

Prediction of conifer natural regeneration in a 'data-poor' environment

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Summary

Recent moves towards the increased use of 'continuous cover' and 'low-impact' methods of managing conifer forests in Britain have led to greater interest in natural regeneration. This paper describes a project that designed and tested a model to predict the likelihood of natural regeneration in an environment where long-term datasets were not available. A spreadsheet based model known as REGGIE (REGeneration Guldance) was designed based on first principles and silvicultural experience. It was tested on 129 sites of four conifer species on a wide range of sites throughout Britain; at each site an expert judged the likelihood of regeneration in the next 5 years in one of five classes: 0-20%, 21-40%, 41-60%, 61-80% and 81-100%. The REGGIE model agreed with the expert prediction on 63 of the 129 sites (48.8%). The validation data were then analyzed using an ordinal logistic regression. The minimal adequate model included fewer terms compared with REGGIE and, not surprisingly, was more accurate with respect to the expert prediction on 113 of the 129 sites (87.6%). An advantage of the ordinal logistic model is that we have devised a simple score based method of application which is easy to apply in the field. Informal validation of this model has suggested that it has potential to be used by forest managers as part of a strategy to raise understanding of how to use natural regeneration when transforming conifer stands to continuous cover in Britain.

Introduction

Using natural regeneration to reduce costs is one of many paradoxes in forest management. Success leads the manager to claim that plans to utilise what is freely produced by the surrounding trees were fully justified. Failure, or partial success, can result in significantly increased costs to pursue agreed plans for the area. However, in some forest ecosystems this uncertainty about natural regeneration has been replaced by confidence that it will work. Examples include stands of loblolly pine (*Pinus taeda* L.) and shortleaf pine (*Pinus echinata* Mill.) in the south-eastern United States (Shelton and Cain, 2000; Lynch *et al.*, 2003); hardwood forests of the Alleghenies in the northeast United States (Marquis, 1994); oak (*Quercus robur* L. and *Q. petraea* (Matt.) Liebl.) and beech (*Fagus sylvatica* L.) forests in northern France (Evans, 1982) and Scots pine (*Pinus sylvestris* L.) in parts of Scandinavia (Tegelmark, 1998). In each of these situations the confidence of success can be attributed to a combination of factors: good silvicultural knowledge about the species and sites; a long-term plan to use natural regeneration; flexible and opportunistic management systems; management control of animals and undesirable elements of the ground flora.

Forest scientists throughout the world have sought to help forest managers by developing

