Journal of
Applied Ecology
1995, 32,
400–411

A comparison of techniques for restoring heathland on abandoned farmland

R.F. PYWELL,*[‡] N.R. WEBB* and P.D. PUTWAIN[†]

*Furzebrook Research Station, NERC Institute of Terrestrial Ecology, Wareham, Dorset BH20 5AS, and [†]Population Biology Research Group, Department of Environmental & Evolutionary Biology, Liverpool University, PO Box 147, Liverpool, L69 3BX, UK

Summary

1. Recent changes in agricultural policies have reduced the extent of cultivated farmland. This has provided opportunities to restore heathland vegetation on lowland sites where it once occurred.

2. Between December 1988 and April 1990 large-scale replicated experiments were established on abandoned farmland in southern Britain to compare the effectiveness of four treatments for heathland restoration: (i) the application of herbicide; (ii) the addition of harvested heather shoots; (iii) the addition of heathland topsoil; and (iv) the translocation of heathland turves.

3. The number of seedlings of heathland plant species on each treatment was counted in December 1990 and 1991, and the shoot frequency of these species was recorded in January 1993.

4. The grassland soil had a significantly higher pH and contained greater concentrations of extractable phosphorus and exchangeable calcium than that of the adjacent heathland. Despite this, the controls showed that there was some natural regeneration of heathers within the grassland.

5. Herbicide treatment inhibited the regeneration of heathland plants. Cultivation followed by the application of harvested heather shoots increased the number of seedlings of heathland plant species, but some key species were missing. All the components of the heathland plant community occurred in greater numbers on the plots where heathland topsoil had been applied, and on the parts of transferred heathland turves which had died from drought.

6. The large-scale translocation of heathland turf appeared to be feasible and instantly recreated the mature heathland plant community. However, some changes in the plant community occurred which probably resulted from differences in soil drainage characteristics between the donor and recipient sites. Of the different sources of heathland plant propagules, harvested heather shoots were a renewable resource, whereas the collection of heathland topsoil and turves involved the destruction of existing heathland.

Key-words: *Calluna*, seed, herbicide, turf, topsoil.

Journal of Applied Ecology (1995) **32**, 400–411

Introduction

The heathlands of lowland Britain are dominated by the evergreen dwarf shrub *Calluna vulgaris* (L.) Hull and are maintained by factors such as exposure, infertile soils, grazing and burning. The once extensive tracts of heathland occur today as remnant fragments within a highly modified landscape (Moore 1962; Webb & Haskins 1980; Farrell 1989; Webb 1990). Much of the loss of heathland has been to agriculture, and was a response to government incentives and improvements in farming methods. The recent re-appraisal of rural land-use policy has led to schemes that seek to take land out of cultivation and, in some cases, to recreate biotopes of conservation interest (e.g. Countryside Stewardship: Countryside Commission 1991) and Environmentally Sensitive Areas (ESA: MAFF

[‡] Present address: Monks Wood, NERC Institute of Terrestrial Ecology, Abbots Ripton, Huntingdon, Cambridgeshire, PE17 2LS, UK.

