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The Potential Distribution and Impact of Bracken in Upland Scotland: An Assessment using a GIS-based Niche Model

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Bracken spread could have very selective impacts on the vegetation of upland Scotland (UK). Information on this would be of value in targeting appropriate management measures. However, it is difficult to establish accurately the current distribution of bracken, so modelling bracken spread using process-based models is not possible at present. An alternative modelling approach is described which uses knowledge of the climatic, soil and topographic limits to the existing bracken distribution in upland Scotland. This knowledge is formalized as a rule-based model. This is applied through a geographical information system (GIS) to identify the maximum potential bracken niche over the whole of Scotland with a nominal spatial resolution of 1 ha. The model is validated against field data from 14 sites around Scotland. Between 64–97% of the existing bracken lies within the predicted bracken niche. Locally low accuracies are ascribed to scale-effects derived from the input datasets, the nature of the ground data, as well as the universality of the model rules. The bracken niche is differentiated into two types: continuous and discontinuous. The total area of the niche is 6036 km^2 or 7·75% of the land area of Scotland with a broad 60:40 split between the continuous and discontinuous niche types, respectively. However, there is a strong regional bias in their distribution with the discontinuous niche type principally occurring in the west of Scotland. Overlaying the potential niche on the Land Cover of Scotland 1988 dataset shows that it impacts on 70% of the national area of 'good rough grassland' and 31% of the 'poor rough grassland' category. In addition, 16% of the national area of 'heather moorland' is impacted. There are strong regional variations in these impacts which may have implications for future bracken management. The limitations of the approach are discussed and the potential for linking it to dynamic models is identified.

Key words: Bracken, uplands, Scotland, ecological modelling, spatial modelling, GIS, impact assessment.

INTRODUCTION

Bracken (*Pteridium aquilinum* (L.) Kuhn) occurs throughout the British Isles and is a member of some 36 communities identified within the National Vegetation Classification (Pakeman and Marrs, 1992). This range of contexts and the associated range in spatial configurations (i.e. from isolated fronds to dense patches or complete coverage of entire hillsides), when combined with the seasonal differences in its appearance, makes bracken a particularly difficult plant to map accurately.

A wide range of mapping and sampling techniques have been used to provide estimates of bracken extent in Great Britain. Principal amongst these are those associated with the national Countryside Surveys conducted by the Institute of Terrestrial Ecology (ITE) on behalf of the then Department of the Environment (Barr *et al.*, 1993). These include limited, detailed field surveys (1:10 000) of sample 1 km squares, selected on the basis of strata within the ITE Land Classification, and a national census of land cover, including bracken, based on the interpretation of Landsat Thematic Mapper (TM) satellite imagery. The sample-based estimates are not spatially explicit and generally have standard errors of around 33% with respect to bracken extent in the uplands (Pakeman *et al.*, this volume). The satellite land cover map has a high spatial resolution, but the mapping accuracy for bracken was shown to be very poor by Pakeman *et al.* (1996). Significantly, they pointed to seasonal effects, the spatial resolving power of the imaging system relative to the complexity of the pattern of bracken distribution, and the existence of bracken in mixed communities, as key factors contributing to these high error rates.

Similar studies on the application of both field survey and remote sensing techniques to mapping bracken have been conducted in Scotland with comparable results (see, for example, Birnie and Miller, 1986; Miller *et al.*, 1989, 1990). These studies generally discounted satellite imagery as a possible source of data, and rigorously compared aerial photography with ground based methods. The definition of what constituted 'bracken' proved a problem with both ground and air photo-based methods, and it was shown that area estimates were strongly dependent on the method of survey used. This is reflected in the range of estimates that exist for bracken extent in Scotland from 63 250 ha (Miller *et al.*, 1989), to 110 000–190 000 ha (Pakeman *et al.*, this volume) and 470 000 ha (Taylor, 1986).

It could be concluded that there is no definitive answer to the question: how much bracken is there in Scotland?