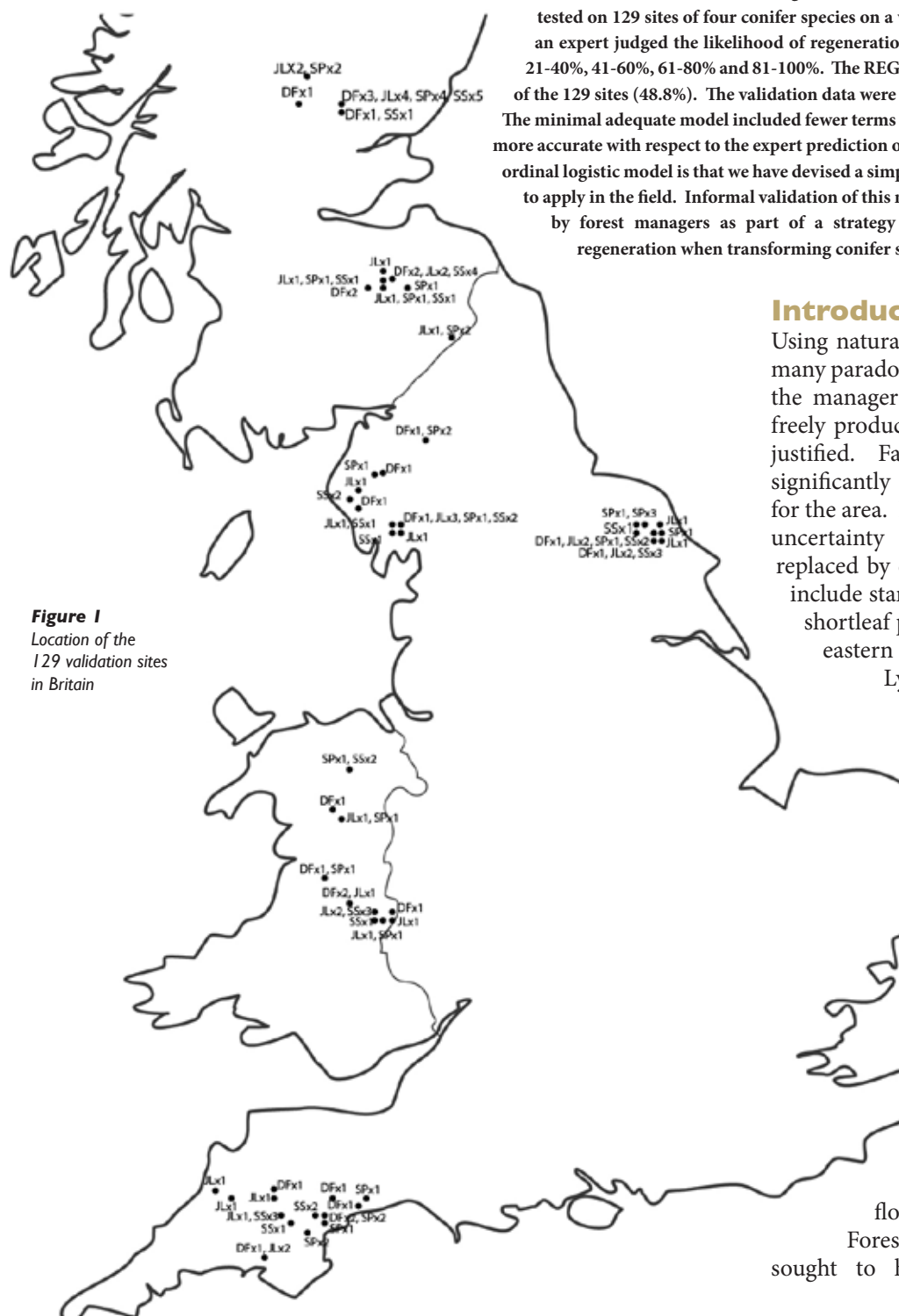


Figure 1
Location of the
129 validation sites
in Britain



Plate 1
A stand of heavily thinned Norway spruce with a well developed ground flora; prospects for natural regeneration are poor.

silvicultural tools that assess the adequacy of the regeneration potential of a stand of trees. In general the approach has been to use statistically derived models that are heavily dependent on relevant data. For example, several models have been developed for

Table 1 Description of main factors in REGGIE

Species	Main data points in relationship between age and probability of natural regeneration (age [years], probability [%])			
	Coning starts	Max. coning-start	Max. coning-end	Final
<i>Abies grandis</i>	40, 0	45, 75	70, 75	200, 68
<i>Abies nobilis</i>	20, 0	40, 75	80, 75	200, 68
<i>Larix</i> spp.	15, 0	40, 60	80, 60	200, 54
<i>Picea abies</i>	30, 0	50, 60	80, 60	200, 54
<i>Picea sitchensis</i>	30, 0	40, 90	70, 90	200, 81
<i>Pinus contorta</i>	15, 0	30, 80	60, 80	200, 72
<i>Pinus nigra</i> *	25, 0	60, 50	110, 50	200, 45
<i>Pinus sylvestris</i>	15, 0	60, 90	120, 90	200, 81
<i>Pseudotsuga menziesii</i>	30, 0	50, 70	80, 70	200, 63
<i>Thuja plicata</i>	20, 0	40, 80	80, 80	200, 72
<i>Tsuga heterophylla</i>	30, 0	40, 90	80, 90	200, 81

Brief description of other factors in REGGIE

(Figures in brackets indicate the modifying effect of each factor level)

Coning	Heavy (+0%); Moderate (-10%); Light (-40%); see Table 2
Ground flora	The cover of favourable vegetation (bare ground and mosses) is X in the model $Y=A + BR^x$ where $A=-1.1526$; $B=-92.10$; $R=0.9386$ and Y gives the reduction in probability.
Soil nutrient regime	Very poor or poor (0%); medium (-5%); rich or very rich (-20%)
Deer Impact Index	Low (0%); Medium (-15%); High (-40%); see Table 2
Advance regeneration	Increase overall probability between $\times 1.0$ and $\times 1.2$ depending on densities of seedlings and saplings; see Kerr (2006) for details

* Corsican pine (*Pinus nigra* subsp. *laricio*)

oak-dominated forests in North America (Rogers and Johnson, 1998); the work of Ferguson *et al.* (1986) focussed on the grand fir-cedar-hemlock forests of the northern Rocky Mountains; recruitment of Norway spruce (*Picea abies* L.) has been studied in Austria by Schweiger and Sterba (1997) and models for white spruce (*Picea glauca* (Moench) Voss) have been published by Fox *et al.* (1984) and Stewart *et al.* (2001). A slightly different hybrid approach was taken by Pukkala (1987) for Scots pine, Norway spruce (*Picea abies* L.), and birch (*Betula pendula* Roth. and *B. pubescens* Ehrh.) in Finland. He used model parameters obtained from past investigations along with 'author proposed' ones where data were not available.

