and production expenses are estimated as £11.21 t^{-1}. Therefore, including cutting and collection (£13.00 t^{-1}), drying to 20% moisture (£9.00 t^{-1})*, briquetting (£26.20 t^{-1}), 20 km transport (£3.20 t^{-1}) and storage (£2.00 t^{-1}), it is estimated that bracken pellets could be produced by a farmer or contractor for around £53.40 t^{-1}. This 1983 figure is similar to the total cost estimated by Martindale (1984) for straw briquettes of £50.47 per tonne.

There are differences of methodology between these 2 costings however. Bracken has a higher yield than straw and is assumed to be free, ex-swath, whereas straw is allocated a value of £5 t^{-1}; harvesting costs for straw are much lower however. Briquetting costs are lower in the straw study because a larger operation is assumed. Packaging and distribution are not included as production costs for

* This figure has been included since Volume 1 was completed because recent observations of field drying in autumn cut bracken have demonstrated that moisture contents below 40% are unlikely ever to be obtained. Drying from 50% to 20% is assumed, with a heat requirement of 1.4 GJ dry tonne $^{-1}$ (equivalent). Allowing for losses this would require 10% of the total harvest to fuel a crop-drying boiler (10% of cutting, storage and transport costs = £1.80 t ha^{-1}). Depreciation charges for 5 years on a £20 000 machinery cost at 12% interest amounts to £4.02 t^{-1}. Labour and ancilliary charges are estimated at £3.20 t^{-1}. There is however considerable scope for integrating pre-drying phases with briquetting, with large savings in drying costs. Pawert-SPM AG of Basel have excellent designs in this regard, but on too large a scale for the assumed size of this enterprise.

bracken since this small-scale enterprise need not carry the large overheads which were assumed for straw. Replacement fertilizers are not costed for bracken, at least in the short term, since experimental observation confirms that 5 continuous years of autumn harvesting are possible without a significant reduction in yield. Fertilizer costs for straw are borne by the main crop. If fertilizer (£8.80 t^{-1}) and packaging/sales costs (say £12.30 t^{-1}) were to be included, then the total costs of farm-based bracken briquette production would rise to £74.50 t ha^{-1}).

Even at a cost of just over £50 t^{-1} it is apparent that bracken is only just competitive in energy terms with household coal, and it is likely to be only in small-scale rural applications, and the luxury or novelty market that bracken briquettes will be sufficiently economic to guarantee the risk undertaken by an enterpreneur.

6.3.2 Thermal conversion

Whilst ETSU (1982) has predicted that the thermal production of methanol or substitute natural gas may be economic at the present time, assuming high rises in conventional fuel prices, a more central set of assumptions points to viability by the year 2000. One problem with prediction is that biomass gasifiers and liquifiers have progressed little beyond the pilot stage, and the assumed economies of scale have not yet been proven. Plants producing methanol from natural gas currently have capacities around 10 000 tonnes per day, which at 50% conversion efficiency, and assuming an average biomass yield of 10 t day^{-1}, would require a 7000 km^2 catchment area. Clearly, intakes from 100 to 1000 t day^{-1} are more realistic, but the technology and economics of small methanol units remain to be proven. With gasification, small units appear to be cheaper than direct combustion furnaces of similar output (Plate II). In the Megawatt range this position is reversed (Beenackers & van Swaaij 1984).

In the near to medium term, it seems unlikely that briquetting will be economically justified when preparing feedstock for thermal conversion (although this need not be the case in developing countries). Thus, natural vegetation will be best used by accepting the degree of comminution achieved by field harvesting, perhaps followed by crushing or chopping. Unfortunately, fixed-bed gasifiers are unable to use feedstock with a small and irregular particle size efficiently. Fluidized beds or cyclone reactors are much better suited to such material, and may indeed be more efficient and economic than other designs for outputs of at least 500 kw (van den Aarsen et al. 1982).

6.3.3 Anaerobic digestion

Data given in Chapter 4 suggest that all 3 study species, particularly Japanese knotweed, can give acceptably high yields of methane after anaerobic digestion. In Volume III, the costs of digestion were included within an economic analysis of a Japanese knotweed plantation. Updating Wheatley and Ader (1979), it was assumed that digestion costs 7.5p m^{-3}, and that 450 m^3 of biogas is produced from one tonne of herbaceous material in a 100 m^3 digester.

