Forest Enterprise Scotland
Managing the National Forest Estate

MINIMISING WIND DAMAGE

Remodelling ForestGALES minimise wind damage in the Inverness, Ross and Skye district

Eelco de Jong
May, 2017

Minimising wind damage
Remodelling ForestGALES to minimise wind damage in the Inverness, Ross and Skye district

Bachelor thesis in the framework of the study Forestry and Nature Management - specialisation Urban Forestry

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Preface

The past four years I've been studying Forestry and Nature-management at Van Hall Larenstein in Velp. The first two years were on Forestry and Nature management in a broad sense. The two years after, I focussed on Urban Forestry and Nordic Forestry through two half-year courses as well as doing two internships. These four years have all led up to this one final project, the Bachelor thesis
During the Nordic Forestry course in Norway, a delegation of Scottish foresters and nature managers gave presentations through an Erasmus scheme. After previous visits to Scotland and the presentations on Scottish forestry, I was convinced I had to go there. I decided I shouldn't let this opportunity slip and asked one of the foresters if it would be possible to do an internship with them. Through him this internship was arranged, thanks for that Marcin Baranski, I am incredibly grateful for the chance!
Soon in the process of arranging the internship, the district came up with the issue of wind damage. The model that they had was not used or not used properly and to me the task of changing this. Although I had little experience with wind damage, it seemed like an informative subject. During the project itself, I started realising what an interesting research it is. Wind damage encompasses almost all themes of forestry. Species, soils, silvicultural measures, ground preparation and many other aspects have their place in predicting and preventing wind damage. This project therefore really feels like the crowning achievement of my education.

This thesis is most informative for users of ForestGALES in the Inverness, Ross and Skye district. However, anyone interested in ForestGALES and the prevention of wind damage should find this helpful in understanding the model and the phenomenon.

During the project, I was supervised by Bob Chester, I would like to thank him for the answers to all my questions and a lot of background knowledge on forestry in Scotland. My knowledge on computing and modelling was small and I am thankful for Stephen Bathgate and his help with the interpretation of the model and all computing related queries. Guidance from my home institution was done by John Raggers, thanks John for mentoring me through this and the past few years! I would furthermore like to thank Doug Mitchell for commissioning this research and guiding the project along the desired course. For the project, I relied on the knowledge and help of many more people at the Forestry Commission. I would sincerely like to thank them for answering all my questions and more importantly, to make me feel at home and part of the team in Smithon!

Eelco de Jong

Smithon, Scotland

May, 2017

Abstract

Recently, the Inverness, Ross and Skye forest district has had multiple occasions of wind damage in their forests. Because these were unpredicted and costly events, the model used to predict wind damage, ForestGALES, was analysed. Both input and output of the model were closely examined to discover why it does not do what it is supposed to do; minimise wind damage. For the district this had multiple reasons, a major one being unawareness of the existence of the model. Furthermore, the quality of the input and therefore the results often contained large errors. Finally, the output could not be generated automatically districtwide. During this research, availability, quality and comprehensibility of the model were improved. This was done by investigating recent windblow and its causes throughout the district. Besides this, the demands of stability data from the district were researched. The input of the model for Inverness, Ross and Skye Forest District has, on this basis, been revised. Stand data were adjusted per species and per forest block. Factors affecting stability, such as rooting, wind direction and exposed edges, were analysed and considered in the new calculations. This, in turn, gave more information about the causes of windblow and thereby the ways of preventing it.

Different ways of showing stability were considered depending on the information required. The result is a set of maps showing stability as an amount of years until unacceptable risk per sub-compartment throughout the district. Stands at high risk of windblow can be felled and thereby the chance of wind damage in the district is reduced. When planning fellings or making land management plans, these maps can be used to determine which stands should be prioritised. The research also exposed reasons for early wind damage, the three major ones being a delay in thinnings, exposed edges due to forest operations and rooting problems. The delay in thinnings and the exposed edges are issues that should be resolved by diligent planning. Soil issues are not so easily solved. At the moment, there is a gap in knowledge on where exactly the shallow soils are located and how this effects stability.

Finally, the predictions of ForestGALES were compared to the management plans to give an estimate of future windblow. Except for Lodgepole pine there is no reason for concern. It is advisable to decrease rotation lengths of Lodgepole pine, as predicted damage rises significantly.

Contents

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List of abbreviations

CCF	*Continuous Cover Forestry*
DAMS	*Detailed Aspect Method of Scoring*
EL	*European larch*
ESC	*Ecological Site Classification*
FC	*Forestry Commission*
FCS	*Forestry Commission Scotland*
FD	*Forest District*
FM Forester	*Forest Management Forester*
FR	*Forest Research*
HL	*Hybrid larch*
IRS	*Inverness, Ross and Skye*
JL	*Japanese larch*
LP	*Lodgepole pine*
SC	*Sub-compartment*
SCDB	*Sub-compartment Database*
SS	*Sitka spruce*
SP	*Scots pine*
VHL	*Van Hall Larenstein*
WDRS	*Wind Damage Risk Status*
WHC	*Wind Hazard Classification*

1. Introduction

In recent history, several storms have caused significant damage to British forests. From the early 1960's research to how wind damage can be prevented and predicted was therefore done (Quine, et al., 1995). Especially the infamous storm of 1987 resulted in measures taken by the Forestry Commission (FC) (Harmer, et al., 2004). Because of this storm, various tests and long-term experiments were set up. Wind speeds were tracked and for various tree species the amount of force needed to uproot and/or snap trees was determined (Nicoll, et al., 2006).