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Any answer must inevitably depend upon both the definition of 'bracken' that is used and the method employed to map it. However, the significance of bracken extent, from agricultural (Birnie, 1985; Varvarigos and Lawton, 1991), natural heritage (Pakeman and Marrs, 1992; Birnie *et al.*, 1996) and archaeological (Rees and Mills, 1999) viewpoints, means that spatially-explicit information on bracken would be valuable in developing appropriate management regimes.

It is our belief that, while it is extremely difficult to provide accurate answers to the question of how much bracken there is in Scotland, recent developments in the availability of environmental datasets with a high spatial resolution (including climate, terrain and soils) mean that it is possible to answer the related question: how much bracken could there be in Scotland?

The aim of this study is to describe the development of an ecological rule-based model for defining the potential niche within which bracken could be present, and to apply it through a geographic information system (GIS) to previously unavailable high resolution environmental datasets. The research builds on the work of Miller (1992) and was conducted on behalf of Scottish Natural Heritage (SNH) and the Scottish Executive Rural Affairs Department (SERAD). Due to the sponsors' interest, the work focused on the potential impact of bracken on upland vegetation and specifically excluded woodland and arable land (Birnie *et al.*, 1996). The results were also summarized according to SNH management regions and this form is retained here.

The paper is in two parts. The first provides a background to the modelling and describes model development and testing. The second provides a description of the results and assesses their implications in terms of the geography of the bracken 'problem' in Scotland and its relative impact on upland vegetation communities.

BACKGROUND TO MODELLING

There are two principal approaches to the problem of modelling the maximum possible extent of bracken in Scotland. These can be broadly described as process-based and empirical. The principal differences between them concern the need for data on actual distributions and a knowledge of processes of vegetation dynamics. The process-based modelling approach includes that based on the concept of cellular automata. This has been applied to the problem of modelling bracken spread, first by Scott (1993, 1995) and more recently by Birch *et al.* (this volume). In this approach 'cells' identified as being occupied by bracken can expand or contract relative to adjacent cells according to heuristic, statistical or mathematical relationships concerning interactions between site conditions and plant communities. The value of this simulation modelling approach is that it can provide insights into the actual transitional dynamics of bracken spread.

Another example of process-based modelling is represented by the work of Pakeman and Marrs (1996). They developed a mechanistic physiological model to describe the yearly growth cycle of bracken (COBRA; COntrol of BRAcken) and extended it (COBRA-X) to enable scaling from site to national predictions of the effects of climate change on the growth of bracken in Britain. This model uses standard site meteorological data to compute daily changes in three compartments of a bracken stand (frond biomass, rhizome tissue biomass and rhizome carbohydrate) over the annual growth cycle. In its extended form it is driven using the 40 km × 40 km resolution Meteorological Office Rainfall and Evaporation Calculation System (MORECS) database. Running the model at this resolution provides valuable indications that bracken biomass is limited by different environmental factors in different regions of Britain. However, the authors recognized that the model predictions were for a 'typical' site and no account was taken of local site conditions or the impact of other factors such as extreme weather, bracken stand dynamics or the effects of management.

The empirical modelling approach contrasts with the process-based one in several respects, particularly in terms of data requirements, the level of ecological knowledge required and the nature of the outputs. While there are several possible empirical modelling approaches that could be used to model maximum bracken extent, including those using statistical methods such as inductive modelling (Aspinall, 1992), the method considered here is based upon a rule-based modelling approach developed originally by Miller (1992). Unlike the process-based models, this does not depend on knowledge of actual bracken distribution. However, its output is deterministic rather than stochastic and it provides no insight into transitional dynamics. It is effectively a static model, which formalizes knowledge of the existing determinants of bracken distribution and applies this knowledge as a series of rules to national spatial datasets on soils, terrain, climate, etc. This procedure defines the extent of suitable sites for bracken growth, i.e. the bracken niche. A key assumption of the approach is that the niche relates to current environmental conditions. The approach gives no insight into patterns or rates of spread and effectively provides an assessment of the worst case scenario of bracken extent in upland Scotland under present conditions.

In the absence of reliable national data on the present distribution of bracken in Scotland, it is not possible to adopt the process-based modelling approach. The rule-based approach can be used because there are existing high-resolution spatial datasets for Scotland relating to the key environmental determinants of the bracken niche. The following sections describe the formal rules employed in this study to define the bracken niche in upland Scotland.