ETSU (1982) estimated that anaerobic digestion of perennial crops, and upgrading of the biogas to SNG, should become economic by 2000 under all price rise scenarios. Doubts over feedstock costs, the under-development of high solids digestors, and the need for extensive feedstock and gas storage have been recognized as problems which may require cheaper solutions.

6.4 Overall costs and integration with other land uses

Further costs are involved in the management of energy crops using fertilizers, herbicides and pesticides. But, because of the innate productivity and dominance of these crops, costs will be less than those in agriculture. Fertilizer costs for the complete replacement of all nutrients removed during the harvesting of bracken are as much as £6.00 t^{-1} in autumn and £14.00 t^{-1} in summer (Volume I, Table 4). However, 4 years of experimental fertilizing have caused no significant increase in yields. By contrast, tissue concentrations have increased to luxury levels, indicating that, at the study site at least, growth is limited by factors other than nutrients. Much of the fertilizer cost assumed earlier could therefore be saved.

Similarly, fertilizer applications to the cordgrass site have had no significant influence on yield, indicating a sufficiency of nutrient supply from the estuarine environment.

Japanese knotweed does respond to fertilizers, however, providing that weed growth can be controlled concurrently. £77 ha^{-1} yr^{-1} is allowed for fertilization during the first 3 years of establishing a Japanese knotweed plantation. Subsequently, digestor residues replace bag fertilizers at a higher cost (£99 ha^{-1} yr^{-1}), but greater benefit to the organic content and structure of the soil. Herbicide spraying rates, typical of those applied to maize - at £29 ha^{-1} yr^{-1}, have been assumed for the first 2 years of the plantation.

We do not yet know how long a stand of Japanese or giant knotweed might remain in continuous production of biomass, but, assuming that the economic life of the plantation may be only 10 years, then the average cost of chopped knotweed delivered to the digeser (including storage) is estimated as £23.20 dry $tonne^{-1}$. Discounting the estimated annual profit indicates that the Net Present Value (NPV) of the plantation is £78.53 ha^{-1}, with an internal rate of return of 14.7% (making the assumption that biogas is as valuable as calor gas, but that this value does not rise in real terms - (Volume III, Table 4)). Using a discounted annual payment multiplier (Grayson & Busby 1981) and a 10% interest rate, the NPV of the knotweed plantation is equivalent to an agricultural crop sustaining a Gross Margin of £127.50 ha^{-1} yr^{-1} for 10 years. From Appendix I this can be seen to be comparble with lowland beef and sheep farming but it is not so 'profitable' as dairying or arable farming.

Cost estimates were derived in the previous volumes for delivery of chopped material to a conversion unit. These were £23 dry $tonne^{-1}$ for Japanese knotweed and £15.35 dry tonne for cordgrass. Bracken pellets could be produced for around £54 dry $tonne^{-1}$. Knotweed, as we have seen, may not yet be competitive with arable agriculture but plantations could profitably be established on more derelict land or on areas which are difficult to cultivate. Cordgrass harvesting, on the other hand, does not compete with other agriculture or forestry uses, but the costs of harvesting are likely to be such (unless justified for amenity reasons) that anaerobic digestion feedstocks will be available more cheaply elsewhere.

Bracken pellets appear to offer some chance of profit and this will be particularly so if harvesting on some areas can restore profitable hill grazing. However, it is only in exceptional circumstances that more than £40 ha^{-1} of extra revenue would be generated by bracken clearance, and this is equivalent to the profit which a farmer would make by harvesting and carting bracken at a cost of £13 t^{-1} and selling it to be made into pellets at £20 t^{-1}.

Farming profits are more than guaranteed by public expenditure under the Common Agriculture Policy. Support for agriculture in less favoured areas of the UK stands at £121 million, and when added to support for capital and other improvements (£197 milion), price guarantees (£14 million) and market regulation (£1247 million) it can be seen that UK agriculture receives annual support of £1690 million. Net Farming Income, on the other hand is only £1536 million. (MAFF, DAFS & DANI 1984). Against this level of subsidy it is understandable that energy crop plantations appear only to be economically attractive on marginal land.