On the basis of this work Forest Research (FR) released ForestGALES in 2000. This program uses a multitude of variables from the trees and the site to calculate the probability of average trees being damaged within a stand (Dunham, et al., 2000). It does this by calculating the force exercised upon the tree by using stand parameters. Opposed to that it calculates what the likelihood of such a force at that location is. This combination gives the so-called 'Return Period' given as a ***1:x*** amount of years, this would mean the event should happen once every ***x*** years. This probability can then be interpreted by the forest manager and mitigating measures can be taken. The model now draws information from the Detailed Aspect Method of Scoring (DAMS) to determine the likelihood of a certain wind speed happening in a sub-compartment (SC) (Figure 1). The DAMS score is based on tatter flag observations, elevation, aspect, topographical exposure, valley shape and direction (White & Quine, 1994).

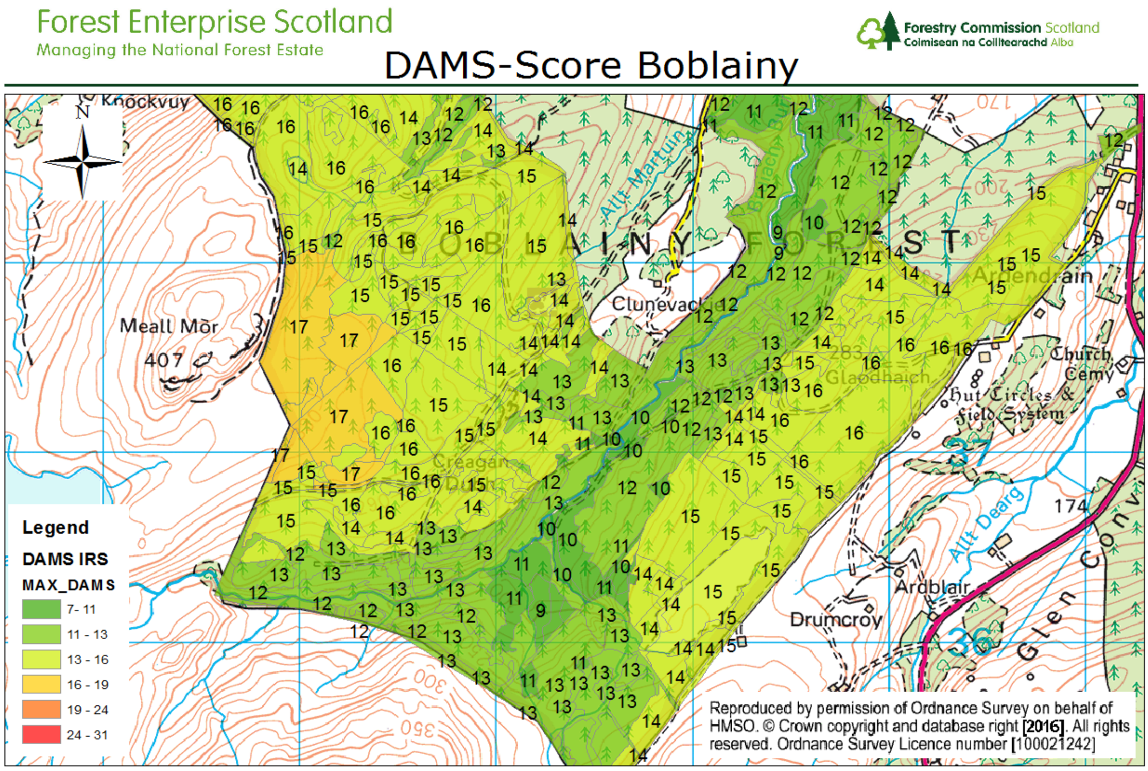


Figure 1: *Example of mean DAMS-Scores this being in the Boblainy forest, 7 is very sheltered, 31 extremely exposed (Source: FCS)*

Since 2013, winter storms have caused extensive damage to the forests in the Northern part of the country. This is due to gales of substantial force combined with an overall increasing maturity of the forests. In the Inverness, Ross and Skye forest district (IRS FD) large areas of forest have been blown and the clean-up of these forests is still in progress. Annually this results in a large percentage of the total harvest consisting of damaged crop (Table 1). Because harvesting costs are higher and wood quality is lower, wind damage results in tremendous loss of income. The extra cost for harvesting alone caused an average loss of £300.000,- per year in the last 3 years. Shorter rotations and therefore less wood of lesser quality are not included in that. For a stand of 9.5ha that blew over, a calculation was made to demonstrate the difference in income (Appendix 1). The stand will now deliver about £40.000 after 33 years, whilst prediction was that it would yield about £200.000 in 60 years.