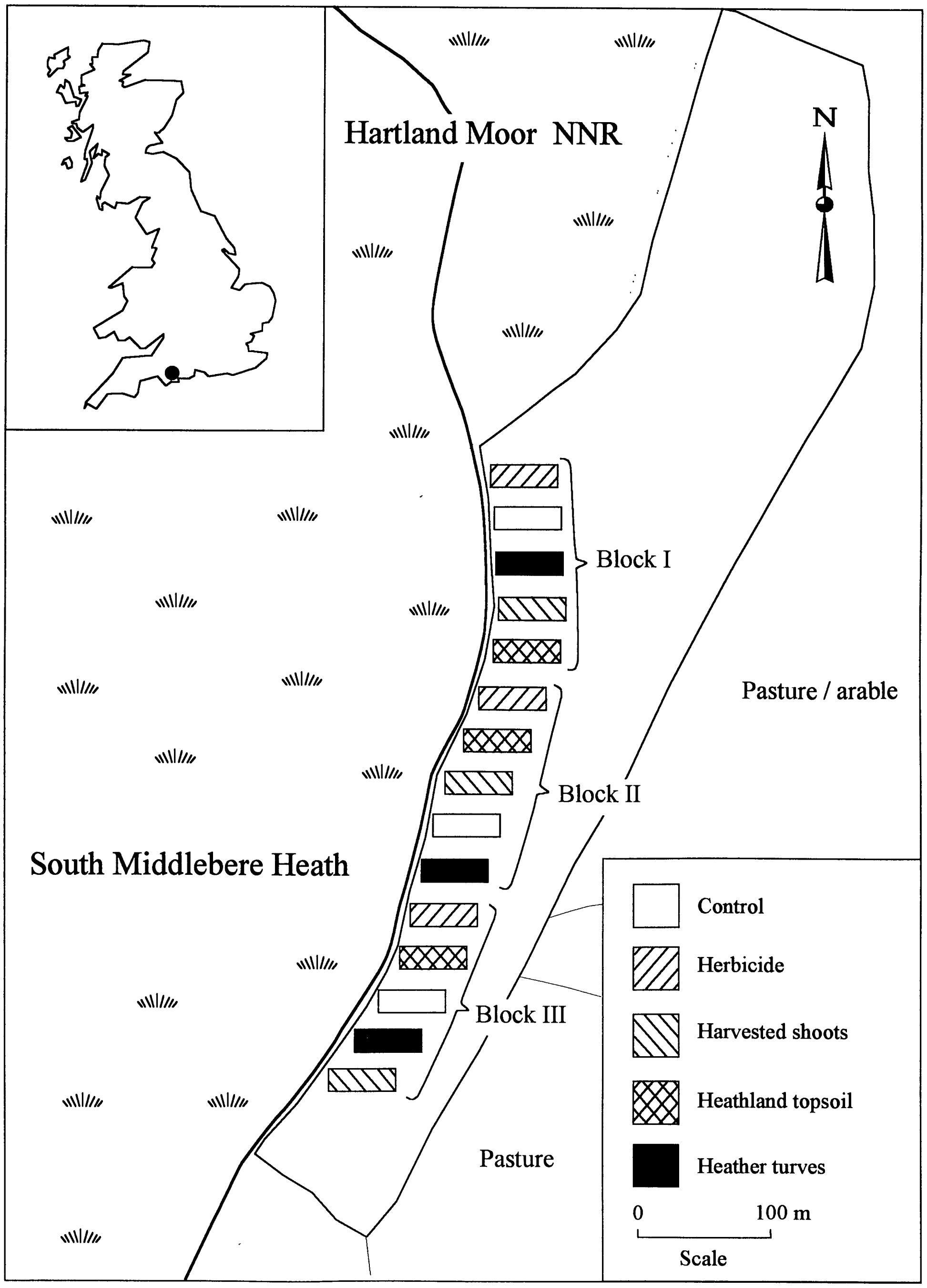

Fig. 1. A map of the heathland restoration trials at South Middlebere Heath, Dorset (Grid Ref. SY 964854).

1986). Given the large area of land with potential for heathland restoration in lowland Britain, the limited supply of heathland plant propagules and the high costs of restoration, it is worthwhile examining the effectiveness of large-scale techniques which initiate or accelerate the regeneration of vegetation on land where cultivation has recently ceased.

Much of the work on restoring heathland on farmland has been on a small scale and has been concerned with encouraging heather regeneration on areas of acidic grassland in the uplands where overgrazing has caused the loss of heather (Scandrett 1989; Newborn, Booth & Hudson 1989). In recent years many Dutch heathlands have become dominated by the grasses *Deschampsia flexuosa* (L.) Trin and *Molinia caerulea* (L.) Moench. This change took place during a period when nutrients accumulated in the heathland soils owing to lack of management combined with increasing atmospheric deposition of ammonium from adjacent farmland (van Breemen *et al.* 1982; Heil *et al.* 1988). Field trials have shown that increased nutrient availability may be responsible for this change in composition (e.g. Heil & Bruggink 1987; Aerts & Berendse 1988; Aerts *et al.* 1990). Stripping the grassland turf (*plaggen*) was found to encourage heather regeneration (Gimingham & de Smidt 1983; Werger, Prentice & Helsper 1985; Bakker 1989).

Relatively little attention has been devoted to heathland restoration on improved and semi-improved grasslands in lowland Britain where high soil fertility and pH are likely to be important problems. However, Smith, Webb & Clarke (1991) successfully increased the frequency and abundance of heathland plants in two abandoned fields in Dorset both by stripping the top 30–50 mm of soil, and by disturbance of the soil and the addition of flailed heathland vegetation mixed with topsoil.

This paper describes the results obtained from an experiment which tested four methods for heathland restoration on recently abandoned grassland in Dorset, southern England. Throughout the paper *Calluna vulgaris* will be referred to as *Calluna*; the term 'heathers' refers specifically to *Calluna*, *Erica cinerea* L. and *Erica tetralix* L.

Site description

The trials were carried out at a site on South Middlebere Heath, Corfe Castle, Dorset (National Grid Reference SY 964854). Until the early 1960s this area was a large (284 ha) remnant patch of lowland heath. Cultivation of part of this heathland created a narrow field with an area of 15·7 ha along its eastern boundary (Fig. 1). At the southern end the field is flat and it rises gently northwards to form a low, flat-topped plateau which falls away gently at its eastern edge. The site is underlain by the Bagshot Sands (Tertiary deposits). The original soil was a ferro-humic podzol typical of lowland heaths, but repeated cultivation has mixed the well defined organic and mineral soil horizons to produce a relatively homogeneous humic sand with a depth of 100–200 mm. After conversion, crops of rye (*Secale cereale* L.) were grown for about 8 years, then the field was sown with grass and grazed by cattle, with occasional crops of rye. During this time unspecified amounts of lime and chemical fertilizers were applied. Since farming ceased, in about 1986, there has been some natural regeneration of heather, and there are now frequent *Calluna* bushes amongst the grass. At the time of this study, the vegetation was typical of parched, low fertility acid grasslands in lowland Britain, but also contained species which reflected the former agricultural use of the site. The field was dominated by the forbs *Rumex acetosella* L., *Hypochoeris radicata* L. and *Plantago lanceolata* L. together with perennial grasses, such as *Agrostis capillaris* L. and *Dactylis glomerata* L., and the annual grasses *Bromus hordeaceus* L. and *Vulpia bromoides* (L.) S.F. Gray, with large open patches dominated by the moss *Polytrichum juniperinum* Hedw. This vegetation corresponded to the typical sub-community of the *Festuca ovina—A. capillaris—R. acetosella* grassland (U1b) described by the British National Vegetation Classification (NVC: Rodwell 1992).

Methods

A large-scale randomized block experiment was established on the site to initiate the regeneration of heathland. Five treatments were employed: (i) herbicide application; (ii) cultivation followed by the addition of harvested heather shoots and seed capsules; (iii) soil stripping to a depth of 50 mm followed by the addition of heathland topsoil; (iv) soil stripping to a depth of 150 mm followed by the transplantation of intact heathland turves; (v) control. Each of the five treatments was replicated three times in experimental plots which measured 10×50 m and were aligned east-west (Fig. 1). The difficulty in obtaining sufficient quantities of turf and topsoil meant that these treatments were applied 6 months and 16 months later than the other treatments, respectively.

HERBICIDE

In spring of 1989 the vegetation of three designated grassland plots was destroyed using the translocated, non-selective herbicide glyphosate (Roundup Monsanto, Leicester) at a rate of 5 L ha^{-1} active ingredient diluted in 200 L ha^{-1} of water. Application was by back-pack sprayer. No rain was recorded in the 24 hours following application.

HARVESTED HEATHER SHOOTS

In early December 1988 harvested shoots were collected using a double-chop forage harvester from a 4075-m^2 area of mature heathland 4 km north-east of the study site. Cutting removed the upper 350 mm of the heathland canopy and yielded *c.* 3·0 kg m^{-2} of fresh harvested shoots. The vegetation of the donor site corresponded to the *Molinia caerulea* sub-community of *Calluna—Ulex minor* heath (H2c in the NVC: Rodwell 1991). A rotary cultivator was used to prepare a seed bed for the harvested heather shoots which were applied at a rate of 3·3 kg m^{-2} (fresh weight) to a maximum depth of about 40 mm. The seed bed was then rolled with a ring roller.