In contrast to the above 'data-rich' examples the position in Great Britain is 'data-poor'. Natural regeneration has only been studied for a relatively short period of time and datasets on which to base statistically derived models do not exist. Therefore, to satisfy the demand from forest managers for better guidance on natural regeneration of conifers, a different approach was required. After careful consideration we decided to construct a model based on first principles, using a combination of published data and our own silvicultural experience. The objectives of this paper are therefore to:

- outline the construction of this model, known as REGGIE (**REG**eneration **G**uidance **E**).
- Describe the results of the model validation
- Present an improved model formed by analysis of the data collected to validate REGGIE.

**Plate 2**

Cones on the ground are a good sign that the stand is producing viable seed

Material and methods

Description of REGGIE

The REGGIE system is a spreadsheet based model designed to improve understanding of natural regeneration of conifers when managing forests using continuous cover silviculture in Britain. It was based on the knowledge and experience of a number of Forest Research staff and uses first principles in an attempt to quantify the probability of obtaining natural regeneration. The main output from the model is an estimate of the *probability that successful natural regeneration will be achieved during a five year period*. Successful regeneration is defined as achieving 2,500 seedlings (>50 cm tall) per hectare with an assumption of a reasonable distribution across the site.

Table 2: Description of Deer Impact Index and coning assessment

Deer Impact Index		
	Description	Evidence used to allocate index
Low	No deer or browsing mammals present, no visible signs of impact; Zero animals 100 ha ⁻¹	No browsing observed on seedlings and saplings.
Medium	Deer or browsing mammals present, some visible signs of impact; <5 animals 100 ha ⁻¹	Browsing damage on up to 25% of seedlings and saplings.
High	Deer or browsing mammals present, visible signs of impact are common; >5 animals 100 ha ⁻¹	Browsing damage on >25% of seedlings and saplings.
Coning assessment		
Light	A few cones (<50) on about one tree in 50	
Moderate	A significant number of cones (50-100) visible on 25-50% of trees	
Heavy	A large number of cones (>100) on 5-10% of trees, a significant amount on many others and at least a few cones on nearly every other tree	

The model is designed for all the conifers listed in Table 1. An important assumption is that the probability of obtaining successful natural regeneration is nil until the age at which coning starts, increases at a linear rate until the age of maximum seed production and is then constant until the age when maximum seed production ends. After this the probability declines between the end of maximum seed production and 200 years at a linear rate by 10%. The timings were based on values in Gordon (1992; Table 7.1) and the relative values of probabilities between species were established using knowledge and experience of Forest Research staff.

The initial probabilities based on seed production are for optimal conditions (Table 1). REGGIE then adjusts the probability depending on the observed level of coning (Table 2); the cover of favourable ground vegetation for natural regeneration (bare ground and mosses); soil nutrient regime (SNR) (Pyatt *et al.*, 2001) using information on the likelihood of regeneration from Nixon and Worrell (1999; Figure 4.3); Deer Impact Index (Table 2); and the presence of advance regeneration of canopy species present as seedlings or saplings (Table 1).

Collection of validation data

To validate REGGIE it was decided to concentrate on four of the most common species: Sitka spruce (*Picea sitchensis* (Bong.) Carr.), Scots pine (*Pinus sylvestris* L.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and larch (European, Japanese and hybrid; *Larix* spp.). An age range of between 31 and 90 was selected to include standard rotations for the species in Britain and the extension likely to be necessary in transformation; the age range was divided into three classes: 31-45 years, 46-60 years and 60-90 years. The aim was to visit 10 different sites in each of the 12 combinations of species and age class. The search for sites focussed on five Forestry Commission Forest Districts in which Trial Areas of Continuous Cover Forestry (CCF) had been established (McIntosh, 2000). The initial plan was to only use sites where transformation to CCF was in progress but this proved to be too restrictive, so all sites in each Forest District were considered. To locate suitable sites the Forestry Commission's GIS database was searched to find compartments of each species as a mainly pure crop, in the correct age range, which were greater than one hectare in area. Each list was then screened in consultation with local forest managers to remove unsuitable compartments, *i.e.* ones with access problems, where harvesting may be in progress during the survey or there were known reasons to justify exclusion from the list. One of the authors (B. Wylder) then visited each of the sites on the list with the aim of collecting data at two sites in each Forest District for each combination of species and age class. The aim was to visit a minimum of 120 sites but in fact 129 sites were assessed. Sites were not assessed if the initial risk assessment indicated significant health and safety issues or, if on visual inspection, the site already had more than 2,500 seedlings and saplings ha⁻¹ of the