A further complication in economic comparisons between energy crops and agriculture is the difficulty of comparing like with like. Agricultural Gross Margins include only variable costs and assume that farm buildings, equipment, and usually labour, are available free of charge. If a rent is computed to owner occupied land and charges are made for most fixed costs then the profitability of UK agriculture is represented more realistically than by the use of Gross Margins. Net Farm Incomes range from £304/ha on medium sized dairy farms in northern Ireland to £10/ha on large hill farms in Scotland (MAFF, DAFS & DANI 1984). Set against the very low revenues of marginal land (and the fact that there would be considerable losses without subsidy) the income to be derived from energy crops of some native species vegetation appears sufficiently promising to justify further exploration.

Additionally, there are a number of possible side-benefits from energy-cropping for agriculture or society in general:

a. The saving of UK and EEC subsidies on food over-production; 46% of the EEC agricultural budget is spent on disposing of unwanted food produced from 5 million hectares of agricultural land (Dalsager 1983; Meinhold & Kogl 1983).

b. Saving on the costs of weed control. In 1979, the average cost of spraying bracken with herbicide was £120 ha^{-1}, of which the government met half. Intensive bracken harvesting could save this cost and generate revenue whilst controlling bracken infestation.

c. Saving on the cost of bag fertilizers by using digester residues. Anaerobic digestion preserves or increases the concentration of nutrients in plant material, and, although not such a valuable fertilizer as animal slurry, it can be returned to the land in a way that harvested food crops cannot.

d. Providing digester residues which could be used as animal feed (Summers <u>et al</u>. 1980).

e. Permitting the co-production of food and energy. Protein-rich concentrations may be separated from residues which are used for energy, having been partially dried. These residues could provide the cheap support energy necessary to make this process economic (McDougall 1980).

f. Putting unproductive land to productive use. Derelict land, roadside verges, salt marshes, etc, represent areas with no current value where perennial energy crops could be established without displacing agriculture or forestry.

g. Opening the possibility of growing food, fibre and fuel as multiple crops, intermixed in space or utilizing different parts of the growing season.

h. Extracting by-products such as enzymes and insecticides from bracken, before conversion to fuel.

The costs attributed to energy cropping of natural vegetation were largely derived from contractor charges, and scope therefore exists for savings if the work were carried out by farmers or farm co-operatives themselves. Harvests of cordgrass or bracken could be timed to occur in comparatively slack times for the farmer. Energy cropping of natural vegetation can in many cases be conducted with existing machinery and labour, and the facilities necessary for allied operations such as crop-drying, transport, waste spreading and equipment repair are likely to be readily available.

This chapter suggests economic parameters for harvesting systems which require serious testing in field trials. Past institutional difficulties in predicting energy price and demand changes with time indicate that any apparent economic constraints may prove, in the long term, less important than building alternatives for energy self-sufficiency, stimuating rural enterprise and employment, diversifying the use of the land and disposing of food surpluses. Every country in the world, whether it has a bioenergy programme or not, already controls the market price of energy and foodstuffs for political or socio-economic reasons. Similar reasons should stimulate governments to make the positive response to biofuels which may be necessary to overcome initial institutional and consumer inertia.