The maximum potential capsule and seed content of the harvested shoots were estimated by hand-cutting 15 random $0{\cdot}25 \times 0{\cdot}25$ m quadrats a few days before harvesting and counting sub-samples under a binocular microscope (×20). The viable seed content of the harvested material was estimated from 27 samples which were air-dried and from each of which a 100-ml sub-sample was weighed and spread in a 3–5 mm layer on a 3:1 mixture of moss peat and sand in a 204×160 mm plastic seed tray. A further three trays contained the peat-sand mixture only. The trays were placed in a frost-free glasshouse and watered from below. After 3 and 6 months the emerging heathland plant species were identified and counted, and after 9 months they were removed. The trays were left a further 12 months and re-recorded.

THE TRANSLOCATION OF HEATHLAND TURF

Turves were obtained from a site 11 km north-west of the study site (National Grid Reference SY 870887). The vegetation was dominated by *Calluna* and *Erica tetralix* L. with *Erica cinerea* L., *Ulex minor* Roth, *Molinia caerulea*, and *Agrostis curtisii* Kergulen. This community corresponded to both the *U. minor*—*A. curtisii* heath (H3) and the *Calluna*—*U. minor* heath (H2) of the NVC (Rodwell 1991). This suggested that the site was transitional between the humid and dry heaths typical of south east Dorset. The soil of the site was a humo-ferric podzol with a high silt content in the eluvial mineral horizon (E).

In July 1989 1500 m^2 of turves, each measuring $1{\cdot}2\,m \times 2{\cdot}3\,m \times c.\ 150\,mm$, were transferred to the experimental site using an excavator fitted with a steel tine bucket. The severe summer drought of 1989 necessitated irrigation of the turves between July and September.

HEATHLAND TOPSOIL

Heathland topsoil was obtained from the same donor sites as the turves. 6 months before soil stripping, the depth distribution of the seed bank was determined by taking 10 random soil cores. The loose litter was separated from the upper organic horizons and the cores were sectioned at 10-mm intervals to a depth of 80 mm, and then at 20-mm intervals down to 200 mm. The soil was air dried and passed through a 2-mm sieve to remove large stones and roots. About 75 ml of each soil depth fraction and 25 ml of each litter sample were weighed and spread in layers of 8–9 mm and 2–3 mm thickness, respectively in 94 × 94-mm plastic pots containing a 3:1 mixture of sand and vermiculite. The litter was applied in a shallower layer than the topsoil and gently pressed into the sand. This was because of the difficulty of keeping it sufficiently moist for germination to occur. The pots were placed in trays and watered from below in a frost-free glasshouse. Every 3 months for the first 9 months all seedlings emerging in the pots were identified and removed. The pots were then left a further 9 months before being examined again.

Before the application of heathland topsoil the grassland turf was stripped to a depth of *c.* 50 mm. The soil of the donor heath was stripped to a depth of 40–50 mm using a slew excavator which yielded *c.* 70 $kg\,m^{-2}$ of soil. Between 11 and 13 tonnes of topsoil were applied to each 500-m^2 plot giving a rate of application of between 22 and 26 $kg\,m^{-2}$. The heathland topsoil was mixed with the farmland soil using a rotary cultivator and rolled with a ring roller. This was in order to achieve a good contact with the seed bed.

Monitoring and analysis

Rectangular soil blocks, each measuring 200 × 100 mm, were extracted to a depth of 300 mm from random points in the grassland and adjacent heathland. Six blocks were taken from the grassland and five from the heathland. These cores were cut into 40-mm horizontal sections to a depth of 80 mm and into 80 mm sections thereafter to a depth of 240 mm. Analyses closely followed the methods of Allen (1989). The pH of the fresh soil was determined from a 1:1 soil:water solution. The organic content of the soil was estimated from percentage loss on ignition (%LOI). Nitrogen was extracted by shaking sub-samples of fresh soil with 6% sodium chloride solution. Nitrate-nitrogen (NO_3-N) and nitrite-nitrogen (NO_2-N) were estimated colorimetrically by the naphthlyamide-sulphonic acid method using an auto-analyzer (Technicon Instruments Corp., New York). Ammonium-nitrogen (NH_4-N) was determined with the Auto-analyzer using the indophenol blue colorimetric reaction. The major soil cations were exchanged by shaking with 1·0 M ammonium acetate solution and determined using an atomic absorption spectrophotometer. Soil phosphorus (P) was extracted using 2·5% v/v acetic acid solution and was estimated as a phosphomolybdate complex reduced by ascorbic acid using a colorimeter.

Log_e transformation was carried out on the concentrations of nutrients and angular transformation was carried out on the %LOI data. Student's *t*-test was used to investigate differences in the soil nutrient concentrations at different depths between the grassland soil and the adjacent, undisturbed heathland soil of Hartland Moor.

The success of the different restoration treatments was monitored by recording the seedling regeneration and, later, the frequency of established heathland species. In December 1990 and 1991 the numbers of heather seedlings were recorded in 21 permanent $1 \times 0{\cdot}5$ m quadrats in each of the five treatments. The quadrats were placed at random on all of the treatments except the transferred turf plots. On these the quadrats were placed randomly only in areas of turf which had died during the summer drought of 1989. This was necessary because there was very little seedling germination under the mature heather canopy of this treatment. By January 1993 it had become increasingly difficult to identify individual plants, so the shoot frequencies of heathland species were recorded in 45 randomly placed 1 × 1 m quadrats on each treatment.