CLIMATE AND SOIL LIMITS TO BRACKEN IN UPLAND SCOTLAND

This section considers the climatic and soil limits used to develop the rule-based model. Although bracken is a component of a large number of British plant communities (Pakeman and Marrs, 1992), field studies have indicated that it does occur within a restricted set of soil and climatic circumstances in upland Scotland.

Ader (1988, 1990) examined the effect of climate and soils on bracken distribution and vigour at four sites across Scotland over two growing seasons. She demonstrated that early season temperature (frond emergence is related to soil temperature, with a 5·5°C threshold on initiation of bud growth) is the main determinant of the east–west pattern of bracken in Scotland, with the colder and later springs of the higher eastern bracken zone delaying emergence and depressing final frond height. Winter frost is also important in the east where sub-optimal conditions lead to thin litter layers exposing underground frond primordia to frosting.

Ader (1988, 1990) also showed soil drainage to be a factor, although one which operates in rather different ways across the country. In the east, freely draining soils could be depressing vigour through drought stress, while in the west, poor soil drainage is a factor limiting bracken growth at the local site level. One of Ader's key findings was that bracken will actively colonize poorly drained gley soils and peat under dry heather moorland, but rarely or never organic soils under acid grasslands.

The depth of surface soil aeration appears to be the critical factor, and the highly variable nature of soil drainage, particularly in western Scotland, may be a prime determinant in the spatial configuration of bracken at individual sites. Nicholson and Paterson (1976) developed a typology of bracken distribution at the landscape scale. They described two broad distributional types: continuous and discontinuous. These were linked in a qualitative manner to the floristic diversity of bracken stands and the suitability of bracken as an animal habitat. The distinction between continuous and discontinuous is essentially a reflection of the heterogeneity of the local soil landscape and the terrain. Because of the ecological significance of these two distributional types they are distinguished in this study.

The field-based studies are complemented by the Scotland-wide study of the factors limiting bracken distribution conducted by Miller *et al.* (1989, 1990). They used a number of sites distributed across Scotland. At each site, bracken distribution was mapped in the field. This distributional data was correlated with data on altitude, aspect, soil type and climate. The statistical relationships provided a set of criteria which appeared to define the current limit of bracken across Scotland. The topographic factors and climatic criteria related to: altitude (land below 450 m), aspect (easterly or southerly preferred), accumulated temperature (greater than 990 °Cd per annum), and frost (low risk of late frosts). The soil criteria reflected the soil drainage status with brown forest soils and humus iron podzols preferred. These criteria are broadly endorsed by the field observations of Ader (1988, 1990).

Because we are only concerned with defining the maximum possible niche that bracken could occupy under current conditions in upland Scotland, no account is taken of other ecological factors in developing this rule-based model. Factors such as plant species competition (Watt, 1955), and the interactions between the spatial configuration of bracken patches and animal trampling (Birch *et al.*, this volume) are likely to have a strong influence on the actual pattern and rates of spread up to the limits of the niche.

DEFINING AND IMPLEMENTING THE RULE-BASED MODEL

The review of the factors which define the limit of the bracken niche in upland Scotland has identified topographic, climatic and soil factors and related threshold values. Applying this knowledge in the form of a rule-based model depends upon the availability of relevant spatial datasets at appropriate scales. Over the past 10 years, such datasets have become available, although they may be represented as if they have a common spatial resolution (e.g. in upland Scotland soils were mapped at 1:250 000, whereas land cover was mapped at 1:25 000).

The effect of the above is two-fold. Firstly, some of the datasets are of too poor a resolution to compute relevant ecological variables. For example, the 1:50 000 Digital Terrain Model (DTM) available to this study could not be used to compute reliable measures of aspect (Jones, 1998). The second effect is that these scale differences produce unknown errors when the datasets are overlaid within the GIS. These errors may be either those of commission or omission with respect to the area identified as being within the bracken niche. The extent of these effects can only be assessed indirectly by ground truthing since the niche does not necessarily map 1:1 with the current bracken distribution. However, it is reasonable to hypothesize that where we have available ground information, the area of bracken should be contained within the defined bracken niche. This logic is applied in the model validation.