Table 3 Summary of site data

Species	No. of sites	Age range (years)	FGC range and [mean] (%)	BA range and [mean] (m ² ha ⁻¹)*	Deer Impact Index (Low/Medium /High)	SNR (Poor/Mod. /Rich)	Coning (Heavy/Mod. /Light)	Sapling density (Low/Med. /High)	Seedling density (Low/Med. /High)	Thin history (Very recent /Recent /Delayed)*	BA (suitable range/ unsuitable range)*
Number of sites in each category											
Douglas-fir	26	32-84	9-86 [55]	30-91 [53]	1/22/3	8/11/7	6/11/9	16/8/2	21/5/0	10/8/8	6/20
Sitka spruce	36	32-85	1-85 [42]	33-114 [59]	1/30/5	21/14/1	18/12/6	30/6/0	18/11/7	18/6/12	3/33
Scots pine	31	38-87	14-84 [57]	20-64 [39]	0/17/14	23/6/2	4/13/14	30/1/0	31/0/0	5/9/17	14/17
Larch	36	33-86	18-91 [60]	20-52 [35]	0/26/10	15/19/2	19/10/7	30/6/0	34/2/0	9/5/22	13/23
All data	129	32-87	1-91 [53]	20-114 [46]	2/95/32	67/50/12	47/46/36	106/21/2	104/18/7	42/28/59	36/93

* Factors not in the REGGIE model.

canopy species. Figure 1 shows the location of the 129 sites and their distribution in the five Forest Districts. All sites were assessed between November 2008 and March 2009.

At each site information was recorded on its location and age of the trees in the stand. The method of Kerr *et al.* (2002) was used to locate 10 plots of 0.01 ha systematically throughout each stand. All trees in the 0.01 ha plot were assessed for diameter at breast height (dbh) and species, and this information was used to calculate basal area and determine which species were present in the canopy. Using the centre of the plot a quadrat of 2 m × 2 m was established and this was used to count all seedlings (<1.3 m height) and saplings (≥1.3 m height and <7 cm dbh) of each species present and estimate the proportion that had evidence of browsing damage. The ground vegetation was assessed by estimating the percentage cover of grass, bramble, ferns and bracken, woody plants, bare ground, leaf/needle litter, mosses, deadwood and other herbaceous plants. The timing of the survey meant that estimating the cover of some elements was difficult, particularly ferns and bracken (however, this had minimal effects as only the data for bare ground

and moss was fully used in the analysis). In addition, observations were made throughout the stand to assess Deer Impact Index using the criteria in Table 2. To determine the SNR at each site observations of plant indicator species were checked using the ESC Decision Support System (Ray *et al.*, 2001). The coning of each stand was also assessed as heavy, moderate or light using the criteria in Table 2.

At each site the surveyor was asked to rate the future probability of regeneration ('expert prediction') by answering the question: in five years' time will there be 2,500 established seedlings (>50 cm tall) per hectare of the canopy species in the stand? Possible answers were: highly likely (81-100% probability); likely (61-80%); possible (41-60%); some chance (21-40%) or poor (0-20%). The assumption was that management type and intensity would continue as in the past. A series of digital photographs were taken at each site to justify this judgement and additional notes about the site were also recorded. At the end of the survey three of the authors considered each of the sites to verify the expert prediction using field data and photographic evidence. Some gaps in the data were filled (largely assessment of soil nutrient regime)

Table 4 Summary of ordinal logistic model and scores for factors

Factor*	Levels for categorical variables	Range for continuous variables	Degrees of freedom	Estimate	Standard error	Score
Coning	High	1-91	2	2.8745	1.2170	6
	Moderate			1.0851	1.3156	2
	Low			0	0	0
FGC (%)			1	0.0428	0.0195	0.8**
Saplings (ha ⁻¹)	>100 (high)		2	4.5598	1.4984	9
	1-100 (med)			0.8803	0.7346	2
	0 (low)			0	0	0
Seedlings (ha ⁻¹)	>1000 (high)		2	6.2048	1.4799	12
	51-1000 (med)			2.6453	0.7593	5
	0-50 (low)			0	0	0
Thinning history (years since last thinned)	1-3 (v. recent)		2	2.3782	0.9232	6
	4-10 (recent)			1.0258	0.9634	2
	10+ (delayed)			0	0	0

* Factors in the minimal adequate model were fitted as categorical variables except age, which was fitted as a continuous variable. Parameter estimates for the intercept values are shown at the bottom of Table 5.

** For Z% FGC score is calculated by taking the lowest integer value of $((Z \times 0.0428 \times 2) + 0.5)$; Maximum FGC is 90%



Plate 3

Well developed seedling regeneration of Sitka spruce; with careful management the prospects for successful regeneration are good.

but no changes in the expert prediction were judged to be necessary.