The seedling counts per m^2 were log_e transformed to stabilize variances, and differences between treatments and years were examined using a split plot analysis of variance (ANOVA). The fraction of

Table 1. Comparison of the nutrient status of the farmland soil at Middlebere with that of the adjacent undisturbed heathland soil of Hartland Moor. Mean (and standard errors) are given. ConcentratioNS of nutrient ioNS are expressed as mg per 100 g of dry soil

Depth (mm)	pH			LOI (%)			NO_3			NH_4			Total ($NO_3 + NH_4$)		
	Middlebere	Hartland	*P*	Middlebere	Hartland	*P*	Middlebere	Hartland	*P*	Middlebere	Hartland	*P*	Middlebere	Hartland	*P*
0–40	4·93 (0·21)	3·80 (0·04)	**	7·56 (0·59)	52·4 (0·1)	**	0·10 (0·01)	0·20 (0·05)	NS	0·16 (0·04)	1·19 (0·60)	*	0·26 (0·04)	1·40 (0·63)	*
40–80	4·90 (0·21)	3·78 (0·05)	**	6·06 (0·59)	15·3 (2·21)	*	0·10 (0·01)	0·12 (0·04)	NS	0·10 (0·03)	0·21 (0·49)	NS	0·20 (0·04)	0·33 (0·08)	NS
80–160	5·22 (0·24)	3·80 (0·08)	**	5·54 (0·46)	5·93 (2·22)	NS	0·11 (0·02)	0·09 (0·03)	NS	0·12 (0·04)	0·04 (0·01)	NS	0·23 (0·05)	0·13 (0·04)	NS
160–240	5·27 (0·28)	3·92 (0·08)	**	4·18 (0·36)	2·52 (0·89)	NS	0·13 (0·01)	0·18 (0·07)	NS	0·18 (0·06)	0·06 (0·01)	NS	0·30 (0·07)	0·23 (0·06)	NS
Total	5·13 (0·23)	3·83 (0·06)	**	5·84 (0·17)	7·80 (1·70)	NS	0·11 (0·01)	0·14 (0·03)	NS	0·14 (0·04)	0·10 (0·02)	NS	0·25 (0·04)	0·23 (0·05)	NS

Depth (mm)	P			Mg			Ca			K		
	Middlebere	Hartland	*P*	Middlebere	Hartland	*P*	Middlebere	Hartland	*P*	Middlebere	Hartland	*P*
0–40	0·52 (0·07)	0·95 (0·25)	NS	10·24 (1·27)	29·73 (6·26)	**	74·9 (10·6)	55·5 (11·9)	NS	3·51 (1·09)	26·49 (4·70)	***
40–80	0·19 (0·02)	0·21 (0·04)	NS	4·67 (0·68)	9·68 (2·18)	NS	61·7 (15·0)	21·7 (3·5)	**	1·85 (0·46)	4·76 (0·93)	*
80–160	0·19 (0·02)	0·09 (0·02)	**	1·89 (0·41)	4·15 (1·45)	NS	79·6 (14·3)	7·65 (2·47)	***	1·23 (0·36)	1·63 (0·44)	NS
160–240	0·18 (0·03)	0·05 (0·01)	***	1·00 (0·44)	1·76 (0·62)	NS	64·8 (11·9)	4·13 (1·49)	***	0·65 (0·07)	0·78 (0·20)	NS
Total	0·23 (0·03)	0·13 (0·02)	*	3·25 (0·29)	5·04 (1·17)	NS	70·8 (10·4)	9·20 (1·86)	***	1·45 (0·33)	2·92 (0·44)	*

Results of Student's *t*-test for differences between the meaNS in the two situatioNS are indicated as follows: * $P < 0{\cdot}05$; ** $P < 0{\cdot}01$; *** $P < 0{\cdot}001$; NS = not significant at the 5% level; LOI, loss on ignition; for Middlebere $n = 6$ and for Hartland Moor $n = 5$.

Table 2. (a) Mean number of seedlings emerging per kg of air-dried harvested heather shoots and seed capsules together with (b) the estimated yield of viable seeds per m^2 of heathland cut with a forage harvester

	a (thousands of seedlings kg^{-1})		b (thousands of seeds m^{-2})	
Species	Mean	SE	Mean	SE
Calluna vulgaris	1·54	0·17	3·06	0·33
Erica cinerea	0·082	0·017	0·164	0·033
Erica tetralix	0·118	0·017	0·234	0·034
All heathers	1·74	0·19	3·46	0·38
Agrostis curtisii	0·002	0·002	0·004	0·003

SE, standard error of the mean. $n = 27$.

quadrats containing heathland plant species in each treatment was determined from the shoot frequency data. Differences between block and treatment means were investigated using a complete block ANOVA.

Results

THE EFFECT OF AGRICULTURAL PRACTICE ON THE SOIL FERTILITY OF A FORMER HEATHLAND

The relatively intensive cultivation of this heathland for 25 years has had a profound effect on both the physical structure and the distribution and concentration of nutrients within the soil compared with the adjacent, undisturbed heathland soil (Table 1). The heathland soil had significantly higher concentrations of organic matter (%LOI), NH_4, Mg and K in the upper soil layers compared with the grassland soil. However, the grassland soil had significantly higher concentrations of extractable P and exchangeable Ca in the lower layers, and a significantly higher pH at all depths. When the whole profiles were compared, the grassland soil had significantly higher pH and higher concentrations of P and Ca than the heathland, but the heathland soil had significantly more exchangeable K.

THE VIABLE SEED CONTENT OF HEATHLAND TOPSOIL AND HARVESTED HEATHER SHOOTS

Harvested heather shoots contained large numbers of viable seeds in similar proportions to those in the existing vegetation (Table 2). However, the harvested shoot material lacked seeds of *Ulex minor* and those of *Agrostis curtisii* occurred in a greater proportion than in the existing vegetation. From the seed capsule counts (Table 3), it would appear that the glasshouse experiment estimated only a small fraction of the seed present in the heathland canopy. This may have been be due to the failure of the seed capsules to release seed and the dormancy of a proportion of the seed during the period of the trial. Also, these hand-cut samples may have retained more seed than those collected by the forage harvester.

95% of the seed bank of the donor site was in the top 50 mm of the profile (Table 4). Furthermore, the topsoil contained viable seed of all the heathland plants recorded in the existing vegetation, but in very different proportions. The seed bank was dominated by *Erica tetralix* (*c.* 80%) with smaller proportions of *Calluna* (14%) and *Erica cinerea* (3%). The composition of the seed bank bore little similarity to the existing vegetation.