The following describes the rules and the datasets used to apply them: (1) Elevation. A 450 m upper elevation limit was used (Miller *et al.*, 1989; Miller, 1992). It was applied to a 100 m raster version of the 1:50 000 based Ordnance Survey DTM (Ordnance Survey, 1996), which has a 0·1 m vertical resolution. The land area below 450 m is 71 267 km^2 (91% of the country). (2) Soils. The soil criterion was based upon the following major soil subgroups identified within the map units of 1:250 000 Soil Survey of Scotland (MISR, 1984): brown forest soils; brown forest soils with gleying; humus-iron podzols. Because of the scale of original mapping, map units often contain several component soils. As a consequence, all those map units which contain these three major soil subgroups either as dominant or subdominant components were included as being suitable for bracken. (Note: Where these are subdominant the effect of including the whole map unit will be to over-estimate the area of the niche). In total, 324 out of the 580 map units identified by the Soil Survey were included within the niche (Table 1). This covers an area of 36 343 km^2 (48% of the country). The soil criterion was applied to a 100 m raster version of the 1:250 000 soil map of Scotland. (3) Climate. The climatic criterion was limited to use of a growth threshold value of 990°Cd per annum. No high spatial resolution data were available for numbers of frost-free days. The threshold was applied to a 1 km resolution climate database. This was developed by Matthews *et al.* (1993, 1994) using monthly temperature data from the

TABLE 1. *Areas of the major soil subgroups identified as being within the bracken niche (brown forest soils: brown forest soils with gleying; humus iron podzols) according to their occurrence as dominant or subdominant components within 1:250 000 soil map units*

Description	No. of soil map units	Area (km^2)	% Scotland
A. 100% one soil	41	6146	7·8
B. One dominant/one subdominant	31	5978	7·6
C. One dominant/other types sub.	101	11 295	14·3
D. 2 subdominant	2	444	>1·0
E. 50% dominant + subdominant	9	323	>1·0
F. 50% dominant no subdominant	65	6943	8·8
G. 33% dominant	7	408	>1·0
H. 25% dominant	5	185	>1·0
I. Only appears as subdominant	65	4621	5·9
Total within niche		36 343	48·0
Total outside niche		42 435	52·0
Total area of Scotland		78 778	

Meteorological Office for the reference period 1951–80. The monthly temperature surfaces were estimated using trend surface analysis/stepwise multiple linear regression to establish the relationship between altitude, geographic location, and distance to the sea. Final surfaces were produced by interpolation of the residuals from the trend surface using a kriging procedure. Accumulated temperatures were calculated by fitting a sinusoidal curve to the monthly temperature values using Fourier Analysis. The accuracy of this method is high close to the original observation stations, but may decay with distance away from them. The total area of Scotland that lies above this threshold (i.e. inside the climatic bracken niche) is 55 917 km^2 (71% of the country). (4) Landform. A distinction was made between continuous and discontinuous bracken niche (following Nicholson and Paterson, 1976). This was done on the basis of landform. Within the 1:250 000 soil map of Scotland, soil map units are described on the basis of landform (MISR, 1984). Those soil map units identified as being rocky and/or having undulating, rugged or complex strong slopes were allocated to the discontinuous bracken niche type. All other rockiness/landform combinations were allocated to the continuous niche type. This rule was applied to the 100 m resolution 1:250 000 digital soils map. The result was some 2503 km^2 being classified as discontinuous niche and some 4056 km^2 as continuous. (NB: Only soil map units that were identified as fulfilling the soil criteria were sub-divided in this way). (5) Existing land cover. Because the bracken niche was to relate specifically to non-wooded upland areas of Scotland, known areas of woodland, arable ground, improved pasture and built-up land were excluded. This rule was applied using the 100 m raster version of the 1:25 000 Land Cover of Scotland 1988 (LCS88) produced from interpretation of national air photo coverage obtained between 1987–89 (MLURI, 1993). Validation of this dataset revealed that interpretation error is very low for the agricultural land classes and built-up areas but woodland cover had rates of 14·7%. However, this was generally due to confusion between woodland categories. Because all the LCS88 woodland has been grouped together here, it is assumed that there are few errors deriving from this data element.