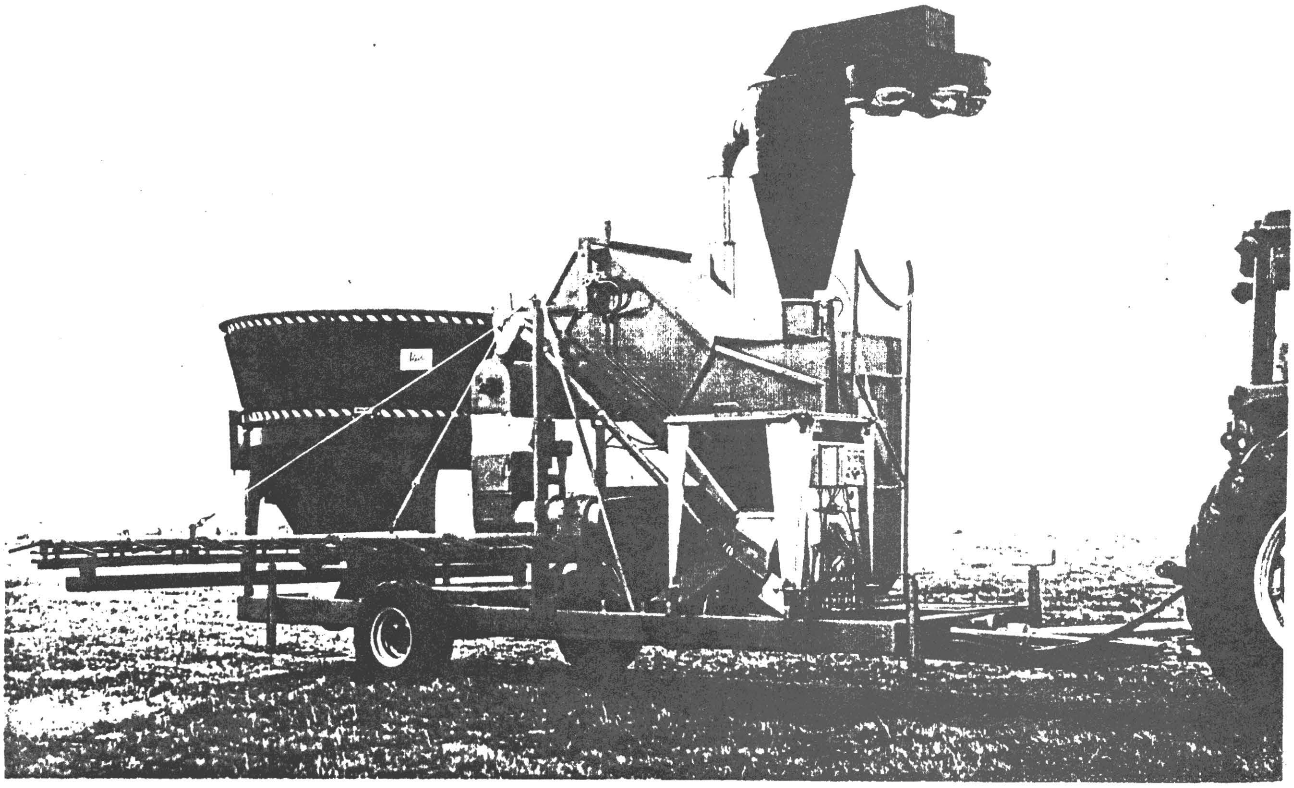
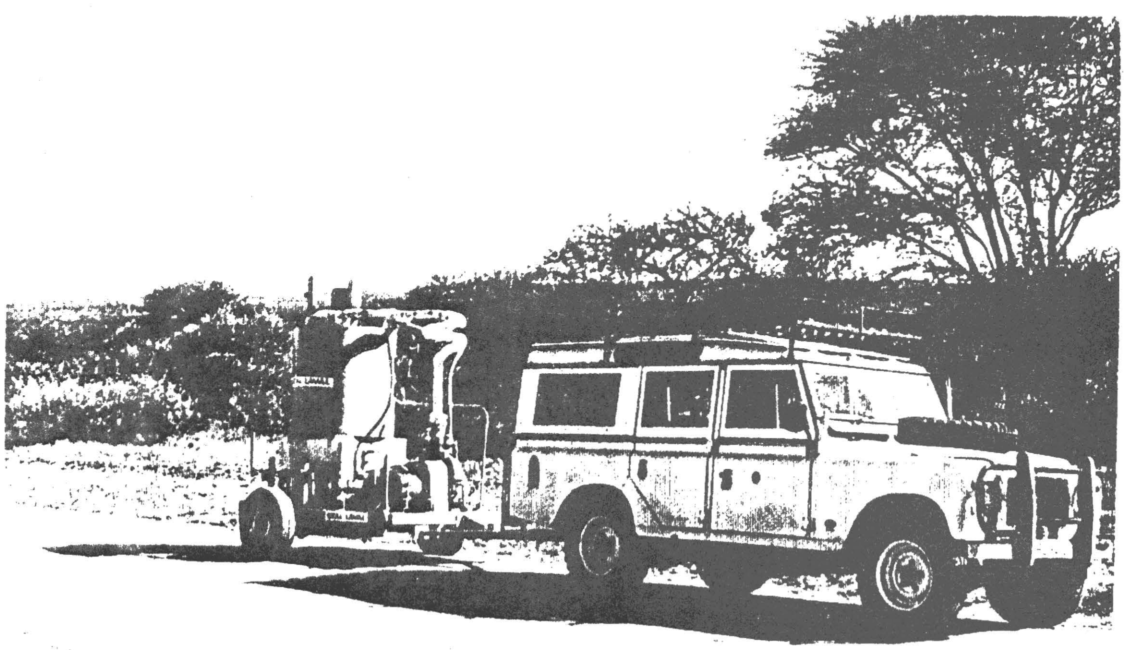


Plate I An 'Ecobriquet' transportable briquetting plant. Powered by a 100 HP tractor, accepts 20% maximum water content in feedstock and has throughput of 800-1000 kg/hr.