The data for each site were then used to calculate the mean density of seedlings and saplings for each of the canopy species. The percentage of ground flora cover that was favourable for natural regeneration (favourable ground cover - FGC) was calculated by adding the cover of bare ground and moss together; all other elements were assumed to be unfavourable to the development of natural regeneration. These data along with the other assessments were then input into REGGIE to calculate the probability of regeneration in the next five years ('model prediction').

Information on thinning history was obtained from local managers and this was recorded as very recent (1-3 years); recent (4-10 years) or delayed (>10 years). The basal area for each stand was calculated from the plot data and rated as being within a range conducive to natural regeneration or outside this range. The ranges were determined with reference to Kerr (2008; Table 7.2) and for larch was 10-30 m² ha⁻¹; Scots pine 15-35 m² ha⁻¹; Sitka spruce 20-40 m² ha⁻¹ and Douglas-fir 25-45 m² ha⁻¹. The site data are summarized in Table 3.

Data analysis

The first part of the data analysis compared the 'expert prediction' of the likelihood of regeneration with that produced from REGGIE for all sites, by age class, species and coning.

The second part of the analysis used an ordinal logistic regression (SAS, 2004). The response variable

was 'expert prediction' grouped into five classes (0-20, 21-40, 41-60, 61-80, 81-100%). The explanatory variables were species, age, Deer Impact Index, Soil Nutrient Regime (SNR), Favourable Ground Cover (FGC), coning, density of seedlings and density of saplings, *i.e.* the main inputs into REGGIE. The data on thinning history and basal area range were also included in the model fitting. Terms were fitted as either categorical or continuous variables (Table 4). Because all factors are known to have the potential to account for variation in the data every term was initially fitted to the model and then backward elimination was used to determine the minimal adequate model. The fact that all the data for Scots pine had an expert prediction of 0-20% caused an issue with the model fitting procedure. As to be expected with such data, an accurate parameter estimate for Scots pine could not be achieved. An initial fit of the model produced an unrealistic parameter estimate with huge standard error, so it was decided to exclude the species term from any potential model.

To develop a simple scoring system that could be used to estimate the probability of natural regeneration a score was generated for each of the terms in the minimal adequate model. The score for each level of each factor was related to the fitted estimate from the model. However, the fitted term for FGC was 0.0428 and for low values the score would be <0.5. For example, for 10% the term would be 0.428. To overcome this problem for FGC it was decided to multiply each fitted term by 2, add 0.5 and then round down to the nearest integer. To assign each value of a cumulative

score to a probability level (0-20, 21-40, 41-60, 61-80, 81-100) the minimal adequate ordinal logistic model was used to generate a probability distribution. Each cumulative score was then allocated to a probability level based on the position of the highest probability in the distribution as shown in Table 5.

Results

A key part of this project was the range of characteristics of the 129 sites that were visited to validate the REGGIE model (Table 3). The distribution of sites between the four species and the age range was good reflecting the fact that sites had been selected to achieve this. Of the factors included in REGGIE the range and distribution of sites for FGC and coning was good. For Deer Impact Index the majority of sites (73.6%) were rated as medium and only 1.5% were low. This reflects the assessor's comment that it was difficult to be objective about this on brief visits to a site. For SNR most sites were rated as poor or moderate and this reflects what would be expected from appropriate species choice; notably most of the rich sites were planted with Douglas-fir, a result that would be expected from knowledge of silvicultural characteristics. The distribution of sites with reference to the density of saplings and seedlings reflects the fact that sites that already had more than 2,500 seedlings per hectare were not assessed. Of the factors not in REGGIE but included in the ordinal regression model, recent thinning history had a good distribution between very recent/recent/delayed. However, only a few of the sites for Douglas-fir and Sitka spruce were in the recommended basal area range for natural regeneration and generally had high basal areas. More sites were in the recommended basal area range for larch and Scots pine; basal areas were lower compared with the other two species, probably because larch and Scots pine are both light demanders. This can be explained by the fact that some sites visited were not being actively managed for natural regeneration and many forest stands are overstocked due to the vagaries of thinning practice.

The REGGIE model agreed with the expert prediction on 63 of the 129 sites (48.8%) (Table 6). For 44 sites (34.1%) scores differed by one category and for 22 sites (17.0%) they differed by two or more categories. There was a marked tendency for REGGIE to be more optimistic than the expert prediction; for 57 sites (44.2%) the REGGIE score was higher than the expert score but on only 9 sites (7.0%) the expert prediction was one higher than REGGIE and never by more than one class.