Each of these five data elements was created by recoding the relevant source dataset. (Details of the exact recodings are not presented here but are available from the authors). They were combined using the overlay function within an ARC/INFO GIS environment (ESRI, 1997). The output is the putative maximum bracken niche map given in Fig. 1.

VALIDATION OF THE MODEL OUTPUT

Validation of a GIS output that represents a potential rather than an actual bracken distribution is uncommon as, by definition, the feature of interest (i.e. bracken) may not be present at the time of validation. The approach adopted was that ground information on existing bracken distribution should be 'contained' within the potential bracken niche. This should hold true except where errors in, or scale effects due to, the original data inputs have propagated through to the output.

There are two possible sources of extensive 'ground' information on bracken distribution in Scotland. The first relates to the original field survey work of the present authors and others in the course of a bracken mapping project for the then Scottish Office Agriculture, Environment and Fisheries Department, now SERAD (Miller *et al.*, 1989). This exists as a series of annotated 1:50 000 OS map sheets for 14 areas around Scotland.

A second possible source is the LCS88 dataset where bracken was interpreted as a land cover feature within the semi-natural vegetation category. This source was, however, discounted because of the generally low accuracy achieved, as measured by the associated validation (MLURI, 1993).

In view of the above, the 1:50 000 annotated map sheets, relating to field work conducted between 1985 and 1988, were used as the source of ground information. Although the maps were nominally 1:50 000 representations it was recognized that the locational error associated with the rapid field mapping would be best accommodated by representing the distribution in terms of bracken coverage at 1 km^2 resolution. The field maps were therefore digitized on the basis of the 1 × 1 km OS grid using classes of bracken cover: no bracken; <25% bracken: >25% bracken. Where grid cells had areas of water within them,