Plate II A 'Stal-Laval' portable gasifier/furnace producing 300-3000 kw of electric power and fueled by wood chips, charcoal or briquettes.



7 SOCIAL AND ENVIRONMENTAL IMPACT

7.1 Land use

If biofuels are to make as much as a 10% contribution to UK energy supply then energy crops must develop to at least the area of land presently afforested. Land could be diverted from scrub and low grade farming, and vegetation could be harvested from other areas, eg derelict land, which at present have no economic value.

To replace existing vegetation and bring in new forms of management would result in fundamental visual and ecological change. Conflicts with existing use could be alleviated by dual purpose crops, reconciling fuel production with the original function, eg food production, by such processes as crop fractionation for animal feed and energy. In many cases, the management aims of hitherto unproductive sites would be enhanced by regular crop removal, retaining open ground and preventing invasion by shrubs and trees. Use of the biomass in these cases would provide revenue to support the cost of control measures. There may be problems in convincing landowners of the benefits of changing present land use. A study in USA (Koelsch *et al*. 1977) revealed that farmer attitudes could be a barrier to development, even for the launch of schemes to utilize farm residues. Most of the institutional and environmental interests will militate against new development of any kind, but it is possible to show that there can be environmental benefits from energy crop production.

7.2 Fuel, food and fibre production

The economic success of energy crops could lead to diversion of land from the production of food and traditional forest products. Ideally, integrated planning would apportion land to different uses in order to avoid costly surplus or shortage of particular commodities. In practice, the interplay of market forces and subsidy will remain. The use of dual purpose crops would provide some stabilization of supply by the ability to switch to either the fuel or food market. Grossly elevated energy prices could have undesirable consequences, both nationally and internationally, if bulk food were denied to that market and used as fuel. In areas which are presently devoted to forestry, the production of new energy crops could integrate well with the use of forest residues and fuel use of the main crop when appropriate. In agricultural areas, the replacement of grasslands with new crops would be a greater change but one which may often be economically justified (Mitchell *et al*. 1983).

7.3 Energy distribution

The consequence of the introduction of large fuel conversion plants, eg 50 MW wood-fired power plants, would be decentralization of electricity generation. Modifications to the main supply grid might be necessary, but with wider use of small-scale fuel and power generation there could be a reduced need for upgrading or installing new local electricity supply lines. Industrial plants in isolated locations could have their own generators, thus reducing obtrusion from new power lines. On-farm use of biofuels would lower the need for delivery of fossil fuels, particularly if farm vehicles are modified to run on biogas (Baird & Mowbray 1984). The penalty at farm level would be the extra space required for processing and storage. Considerable investment would also be involved, as well as extra labour.

If fuel products were to be marketed, then there would have to be facilities for compressing, pelleting, packaging or bottling, and the provision of road vehicles to transport them. For high value products, long distance distribution could be economic but, for cheaper fuels, a local market would have to be established.

7.4 Roads

New road construction may be required in the immediate area where energy crops are harvested. Heavy vehicles would make a serious impact on minor roads and upgrading might be necessary for safety reasons. The side-effects of destruction of hedgerows and increased speed of traffic would be adverse. Road improvements would aid communications in country areas but could stimulate greater access for through traffic previously using other routes and also increase tourist penetration into formerly less accessible areas.

Transport of fuel products away from a hypothetical 12.5 km^2 catchment (rated at 8 t ha^{-1} yr^{-1}) would involve 500 vehicle loads of 20 t. Even assuming this traffic all passes down one road, the mean daily number of vehicle movements including return trips is only 4. Clearly, there would be a seasonal pattern to the frequency of loads but at this number there would not appear to be a critical problem. However, within catchments, smaller vehicles would be necessary because of the low density of harvested material and difficulties of access on minor roads. Harvests would be seasonal and the 10 000 t catchment might need all its material transporting in a month. In 10 t vehicles, this would involve 46 return journeys each working day. Although not all would be on the same road, the amount of local disturbance would be serious during the harvest period.