The differences between REGGIE and the expert judgement can also be examined in relation to the age of the stand (Table 7). In general this shows that as age increases agreement between the two methods decreases. For the youngest sites there was agreement between the scores on 27 sites (73%) and they were all low (0-20%). For mid-range age stands there was agreement between the scores on 24 sites (47%) and all but two were low (0-20%). For the oldest stands

Table 5 Relationship between cumulative score and predicted probability class showing derivation using probability distribution from the ordinal logistic model

Cumulative score	Expert score (Probability)					Predicted class (Probability %)
	0-20	21-40	41-60	61-80	81-100	
0	0.9998	0.0002	0.0000	0.0000	0.0000	0-20
1	0.9997	0.0003	0.0000	0.0000	0.0000	0-20
2	0.9995	0.0005	0.0000	0.0000	0.0000	0-20
3	0.9992	0.0008	0.0000	0.0000	0.0000	0-20
4	0.9986	0.0013	0.0001	0.0001	0.0000	0-20
5	0.9977	0.0021	0.0001	0.0001	0.0000	0-20
6	0.9962	0.0034	0.0002	0.0002	0.0000	0-20
7	0.9938	0.0056	0.0003	0.0003	0.0000	0-20
8	0.9898	0.0091	0.0005	0.0005	0.0000	0-20
9	0.9832	0.0150	0.0009	0.0009	0.0000	0-20
10	0.9727	0.0244	0.0014	0.0015	0.0000	0-20
11	0.9557	0.0394	0.0024	0.0024	0.0000	0-20
12	0.9290	0.0630	0.0039	0.0040	0.0000	0-20
13	0.8881	0.0988	0.0064	0.0066	0.0001	0-20
14	0.8281	0.1506	0.0104	0.0108	0.0001	0-20
15	0.7450	0.2204	0.0168	0.0177	0.0001	0-20
16	0.6392	0.3049	0.0268	0.0289	0.0002	0-20
17	0.5180	0.3931	0.0418	0.0468	0.0004	0-20
18	0.3946	0.4668	0.0632	0.0748	0.0006	21-40
19	0.2833	0.5070	0.0912	0.1175	0.0010	21-40
20	0.1934	0.5022	0.1229	0.1798	0.0017	21-40
21	0.1270	0.4540	0.1513	0.2649	0.0028	21-40
22	0.0811	0.3757	0.1672	0.3715	0.0046	21-40
23	0.0508	0.2870	0.1638	0.4909	0.0076	61-80
24	0.0314	0.2048	0.1428	0.6086	0.0124	61-80
25	0.0193	0.1387	0.1122	0.7095	0.0203	61-80
26	0.0118	0.0904	0.0812	0.7836	0.0331	61-80
27	0.0072	0.0574	0.0553	0.8268	0.0534	61-80
28	0.0044	0.0358	0.0361	0.8387	0.0851	61-80
29	0.0027	0.0221	0.0229	0.8194	0.1329	61-80
30	0.0016	0.0136	0.0143	0.7688	0.2017	61-80
31	0.0010	0.0083	0.0088	0.6878	0.2941	61-80
32	0.0006	0.0050	0.0054	0.5818	0.4072	61-80
33	0.0004	0.0031	0.0033	0.4622	0.5311	81-100
34	0.0002	0.0019	0.0020	0.3447	0.6512	81-100
35	0.0001	0.0011	0.0012	0.2427	0.7548	81-100
36	0.0001	0.0007	0.0007	0.1631	0.8354	81-100
37	0.0000	0.0004	0.0005	0.1058	0.8933	81-100
38	0.0000	0.0003	0.0003	0.0670	0.9324	81-100
39	0.0000	0.0002	0.0002	0.0418	0.9579	81-100
40	0.0000	0.0001	0.0001	0.0258	0.9740	81-100
41	0.0000	0.0001	0.0001	0.0158	0.9841	81-100
Fitted intercept value						
0	-8.5719	-10.8266	-11.5062	-16.3756		

there was only agreement between the methods for 12 sites (29.2%) and all but two were low (0-20%).

There were also differences between REGGIE and the expert judgement for the four species (Table 8). Agreement between the two methods was near or above 50% for Douglas-fir (17 of 26 sites, 65%), larch (19 of 36 sites, 52.7%) and Scots pine (15 of 31 sites agreed, 48.3%). However, the results were much lower for Sitka spruce (11 of 36 sites agreed, 30.6%) and there was marked tendency for REGGIE to be at least one probability class more optimistic for the sites the expert had rated in the 0-20% class. In addition,

Table 6 Comparison of expert and REGGIE assessment of likelihood of regeneration for 129 sites

Expert (% probability of regeneration)	REGGIE (% probability of regeneration)					Total
	0-20	21-40	41-60	61-80	81-100	
0-20	59	27	13	8	0	107
21-40	4	2	4	1	0	11
41-60	0	0	1	1	0	2
61-80	0	0	4	1	3	8
81-100	0	0	0	1	0	1
Total	63	29	22	12	3	129

agreement between the two methods was inversely related to the amount of coning in the stands: low (91.4%)>moderate (38.3%)>high (27.7%) (data not shown).