THE REGENERATION OF HEATHLAND VEGETATION ON THE RESTORATION TRIALS

The success of the restoration trials was assessed by comparison of the mean number of seedlings of heathland plant species occurring on the plots in November–December of 1990 and 1991 (Table 5). Heather seedling regeneration on the control and herbicide treatments was very poor in both years. The seedling community developing on the harvested shoots treatment was dominated by *Calluna* and *Erica cinerea*, and the other heathland plant species

Table 3. Mean capsule and seed content of the vegetation of the donor site for harvested heather shoots. The capsule counts were determined from 15 0·25 × 0·25 m quadrats examined in December 1988 and the numbers of seeds were counted in subsamples of 22 capsules per species

	Thousands per kg of fresh material				Thousands per m^2 of heathland			
	Capsules		Seeds		Capsules		Seeds	
Species	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Calluna vulgaris	20·8	4·97	87·0	20·8	40·1	10·6	168	44·3
Erica cinerea	3·46	2·14	18·9	11·6	6·11	3·88	33·3	21·1
Erica tetralix	4·92	2·32	59·2	27·9	11·7	6·71	141	80·8
Total heather	29·2	3·0	165	15·9	57·9	8·01	342	64·8

SE, standard error of the mean. $n = 15$.

Table 4. Mean number of seedlings (in hundreds per m^2) of heathland plant species emerging from different depths in soil cores taken from the heathland topsoil donor site in October 1989 (with SE); $n = 10$

Depth (mm)	Total heather	*Calluna vulgaris*	*Erica tetralix*	*Erica cinerea*	*Ulex minor*	*Agrostis curtisii*	*Molinia caerulea*
Litter	16·9 (2·7)	1·42 (0·68)	15·2 (2·5)	0·274 (0·183)	—	0·139 (0·139)	—
0–10	105 (12)	12·9 (3·4)	91·9 (10·3)	0·667 (0·535)	0·533 (0·295)	0·267 (0·178)	0·933 (0·400)
10–20	59·5 (9·4)	11·9 (2·2)	45·6 (6·9)	2·00 (1·25)	0·133 (0·133)	—	—
20–30	17·5 (3·0)	6·67 (1·69)	10·1 (2·0)	0·667 (0·455)	—	—	—
30–40	4·54 (1·67)	1·60 (0·68)	2·67 (1·03)	0·267 (0·178)	—	—	0·133 (0·133)
40–50	2·53 (0·90)	0·533 (0·395)	2·00 (0·667)	—	—	—	0·40 (0·40)
50–60	5·20 (3·29)	2·93 (1·97)	2·27 (1·33)	—	—	—	—
60–70	0·133 (0·133)	—	0·133 (0·133)	—	—	—	—
70–80	1·47 (1·33)	0·667 (0·667)	0·800 (0·665)	—	—	—	—
80–100	1·33 (1·07)	0·80 (0·80)	0·553 (0·356)	—	—	—	—
100–120	4·53 (2·67)	0·267 (0·267)	4·27 (2·46)	—	—	—	—
120–140	1·60 (0·82)	0·267 (0·267)	1·33 (0·60)	—	—	—	—
140–160	1·33 (1·33)	0·53 (0·53)	0·80 (0·80)	—	—	—	—
160–180	—	—	—	—	—	—	—
180–200	—	—	—	—	—	—	—

were absent. Seedlings of heathland plant species were both more numerous and diverse on the heathland topsoil treatment. All the heathland plant species present in the vegetation of the donor site occurred on this treatment, but the relative proportion of each species was markedly different from those found in the glasshouse seed bank determination; *Calluna* replaced *E. tetralix* as the most abundant heather species. The proportion of *E. cinerea* remained largely unchanged in the first year, but increased markedly in the second year, suggesting substantial recruitment of this species. The heather seedlings on the transferred turf plots occurred in similar numbers and in the same relative proportions as on the topsoil treatment.

Split plot ANOVA showed there were no significant differences in the mean density of *Calluna*, *E. cinerea* and all heathers between blocks, but there were highly significant ($P < 0{\cdot}001$) differences between treatments (Table 6). Only *E. cinerea* showed a significant increase in density between years. This increase was only on the topsoil and turf treatments which explained the significant year × treatment interaction. This was probably caused by the considerable germination and recruitment of this species on these treatments between 1990 and 1991.

Perhaps a better comparison of the success of each restoration treatment was the measurement of shoot frequencies of heathland plant species occurring on them in 1993 (Table 7). These results showed a similar pattern to those of seedling density. The shoot frequencies of heathland plant species on

Table 5. Mean number of seedlings of heathland plant species per m^2 on the heathland restoration trials at Middlebere, Dorset recorded between Nov–Dec 1990 and 1991 (with SE); $n = 21$

	Control		Herbicide		Harvested heather shoots		Heathland topsoil		Transferred heathland turves	
	1990	1991	1990	1991	1990	1991	1990	1991	1990	1991
Ericaceous seedlings	—	—	0·1 (0·1)	—	—	—	—	—	—	—
Calluna vulgaris	0·8 (0·4)	0·2 (0·2)	—	—	44·1 (5·8)	30·3 (5·3)	421 (21)	286 (28)	292 (24)	484 (37)
Erica cinerea	—	—	—	—	9·9 (2·5)	14·3 (4·1)	11·4 (3·0)	57·4 (8·5)	15·9 (4·7)	34·2 (12·9)
Erica tetralix	—	—	—	—	—	—	0·1 (0·1)	0·3 (0·2)	13·6 (3·3)	16·4 (4)
All heathers	0·8 (0·4)	0·2 (0·2)	0·1 (0·1)	—	54 (7·9)	44·6 (8·8)	432 (22)	344 (27)	321 (26)	534 (39)
Ulex minor	—	—	—	—	—	0·1 (0·1)	17·9 (2·4)	15·7 (1·9)	8·4 (2·8)	8·3 (2·8)
Molinia caerulea	—	—	—	—	—	—	12·0 (2·1)	10·5 (1·8)	Not recorded	Not recorded
Agrostis curtisii	—	—	—	—	0·1 (0·1)	0·1 (0·1)	0·4 (0·2)	1·1 (0·4)	—	—
Polygala serpyllifolia	—	—	—	—	—	—	—	1·4 (0·5)	—	0·3 (0·2)
C. vulgaris fragment	—	—	—	—	—	—	0·1 (0·1)	0·1 (0·1)	—	—
E. cinerea fragment	—	—	—	—	—	—	—	—	—	—
E. tetralix fragment	—	—	—	—	—	—	0·6 (0·3)	0·6 (0·3)	—	—