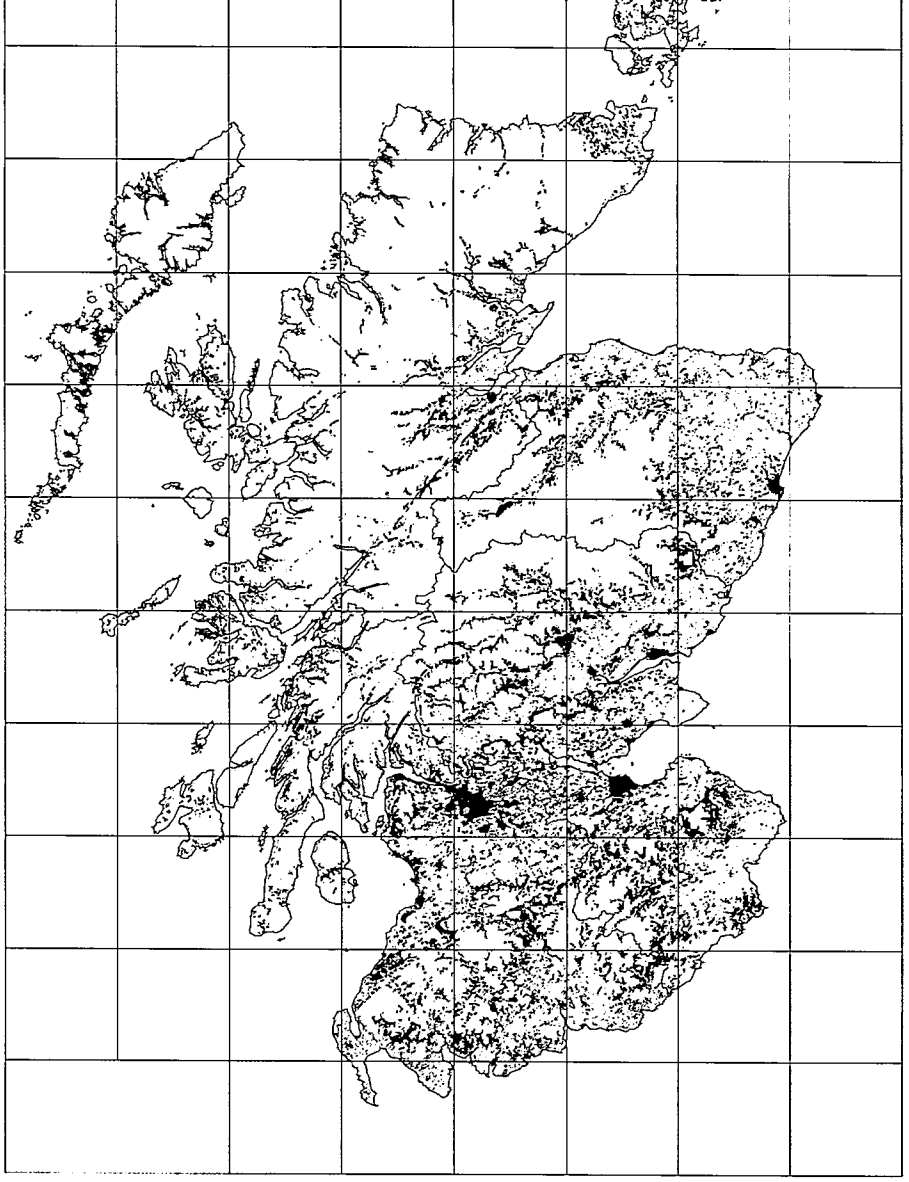

FIG. 1. Distribution map showing the breakdown of the continuous (red) and discontinuous (green) bracken niche types across Scotland. Black indicates built-up land. Nominal spatial resolution is 1 ha.

the area estimates were based upon land area. To provide a comparable dataset for validation purposes, the 100 m raster version of the potential bracken niche was summarized in an identical way. This procedure provided a validation dataset covering some 2996 km^2 or about 3·8% of Scotland.

The results of the validation exercise are summarized in Tables 2 and 3. Table 2 provides an example of the confusion matrices that were obtained for each of the 14 sites. It relates to the area located around Gatehouse of Fleet in south-west Scotland (Fig. 2). The matrix summarizes the field observations of bracken presence compared to the predicted bracken niche. The observations are shown as the columns with the bracken niche summarized in the rows. The values are the number of 1 km squares which fall into the appropriate intersections of the rows and columns.

Because the bracken niche is not an estimate of actual bracken distribution we assume that all the existing bracken should fall within the bracken niche. Therefore in this analysis we are only concerned with the number of cases where bracken is observed outside the limits of the predicted niche. These are errors of omission and are obtained by summing the appropriate cells in the 'no bracken' row and expressing them as a percentage of the total number of observations. For the Gatehouse example, five of the 186 observations are cases of omission, i.e. 2·7%.

TABLE 4. *Breakdown of the potential bracken niche according to type and SNH management region (see also Fig. 1)*

SNH Region	Region (km²)	Bracken niche (km²)	Continuous (% of niche)	Discontinuous (% of niche)
North-west	26 439	1072	38	62
North-east	13 806	806	72	28
South-west	20 185	2107	22	78
South-east	18 155	2051	68	32
Scotland	78 585	6036	62	38

TABLE 5. *National breakdown of bracken niche relative to LCS88 land cover summary categories*

LCS88 land cover class	National area (km²)	Area of bracken niche	Percentage of national total (%)	Percentage in bracken niche type	
				Continuous	Discontinuous
Good rough grassland	2472	1742	70	70	30
Poor rough grassland	2011	619	31	85	15
Bracken*	(117)	(79)	(67)	(43)	(57)
Heather moorland	6881	1124	16	66	34
Peatland	6600	284	4	56	44
Heather moorland/peatland	12 371	421	3	29	71
Poor rough grassland/heather moorland	3230	416	13	57	43
Good rough grassland/heather moorland	1453	479	33	55	45
Good rough grassland/poor rough grassland	848	386	46	69	31
Good rough grassland/bracken*	(661)	(375)	(57)	(42)	(58)
Poor rough grassland/peatland	634	74	12	38	62
Heather moorland/montane	540	33	6	30	70

*Note that the bracken land cover class as interpreted by LCS88 has a very low accuracy and is included here for completeness. This accounts for some 21% of the interpreted bracken as being outside the niche.

higher percentages in the discontinuous niche type, but not exclusively so.