The minimal adequate ordinal logistic model included five terms: coning, FGC, sapling density, seedling density and thinning history; parameters and standard errors for each of these are shown in Table 4. The logistic model was far superior to REGGIE in terms of its agreement with the expert prediction. The model agreed with the expert prediction on 113 of the 129 sites (87.6%) (Table 9). The model predictions only differed by more than one category for three sites (2.3%). In contrast to REGGIE, the logistic model tended to underestimate the probability when the two methods did not agree; for 11 sites (8.5%) the model score was lower than the expert prediction and on 5 sites (3.9%) it was higher.

The scoring system developed using the logistic model is shown in Tables 4 and 5. This provides a neat, quick method for assessing the probability of natural regeneration on each of the 129 sites in the survey. The relative size of the scores for each of the five factors gives an accurate indication of their influence in the model. Hence, the five factors can be ranked as: density of seedlings>density of saplings>FGC>coning=recent thinning. So for example, if a site has high coning, no saplings, 500 seedlings per hectare, was thinned 2 years ago and has

50% FGC then its cumulative score is 21 (6+0+5+6+4) (Table 5). This is equivalent to a 21-40% probability of obtaining successful natural regeneration in the next five years. One unfortunate characteristic of the logistic model is that, reflecting a paucity of data, it predicts that no sites will have a probability of 41-60% (Table 9).

Discussion

The crux of this project is: how good at predicting the probability of natural regeneration in a five year period was the surveyor? The validation of REGGIE and the accuracy of the scoring method based on the logistic model are both heavily dependent on this. The surveyor is a trained forester who has over five years experience working for Forest Research on the management and assessment of a wide range of research projects, many of which require silvicultural expertise. Before the assessment commenced the authors visited a number of sites to test the methodology and harmonize views on the assessment criteria for each of the factors. In addition to this authors were in regular contact as the work progressed and any problems were quickly resolved. The digital images of each site were a useful record that allowed the authors to compare judgements about each site; the fact that it was not felt necessary to change any of the 'expert predictions' is a strong endorsement of his judgement in the field. Only one person assessed all of the 129 sites in an attempt to minimize measurement error. The authors are confident that the expert predictions are as accurate as possible. However, the real test of this would be to repeat the survey in the future and record the changes that have taken place, both to the stand and the status of the regeneration.

One of the main objectives of the work was to validate the REGGIE model and it was shown to be accurate for 48.8% of sites where it was tested. The question arises: is this good enough? This is not easy to answer because the model has not been statistically

Table 7 Comparison of expert and REGGIE assessment of likelihood of regeneration for 129 sites by age class

Age class	Expert (% probability of regeneration)	REGGIE (% probability of regeneration)					Total
		0-20	21-40	41-60	61-80	81-100	
31-45	0-20	27	7	1			35
	21-40	1	0				1
	41-60	0	0	0	0	0	0
	61-80			1	0		1
Sub-total		28	7	2			37
46-60	0-20	22	9	6	3		40
	21-40	2	1	2	1		6
	41-60			0	1		1
	61-80			2	1	1	4
Sub-total		24	10	10	6	1	51
61-90	0-20	10	11	6	5		32
	21-40	1	1	2			4
	41-60			1			1
	61-80			1	0	2	3
	81-100				1	0	1
Sub-total		11	12	10	6	2	41
Total		63	29	22	12	3	129

Table 8 Comparison of expert and REGGIE assessment of likelihood of regeneration for 129 sites by species

Age class	Expert (% probability of regeneration)	REGGIE (% probability of regeneration)					Total
		0-20	21-40	41-60	61-80	81-100	
DF	0-20	14	4	2			20
	21-40		2	1			3
	41-60			1			1
	61-80			2			2
DF Sub-total		14	6	6			26
JL	0-20	19	13	1			33
	21-40	2	0	1			3
JL Sub-total		21	13	2			36
SP	0-20	15	8	5	3		31
SP Sub-total		15	8	5	3		31
SS	0-20	11	2	5	5		23
	21-40	2	0	2	1		5
	41-60			0	1		1
	61-80			2	1	3	6
	81-100				1	0	1
SS Sub-total		13	2	9	9	3	36
Total		63	29	22	12	3	129