7.5 Disturbance and soil depletion

Vehicles passing over previously undisturbed ground could compact or erode the soil surface. In extreme cases, severe run-off of soil and nutrients would result, and greatly reduce the stability and fertility of the area. Biomass removal itself would have the effect of lowering the total nutrient and organic matter content of the ecosystem (Braunstein et al. 1981). This would give greater temperature extremes in the soil, resulting in more rapid biological turnover and a lowering of the capacity of the system to intercept and hold water. Downstream increases in eutrophication and sedimentiation would then occur.

In line with agricultural practice, regular removal of biomass would need to be accompanied by replenishment of nutrients in the form of fertilizer, and there is some scope for returning the residues from anaerobic digestion to the land. Autumn harvesting of senescent deciduous crops seems a sensible option: nutrient status and root vigour are preserved, but at a cost to the potential total yield. Problems could arise with late harvests on wet or sloping sites and some extra soil disturbance is to be anticipated.

7.6 Pollution

Air pollution from residue burning will be absent in plantations, but emissions will result from processing, fuel use and transport. Vehicles emit unburnt hydrocarbons, NOx, SO_2, C and particulates, but at insignificant levels compared with the fuel load they carry. Gikis et al. (1978) calculated that 75 diesel truck journeys of 93 km would generate 213 kg of air pollutants in total. For wood combustion, emissions of the order of 15 kg t^{-1} would be expected for the transport of 2700 t of fuelwood. Combustion of this fuelwood would therefore generate 40.5 t of air pollutants: a ratio of 190:1 compared with the diesel-produced pollutants.

Greatest levels of emission would be close to combustion plants and the problem of local concentration of pollutants would increase with size. This could pose a human health hazard without proper dispersal or containment. Overall, the production of pollutants should be less with larger, better controlled facilities. Small stoves are notoriously dirty (Allaby & Lovelock 1980), emitting disproportionately large concentrations of polycyclic aromatic hydrocarbons (PAH's) which are carcinogenic and do not readily degrade in the environment (Edwards 1983). Wide dispersal ensures the contamination of food plants both externally and by root uptake. For this reason, it may be necessary to confine the use of wood stoves to areas of low population density and away from food crops. Decommissioning and servicing of combustion and gasifying plant could also be a health hazard and will require strict precautions to avoid contact with PAH's.

Use of fresh biomass containing living tissues for biogas production carries the risk of emission of H_2S and NH_3. Highly eutrophic liquids and some solid matter will also have to be disposed of. Health and safety aspects of leakage of methane would also require attention (El-Hinnawi 1981), if accidents are to be avoided. In all other ways, anaerobic digestion is cleaner than thermal processes.

7.7 Nature conservation

Proposals for using natural vegetation as fuel in the UK (Lawson et al. 1981) involve removing biomass from productive stands of vegetation in a range of habitats which would otherwise be uncropped. In general, this harvesting would truncate the normal vegetation succession and result in plant communities which show little long term change in composition, though subject to periodic, probably annual, disturbance. In contrast, even-age trees, notably forest plantations, offer little biological diversity compared with the communities which develop under continuous cropping. Additionally, forests are subject to a massive ecological change at the time of final harvest; coppiced trees and mixed cropping are much more stable ecological options.

Biomass removal in many British habitats previously grazed, but now lapsed (Green in press), would provide benefits for floral and faunal diversity. In the absence of grazing on chalk downlands in southern England, a programme of regular burning is recommended. Darrall (1984) and Marrs (1984) suggest the use of herbicides to control woody plants, but both burning and using herbicides have more undesirable side-effects than biomass removal. Provided harvesting is in the autumn, a minimum of disruption should occur to breeding cycles of plants and animals in the habitats concerned, though there will be disturbance and some loss of cover and food reserves. Encouragement of mammmals such as rabbits and deer might be unwelcome to adjacent agricultural interests and, if numerous, could cause damage to energy crops.