Table 6. Variance ratios (with significance) summarizing the split plot ANOVA which compares the log-transformed number of ericaceous seedlings (*Calluna* and *Erica cinerea*) per m^2 separately and in total on the heathland restoration trials at Middlebere, Dorset in 1990 and 1991

Interaction	df	All heathers	*Calluna vulgaris*	*Erica cinerea*
Block	2	0·32 NS	1·52 NS	3·61 NS
Treatment	4	262***	579***	24·2***
Year	1	0·01 NS	2·15 NS	33·4***
Year × treatment	4	2·20 NS	2·91 NS	22·4***

*** $P < 0{\cdot}001$; NS = not significant; df = degrees of freedom.

Table 7. A comparison of shoot frequencies (mean ± SE) of heathland plant species per m^2 on the heathland restoration trials at South Middlebere Heath, Dorset recorded in January 1993; $n = 45$

	Control	Herbicide	Harvested heather shoots	Heathland topsoil	Transferred heathland turves
Calluna vulgaris	3·9 ± 1·3	0·7 ± 0·4	3·9 ± 0·9	43·2 ± 4·0	90·0 ± 2·4
Erica cinerea	0·2 ± 0·2	0·8 ± 0·4	8·5 ± 2·0	21·8 ± 2·3	9·7 ± 1·8
Erica tetralix	—	—	—	1·0 ± 0·3	4·6 ± 1·0
Ulex minor	0·3 ± 0·2	0·2 ± 0·2	0·04 ± 0·04	12·5 ± 2·0	4·9 ± 1·5
Molinia caerulea	—	—	—	2·6 ± 0·6	7·8 ± 1·0
Agrostis curtisii	3·2 ± 1·4	2·8 ± 0·8	0·8 ± 0·4	0·4 ± 0·2	2·8 ± 0·7

Table 8. Variance ratios (with significance) of the ANOVA which compare the frequency of occurrence of heathland plant species in random quadrats on heathland restoration trials at Middlebere, Dorset recorded in 1993

Interaction	df	*Calluna vulgaris*	*Erica cinerea*	*Ulex minor*	*Agrostis curtisii*
Block	2	2·21 NS	0·41 NS	1·48 NS	0·37 NS
Treatment	4	20·0***	19·1***	51·5***	19·5***

Significant differences between block, treatments, and treatments within blocks are indicated as follows: *** $P < 0{\cdot}001$; NS = not significant; df = degrees of freedom.

Table 9. Changes in the mean shoot frequencies of the heathland turf between 1989 and 1993

Species	Turf donor site 1989 ($n = 30$) Mean (SE)	Middlebere recipient site 1993 ($n = 45$) Mean (SE)	Meanchange1989–1993	*P*
Calluna vulgaris	87·3 (2·8)	90·0 (2·4)	2·7	NS
Erica cinerea	12·3 (3·1)	9·7 (1·8)	−2·6	NS
Erica tetralix	58·5 (4·5)	4·6 (1·0)	−53·9	***
Ulex minor	6·9 (1·6)	4·9 (1·5)	−2·0	NS
Molinia caerulea	10·3 (1·5)	7·8 (1·0)	−2·5	NS
Agrostis curtisii	0·90 (0·71)	2·78 (0·75)	1·88	NS

*** $P < 0{\cdot}001$; NS = not significant.

the herbicide treatment were much lower than those of the controls. This may have been because the application of herbicide destroyed or damaged many of the naturally regenerating heather bushes and there was little or no regeneration from the seed bank which was found to be small (Pywell 1993). After 4 years the harvested shoots treatments had about the same frequency of *Calluna* shoots as the controls, but a much greater number of *E. cinerea* shoots. The total number of individual heather plants was higher on the shoots treatments compared with the controls because the naturally occurring bushes were much older and larger, and hence had a greater shoot frequency. Also there were likely to be considerably more seedlings contributing to the shoot frequency on this treatment in future years. Like the control plots, *U. minor* and *M. caerulea* were missing or poorly represented on the shoots treatment. In contrast, the overall frequency of occurrence of heathland plant species in both the topsoil and turf treatments was similar to that of the donor vegetation, but the proportion of each species was different. ANOVA of the mean proportion of quadrats containing heathland species showed there were no significant differences between blocks, but highly significant differences ($P < 0.001$) between treatments (Table 8).

A comparison of the shoot frequencies of the vegetation of the donor site in June 1989 with those of the transferred turf plots in January 1993 showed that *E. tetralix* had declined significantly ($P < 0.001$) in abundance (Table 9), but the frequency of the other species remained largely unaltered. The loss of *E. tetralix* caused the plant community to change from one which was transitional between humid and dry heathland (H3—H2; Rodwell 1991), to one typical of dry heath only (H2). This suggested that the soil drainage characteristics of the donor and recipient sites were different and the soil moisture regime of the turves was altered by cutting at a depth of 150 mm.

Discussion

The comparison of soil chemistry suggested that the soil of abandoned farmland was more fertile than the adjacent heathland soil. This was probably due to past additions of fertilizer and lime, and the possible increase in phosphorus adsorption capacity of the soil which would have resulted from the ploughing and mixing of the soil. The effects of liming appeared to be persistent as the pH was still much higher than that of the heathland soil some 6 years after the end of farming. This influences soil fertility indirectly both by increasing the rate of microbial mineralization and through its effects on ion solubility and the non-labile nutrient pools (Gough & Marrs 1990).

The control treatments showed that since the end of farming there had been significant natural regeneration of heather within the grassland. It is likely that the soil fertility is still sufficiently high to allow the grasses and perennial herbs to remain competitive, thus reducing the occurrence of microsites suitable for germination and establishment of heathland species. Most heather seedlings germinated in the bare areas under existing heather bushes and rarely survived until the following year. Without significant recruitment into the population it is possible that these heather bushes will become degenerate and die without being replaced by younger heather plants.