derived and then validated against an independent set of data (Vanclay, 1992). However, investigation of two other regeneration models does help to make a judgement on an acceptable level of accuracy. The model described by Ferguson *et al.* (1986) was found to have unacceptable large prediction errors for 55 of the 190 stands (29%) on which it was tested and for many of these sites reasons were suggested that could account for this, which were not factors in the model. The model described by Schweiger and Sterba (1997) had two parts, the first model predicts the probability that natural regeneration of Norway spruce is present and, if so, the second model predicts the probability of Norway spruce regeneration having a given height and stem number. Unacceptable deviations from the models were found for 13% of stands for the first model and 17% for the second model. It is difficult to make direct comparisons between such widely differing models but the work of Ferguson (*op. cit.*) and Schweiger and Sterba (*op. cit.*) suggest that REGGIE is not bad considering it has been built from first principles but, perhaps not surprisingly, is inferior to statistically derived models.

The fact that REGGIE only performed moderately well in the validation test is reflected in the fact that it has been superseded by the logistic model. Whereas REGGIE agreed with the expert prediction for 48.8% of sites the logistic model performed much better and agreed with the expert prediction on 87.6% of sites. Other aspects of the logistic model are also superior to REGGIE: it only uses five factors and the presentation of the model as scores means that the probability of natural regeneration can be assessed in the field without access to a computer. Each of the five factors is also relatively straightforward to assess based on careful visual inspection of the stand (coning, sapling density, seedling density, FGC) and knowledge about its recent past (thinning history). However, it is also important to consider the constraints on the use of this model. Strictly it is only applicable to the 129 sites

that produced the data on which it is based: it has not been validated against an independent set of data in the same way that the 129 sites tested REGGIE. However, informal validation of the model by two of the authors suggests that it is generally applicable to a much wider range of sites and calls for strict validation should not delay the wider use of the model by forest managers. Another constraint of the model is that it is not species specific. This could be a problem as the test of REGGIE showed how differently four species performed. The lack of a species factor in the model was caused by all the expert predictions for Scots pine being in the 0-20% category. However, with any model there is a balance between simplicity and accuracy; it may be that having just one model applicable to four species may be more convenient for the people who will use the model in the field.

Despite some of the factors being eliminated by the fitting procedure of the logistic model there is overwhelming evidence that they influence the potential of a site to naturally regenerate. For example there is a large body of scientific evidence that deer and other animals can affect natural regeneration (Rooney, 2001) but the Deer Impact Index used in this study was not included in the final model. The Deer Impact Index relates to earlier work by Kerr and Nowak (1997) but has not been fully developed and hence was loosely specified and difficult to apply in the field. Recent developments described by

Table 9 Comparison of expert and logistic model assessment of likelihood of regeneration for 129 sites

Expert (% probability of regeneration)	Model (% probability of regeneration)					Total
	0-20	21-40	41-60	61-80	81-100	
0-20	104	3	0	0	0	107
21-40	7	3	0	1	0	11
41-60	0	1	0	1	0	2
61-80	1	1	0	6	0	8
81-100	0	0	0	1	0	1
Total	112	8	0	9	0	129

Armstrong and others (Forestry Commission, 2010) in their 'Grazing tool-kit' could be used to refine the idea of a Deer Impact Index. There is also good evidence that natural regeneration tends to be easier to initiate on nutrient poor sites compared with richer ones (Nixon and Worrell, 1999). Hence it was surprising that SNR was not included in the final model and the reasons for this are unclear as the basis of the assessment was sound and there was a reasonable distribution of sites between the three categories. Lastly, the non-appearance of basal area as 'in-range' or 'outside range' in the model is also difficult to explain as the ranges are based on good science (Hale, 2004; Mason and Kerr, 2004). Part of the explanation of why some of these factors were not included in the model may relate to the decision to widen the search for sites beyond those being actively managed as a transformation to continuous cover. However, it remains possible that if all sites were being managed as part of a transformation plan, and guidance in Kerr (2008) was being followed, the range of attributes on the 129 sites could have been much smaller.

Conclusion

The REGGIE model is a reasonable method for predicting the likelihood of the natural regeneration of Sitka spruce, Scots pine, Douglas-fir and larch. However, it tended to overestimate the likelihood of regeneration, especially for Sitka spruce compared with 'expert assessment'. The logistic model is a better model for the prediction of natural regeneration of the four species. It was more closely related to the 'expert assessment' and the score-based system of implementation means that it is simple to use and does not need access to a computer. Informal validation has suggested that the logistic model can be used with some confidence as part of a strategy to raise understanding of how to use natural regeneration when transforming conifer stands to CCF in Britain.

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