7.8 Amenity and tourism

The visual effects of forest plantings in rural Britain are viewed by the public as an intrusion into what is regarded as the traditional scenery. Much of this reaction relates to insensitively-placed blocks, the straight-line boundaries of evergreen forests contrasting with the curves of the hills on which they are imposed. Biological monotony is the second objection: few species co-exist with forest trees and the areas are seen as impenetrable and featureless. Similar problems could be anticipated with energy crops such as Japanese knotweed, which has a tall growth form. Cordgrass already forms stands of impressive monotony, but it is a species of featureless coastal habitats. Often its incursion is regarded as undesirable because it closes up what were formerly clear views of open intertidal sediment. In the case of bracken, large expanses of the plant are generally held by tourists to enhance the appeal of hillsides by adding colour, and as the species frequently occupies steep slopes the monotony in biological terms is unimportant visually because the stands are broken up by cliffs and other landscape features.

Much of the land which we have indicated might be used for energy crops lies in the broad category of amenity use. To make development acceptable, the continuation of traditional access provision and enjoyment by the public must be ensured.

The amount of industrialization associated with fuel crops should not be great. As noted in 7.4, the number of extra vehicle movements will be relatively small. Greatest negative impact would be close to large converters, especially furnaces or pyroloysers. These would have to be sited away from towns and out of valleys where pollution could concentrate.

7.9 Fuel policy and demographic impact

The implementation of biofuel harvesting in Britain and investment in local generators would be a reversal of energy policy. Very large coal, oil and nuclear power stations feed a central grid and for large conurbations there seems to be little alternative to grid supply systems, gas included. Local pollution considerations and real economies of scale in the maintenance of supply to consumers closely grouped together make dispersed energy conversion unattractive in cities, economically and environmentally.

The use of indigenous fuel supplies such as wood, natural vegetation and peat should be encouraged in rural areas, preferably with improved designs of stoves and digesters to maximize efficiency and reduce pollution. Consumer resistance, even to demonstrably more efficient designs of stove, has been encountered (El-Hinnawi & Biswas, 1981), so there may be problems in persuading British people to return to solid fuel stoves from the convenience of electricity and gas. District schemes could be the answer.

As the size of fuel converter rises, so does the size of its catchment. Although the rate of increase of transport cost declines with distance, the costs are still high. Increased size does give the advantage of better emission control and technical sophistication. Against large plant is the massive investment necessary and the scale of organisation for planting and transporting the crop. The nearest equivalent in Britain is the sugar beet industry, based largely in East Anglia. According to Fincham (1976), it took the 1925 Beet Sugar Subsidy Act to float the industry and the progressive use of new machines to improve efficiency. The UK crop area grew from 1870 ha in 1925 to 213 000 ha in 1980. Only by the willingness of central government to invest in its success did this industry prosper.

It is difficult to imagine the development of biofuel use, especially in large converters, without government support. Conceivably this could come in the form of regional aid: many of the most suitable areas for its development lie in the north or west, regions in economic decline and also the least favourable conditions for agriculture. Elimination of present livestock stubsidies would drastically reduce the incentive to keep animals and the alternative of support for energy crops needs to be examined.

Although increased use of rural labour is at odds with present trends, the provision of an energy source which will diversify energy supply is consistent. Biofuels and other renewables may be inherently more robust in the face of labour problems or network failure, assuming local supplies could be maintained independently of a national grid. Alternatively, the prospect of crop loss through bad weather would make biofuels appear unreliable.

The ability to store and transport the energy as feedstock or as fuel is a significant advantage of biofuels over most other renewable sources of energy. Output can be matched to load without the original source being active at the time of peak load. However, storage and handling are likely to be a significant cost factor, but may provide benefits by creating a need for new processes and products. Large scale utilization of fuel wood could provide a source of new jobs (Gronki _et al_. 1978), subject to the availability and willingness of suitable labour. Costs would have to be justified by the value of the product or the social desirability of maintaining working populations in rural areas, though many agricultural and forestry workers have already moved so that their families can be close to shops and schools. It may be unrealistic at local level to expect movement back to the country, though some may be attracted to the region for jobs connected with biofuels.

Finally, the attitude of landowners will be important. Clear demonstration of the economic benefits of energy crops will be essential. Private owners with relaitvely modest areas of land in the marginal categories will be best-equipped to switch use. Large landownders and institutions with amenity or other interests will have more conflicts to resolve. However, for large diverse estates, it is possible that allocation of some land to energy production would reduce the need to buy in fossil fuels. Overall, the effect of energy crops would be to take away revenue from fossil fuel suppliers and to replace it with local labour, both in harvesting and processing and in the supply and maintenance of appliances.