The destruction of the grassland sward with herbicide killed many of the naturally recolonizing heather bushes. One possible reason for the poor heather regeneration following this treatment was the presence of a mat of dead vegetation preventing light from reaching the small heather seed bank in the soil (Pywell 1993). It is recommended that following herbicide treatment, the soil surface should be scarified or disturbed in some other way to expose the seed bank and provide microsites for germination, and a source of heathland plant propagules should be applied where necessary. Herbicide application followed by the addition of heathland litter has been used successfully to re-establish heathland vegetation in experiments at upland and lowland sites in north west Britain (N. Michael & P.D. Putwain, unpublished). When using herbicide treatments it is also important to consider the potentially harmful side-effects on the fauna and surrounding plant communities.

Following the application of herbicide, the plant community which replaced the grass sward was much more open, and contained more ruderal species and bryophytes. Despite the destruction of the vegetation it is likely that many of the nutrient producing processes in the soil continued to operate, but there was little or no uptake by the vegetation. Consequently, there were likely to have been greater nutrient losses by leaching and erosion (Marrs & Gough 1989; Marrs 1993). Although the application of herbicide appeared to have no immediately beneficial effects on heather regeneration, the apparent loss of fertility may cause gaps in the vegetation which could enable heather regeneration in subsequent years.

Heather seedling recruitment was much greater following the application of harvested shoots and seed capsules. Cultivation appeared to remove temporarily the competition from the grasses and they were prevented from immediately re-invading the site by the mulching effect of the woody shoots. It is likely that the shoots provided protected microsites for the germination and recruitment of some of the large numbers of seeds contained in this material. Compared with the other sources of heathland plant propagules, harvested heather shoots are a cheap, renewable, and relatively abundant resource. It is possible that an excessively high rate of material was applied to the plots in places so that light was not able to reach the seeds or seedling radicals were prevented from reaching the soil (Putwain & Rae 1988). In other heathland restoration trials on mineral wastes successful heather regeneration has been achieved by applying harvested shoots at the rate of $1.8\,\mathrm{kg\,m^{-2}}$ (Pywell 1993). At this rate of application it would be possible to restore heathland vegetation on approximately twice the area harvested. The main disadvantage with this resource is that some of the heathland plant species found on the donor site were poorly represented or absent on the trial plots. It may be necessary to sow seed or transplant container grown specimens of these species if a representative heathland plant community is to be restored.

In contrast, seedlings of heathland plant species were both more numerous and diverse on the heathland topsoil treatment. All the heathland plant species present in the vegetation of the donor site occurred on this treatment, but the relative proportion of each species had markedly changed from those found in the glasshouse seed bank determination. It is possible that the shift in dominance from *E. tetralix* to *Calluna* can be explained by differences in soil drainage conditions at the two sites. The donor site had seasonally impeded soil drainage, whereas the farmland site had freely drained soil. The germination and establishment of *E. tetralix* has been shown to be markedly depressed on dry soils, whereas *Calluna* established well and showed greater root development (Bannister 1964). The increased abundance of *U. minor*, *M. caerulea* and *Polygala serpyllifolia* Hose were probably due to the disturbance of the soil.

Some fragments of heather species survived cultivation of the soil. These improved the visual appearance of the trial plots and acted as sources of seed. However, topsoil is a relatively scarce source of propagules and its availability is usually associated with the destruction of a heathland elsewhere. Despite this it is possible to restore heathland vegetation successfully on an area three times greater than that destroyed at this rate of application, and up to five times the area destroyed on mineral wastes (Pywell 1993). It is possible that small amounts of topsoil can be produced in a renewable way from firebreaks, or if turf-cutting or turbary is used to reduce the fertility of heathland soil. However, this management technique is not widely used at present.

It is possible to restore heathland vegetation on farmland using both harvested shoots and heathland topsoil, but it will be several years before the cover of heather is complete. During this time, weed invasion will be a problem and the land will look neglected. The translocation of blocks of heathland turf rapidly and effectively recreated the heathland plant community within the grassland. Even following the death of some of the plants due to drought, regeneration from seed rapidly produced a dense cover of heather seedlings. *Erica tetralix* occurred in slightly higher numbers on the transferred turf than on the topsoil treatments. This may be because the turf retained some of the soil drainage characteristics of the donor site, and the dead heather stems provided some protection for the seedlings. It is also possible that the irrigation of the turves in the summer of 1989 had some beneficial effects on seedling germination in the winter of 1990 and 1991. Other heathland species occurred in lower densities than on the topsoil. This was probably due to the lack of soil disturbance on the turf and the persistence of the heather litter layer. Furthermore, it is likely that some of the heathland invertebrate fauna were also transferred with the turf. However, heathland turf transfer also involved the destruction of the donor site and cannot increase the area of heathland as effectively as the other sources of propagules can. In addition, this study has shown that care must be taken when matching the drainage characteristics of the donor site with that of the recipient site. Fortunately, the donor site supported humid—dry heath vegetation (H3—H2), which contained most of the plant species present in dry heath (H2), but in different proportions. When the turf was transferred to the more freely drained farmland soil the proportions of each species simply changed to suit the drainage conditions. However, if wet heath were transferred to dry sites or *vice versa* then some of the key plant species may not be present in the donor vegetation.

Compared with other restoration techniques, both harvested shoots and topsoil are bulk materials which are relatively cheap to collect, transport and apply to the recipient site (Pywell 1991). In contrast, the translocation of heather turves is a very expensive operation because only relatively small areas of turf can be transferred at any one time. There are also the high costs of site preparation and supervision of the operation by a skilled ecologist. The translocation of heathland turves is, therefore, not practical for the restoration of large areas of farmland to heathland, but is probably more applicable to visually sensitive areas and to the creation of 'refuge islands' of mature heathland within large areas where heath is regenerating from shoots or topsoil so that as the seedling plants grow they become colonized by heathland invertebrate fauna which have survived on these 'islands'.