Table 5 also shows that the LCS88 feature 'peatland' has been impacted by the bracken niche to a small degree. This is probably due to the fact that 'peatland' vegetation is not exclusively associated with deep peat soils. These were removed in the definition of the bracken niche, using the soils dataset. Therefore, the remaining 'peatland' vegetation is likely to be on shallower organic soils which could be colonized by bracken (Ader, 1988, 1990).

In order to reveal major regional differences only the results relating to the single LCS88 cover classes most impacted by the bracken niche have been summarized at the regional level in Table 6. These indicate that for both the 'good rough grassland' and the 'poor rough grassland' categories there would be a bias of impact towards the south-east and south-west SNH management regions. This is particularly true for the 'poor rough grassland' category with hardly any falling in the two northern regions. For 'heather moorland' there is no strong regional trend: all regions are impacted.

With respect to regional trends in the associations between land cover category and type of bracken niche, although all of the 'good rough grassland' shows a bias towards the continuous niche type, this holds more true for the eastern regions.

In summary, therefore, the output from the present implementation of the rule-based model indicates that the most severally impacted land cover category would be 'good rough grassland' and this would be most pronounced, in terms of area, in the two southern SNH management regions. Clearly, these results can be represented at much finer spatial resolutions to provide a more site-specific indication of impact. This is, however, outside the scope of this paper.

DISCUSSION AND IMPLICATIONS

This study has shown that it is possible to develop and apply a rule-based modelling approach to define the potential bracken niche in upland Scotland at a comparatively high spatial resolution (i.e. 1 ha). The approach, as implemented here, represented only one realization of this potential niche. The method can be adapted to provide a range of different realizations which might reflect changes in the cut-off criteria used for the rules. For example, the niche could be expanded or contracted by relaxing or tightening the altitudinal limits.

The validation of the model output tends to suggest locally variable accuracies. Further exploration of the reasons for these might improve our understanding of how local factors interact with the more general rules in influencing the local distribution of bracken. This concept that different environmental factors limit bracken in different regions is also reflected in the findings of Pakeman and Marrs (1996). However, any follow-up study would also have to take into account the other factors which might influence these error rates, namely scale-dependent effects associated with the input data, their accuracy and also the accuracy of the ground information.

TABLE 6. *Single land cover classes most impacted by the bracken niche summarized by SNH management region and bracken niche type*

	North-east			North-west		
SNH Region	Niche (km^2)	Continuous (%)	Discontinuous (%)	Niche (km^2)	Continuous (%)	Discontinuous (%)
Good rough grassland	255	82	18	229	59	41
Poor rough grassland	7	48	52	10	41	59
Bracken	2	42	58	19	20	80
Heather moorland	306	71	29	286	28	72
	South-east			South-west		
SNH Region	Niche (km^2)	Continuous (%)	Discontinuous (%)	Niche (km^2)	Continuous (%)	Discontinuous (%)
Good rough grassland	620	78	22	639	63	37
Poor rough grassland	314	88	12	287	84	16
Bracken	9	65	35	50	48	52
Heather moorland	425	83	17	106	83	17

The results of this one realization of a rule-based model strongly endorse the view that bracken encroachment is a particular problem associated with low intensity agricultural land. The finding that around 70% of the 'good rough grassland' in Scotland is impacted would be of great concern to both the agricultural and nature conservation communities.

Looking forward, there are several opportunities for developing this work further. It is recognized that the lack of reliable data on actual bracken distribution is a major limitation in the application of dynamic models of bracken spread (e.g. Birch *et al.*, this volume). There is potential to combine the high spatial resolution approach developed here with a more process based approach. One particularly interesting issue is that identified by Birch *et al.* (this volume) concerning the interactions between patch size and grazing. Since the present national study has differentiated between types of bracken niche on the basis of spatial configuration, there is an opportunity to scale-up some of their findings.

From a management point of view, this national assessment also provides an opportunity to develop some strategic policies concerning the spatial targeting of bracken control in upland Scotland (see also Pakeman *et al.*, this volume).

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