7.10 Planning and institutional issues

Assuming the support of central government in the application of biofuels on a large scale, there will be numerous institutional conflicts to resolve. Regional aid could also involve the EEC. New links would have to be found between agriculture, forestry and the energy sector. Further sources of funding would be the national development agencies in the UK. County councils would be involved in planning control of any non-agricultural developments. New legislative provisions might be necessary for energy processing facilities. At local level there could be active co-operation from District Councils. They should facilitate the development of energy schemes by planning combined heat and power or district heating, adding their domestic organic refuse, roadside grass cuttings, etc, to the biomass feedstocks. Savings would be made in other departments by the use of biofuel converters with the versatility to accept a range of feedstocks. Highway authorities, water boards and railways might also consider crossing institutional boundaries to use their vegetation residues for fuel.

Reaction against the widespread use of natural vegetation can be expected from statutory bodies, such as the Nature Conservancy Council and the Countryside Commission, and from voluntary organisations like the Royal Society for the Protection of Birds, the Botanical Society of the British Isles and the National Trust. In many instances, their fears might be unfounded, as cropping semi-natural vegetation would be compatible with the preservation of key habitats, eg heather moors or reed beds.

Institutional boundaries will be a major barrier to the development of energy harvesting on anything above the very smallest scale. The lack of planning control over the use of land and the absence of a national integrated land use policy will also make the organization of crop areas and markets very difficult. However, particularly away from large towns, a range of benefits could accrue from the development of biofuels and other renewable energy sources. These benefits would include prolonging energy self-sufficiency, preserving petroleum and coal as chemical feedstock, reducing air pollution and providing a stimulus for rural employment and economy.

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APPENDIX 1 SAMPLE GROSS MARGINS FROM AGRICULTURAL CROPS (£/ha)

	Winter Wheat (feed)	Spring Barley (feed)	Oats (feed)
Enterprise Output:	5.75t @ £120/t = £690	4.25t @ £115/t = £489	4.25t @ £112.5/t = £478
Variable Costs:			
Seed	42	42	46
Fertilizer	70	53	52
Sprays	70	27	18
Contract drilling (including fertilizers)	21	21	21
Contract spraying	11	11	11
Contract combining (including carting)	80	80	80
Total	294	234	228
Gross Margin	396	255	250

	Oil Seed Rape (winter)	Potatoes (maincrop)	Sugar beet
Enterprise Output:	2.8t @ £280/t = £784	34t @ £62.25/t = £2080	36t @ £30.1/t = £1085
Variable Costs:			
Seed	23	315	45
Fertilizer	125	195	130
Sprays	47	130	95
Contract drilling	21	96	28
Contract spraying	11	14	30
Contract harvesting	80	500	90
Total	307	1250	418
Gross Margin	477	830	667

APPENDIX 1 (CONTINUED) SAMPLE GROSS MARGINS FROM LIVESTOCK UNITS (£/ha)

	Dairy Cows		Lowland Beef (single suckling)		Sheep (fat lamb production)	
Enterprise Output:	5000 l @ 10.4p	£520	Weaned calf (6-9 mths)	£170	1.35 lambs @ £23	£31
	Value of calf	£ 60	Cow+bull depreciation	-£ 18	Wool	£ 3
	Cow depreciation	-£ 40			Ewe depreciation	-£ 6
Total		£540		£152		£28
Variable Costs:						
	Concentrate(1.5t)	£165	(0.5t)	£ 51	(50kg)	£ 5
	Sundries	£ 25		£ 18		£ 2
	Forage crop costs (.5ha/cow)	£ 60	(.6ha/cow)	£ 40	(9 ewes & lambs/ha)	£ 6
Total		£250		£109		£13
Gross Margin per animal:		£290		£ 43		£15
Gross Margin per hectare:		£580		£ 72		£135

Sources: Nix (1983) for agricultural crops and University of Reading (1978) for livestock.

Note: Gross Margins for agricultural crops assume contractor operations. This is not the normal basis for calculation but it permits closer comparison with contractor based energy cropping.