To summarize, treatment with herbicide without soil disturbance proved to be an unsatisfactory method for the reconstruction of heathland. The best result was obtained by translocating turves; however, this method is expensive and results in the destruction of existing heathland. The most rapid regeneration of a diverse heathland community resulted from the application of heathland topsoil. Although this method enabled three to five times the source area to be treated, it also resulted in the destruction of existing heathland. The application of harvested heather shoots with seed capsules provided a satisfactory method to reconstruct heathland. Although the resulting community was less diverse than applying topsoil, the method was cheap, and the material is abundant and renewable. Furthermore, this method can be used in conjunction with routine heathland management, such as mowing firebreaks or the rotational cutting of blocks of heathland to create a mosaic of vegetation with different age structures.

Acknowledgements

This work was supported by a Research Studentship to RFP from the Joint Programme of the Science and Engineering Research Council, and the Economic and Social Research Council. BP International Ltd provided additional financial support which enabled the field trials to be set up on land made available by the National Trust. We would like to thank the Royal Society for the Protection of Birds and ARC (Southern) for providing sites for the collection of heathland propagules, and W. Bond of Holme Estates who undertook the translocation of heathland turves. We are grateful to R.T Clarke and R.J. Rose for advice and discussion.

References

Aerts, R. & Berendse, F. (1988) The effects of increased nutrient availability on vegetation dynamics in wet heathlands. *Vegetatio*, **76**, 63–69.

Aerts, R., Berendse, F., de Caluwe, H. & Schmitz, M. (1990) Competition in heathland along an experimental gradient of nutrient availability. *Oikos*, **57**, 310–318.

Allen, S.E. (ed.) (1989) *Chemical Analysis of Ecological Materials*. Blackwell Scientific Publications, Oxford.

Bakker, J.P. (1989) *Nature Management by Grazing and Cutting*. Kluwer, Dordrecht.

Bannister, P. (1964) The water relations of certain heath plants with reference to their ecological amplitude. I. Introduction, germination and establishment. *Journal of Ecology*, **52**, 423–432.

Countryside Commission (1991) *Application Pack for Countryside Stewardship*. Countryside Commission, Cheltenham.

Farrell, L. (1989) The different types and importance of British heaths. *Botanical Journal of the Linnean Society*, **101**, 291–299.

Gimingham, C.H. & de Smidt, J. (1983) Heaths as natural and semi-natural vegetation. *Man's Impact on Vegetation* (eds M.J.A. Werger & I. Ikusima), pp. 185–199. Junk, The Hague.

Gough, M.W. & Marrs, R.H. (1990) A comparison of soil fertility between semi-natural and agricultural plant communities: implications for the creation of species-rich grassland on abandoned agricultural land. *Biological Conservation*, **51**, 83–96.

Heil, G.W. & Bruggink, M. (1987) Competition for nutrients between *Calluna vulgaris* (L.) Hull and *Molinia caerulea* (L.) Moench. *Oecologia*, **73**, 105–107.

Heil, G.W., Werger, M.J.A., de Mol, W., van Dam, D. & Heyne, B. (1988) Capture of atmospheric ammonium by grassland canopies. *Science*, **239**, 764–765.

MAFF (1986) *Environmentally Sensitive Areas*: (First report as required under section 18 of the Agriculture Act 1986). HMSO. London.

Marrs, R.H. (1993) Soil fertility and nature conservation in Europe: theoretical considerations and practical management solutions. *Advances in Ecological Research*, **24**, 242–300.

Marrs, R.H. & Gough, M.W. (1989) Soil fertility: a potential problem for habitat restoration. *Biological Habitat Reconstruction* (ed. G.P. Buckley), pp. 29–44. Bellhaven Press, London.

Moore, N.W. (1962) The heaths of Dorset and their conservation. *Journal of Ecology*, **50**, 369–391.

Newborn, D., Booth, F. & Hudson, P. (1989) Restoring heather dominant vegetation in the absence of a heather seed bank. *Game Conservancy Review, 1989*. Game Conservancy, Fordingbridge.

Putwain, P.D. & Rae, P.A.S. (1988) *Heathland Restoration: a Handbook of Techniques* Environmental Advisory Unit, Liverpool University & British Gas, Southampton.

Pywell, R.F. (1991) Heathland translocation and restoration. *History and Management of Southern Lowland Heaths* (eds M.H.D. Auld, B.P. Pickess & N.D. Burgess). Royal Society for the Protection of Birds, Sandy.

Pywell, R.F. (1993) *The Restoration of Heathland on Farmland in Southern Britain*. PhD dissertation University of Liverpool.

Rodwell, J.S. (1991) *British Plant Communities, Volume 2. Mires and Heaths*. Cambridge University Press, Cambridge.

Rodwell, J.S. (1992) *British Plant Communities. Volume 3. Grasslands and Montane Communities*. Cambridge University Press, Cambridge.

Scandrett, E. (1989) *Regenerating Heather Moorland: A Study of Methods to Encourage Regeneration of Heather* (Calluna vulgaris) *from Seed*. Macaulay Land Use Research Institute, Aberdeen.

Smith, R.E.N., Webb, N.R. & Clarke, R.T. (1991) The establishment of heathland on old fields in Dorset, England. *Biological Conservation*, **57**, 221–234.

van Breemen, N., Burrough, P.A., Velthorst, E.J., van Dobben, H.F., de Wit, T., Ridder, T.B. & Reynders, H.F.R. (1982) Soil acidification from atmospheric ammonium sulphate in forest canopy throughfall. *Nature, London*, **299**, 548–550.

Webb, N.R. (1990) Changes on the heathlands of Dorset, England, between 1978 and 1987. *Biological Conservation*, **51**, 273–286.

Webb, N.R. & Haskins, L.E. (1980) An ecological survey of heathlands in the Poole Basin, Dorset, England in 1978. *Biological Conservation*, **17**, 281–296.

Werger, M.J.A., Prentice, I.C. & Helsper, H.P.A. (1985) The effect of sod-cutting to different depths on *Calluna* heathland regeneration. *Journal of Environmental Management*, **20**, 181–188.

Received 1 January 1993; revision received 20 May 1994