On top of that, there is still at least 150.000 m3 of wind damage wood lying in the forest. This volume is mostly composed of small patches of trees being blown that are not worth harvesting. Because the trees have stopped growing and forest edges are exposed, the economic loss of these patches is substantial (Black, 2017). Even if there is no wind damage this winter (17/18) the harvesting will include clearance of remaining wind damage from the last two years (Mitchell, 2017). This has raised the question whether ForestGALES is functioning the way it should.

Table 1: Estimate of wind damage harvest volume compared to total harvest in m3 in IRS FD (Black, 2015/2016/2017)

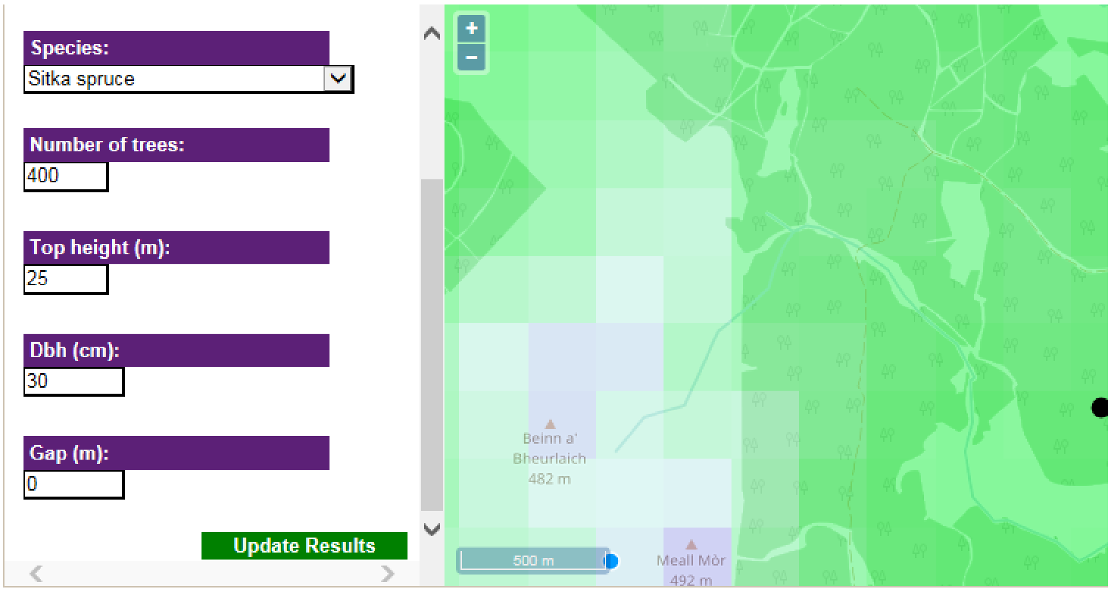
Year	wind damage harvest in m3	Total harvest in m3	Percentage of harvest due to wind damage
2015/2016	84000	223000	37%
2016/2017	147000	298000	49%
2017/2018	101600	290000	35%

The central thesis of this paper is remodelling ForestGALES so that it will be better applicable in the district which then should results in less wind damage. First off, an analysis will be made on the current use of the model and current measures being taken to counter wind damage. Secondly, the model will be updated based on research done to recently blown stands. Thirdly, the format in which risk of wind damage was presented will be changed to give easier access to the relevant data. Lastly, an assessment will be made to where and how the district can take measures to prevent wind damage. The results of the report will also be presented to Forest Research to make sure that the relevant results can be used throughout the United Kingdom

2. Problem definition

Wind damage in IRS FD causes substantial economic losses. To combat wind damage, ForestGALES is used to calculate the probability of wind damage. Even though ForestGALES is available, wind damage is still at a level which is considered too high.

Within the district they have concluded that there are certain local variables not accounted for in ForestGALES. The main output, a return period and Wind Damage Risk Status, are hard to interpret and therefore do not encourage planners and foresters to work with ForestGALES (Figure 2).



Download results as a CSV file

Eastings(m)	Northings(m)	Site Grid Reference	Exposure(DAMS)	Soil
275231	836098	NH752360	13	Mineral soil shallow rooting

Species	Top height (m)	Dbh (cm)	Trees (n/ha)	Gap (m)
Sitka spruce	25	30	400	0

Type of damage	Critical Wind Speed (km/h)	Return Period (years)	Wind Damage Risk Status (1 low risk, 6 high risk)
Overturn	73.6	200	1
Windsnap/break	68.6	62	2

Figure 2: Screenshot ForestGALES in- and output at random location (Source: Forest Research Decision Support tool)

Thesis statement

To achieve optimal application of ForestGALES it needs a two-way update. For IRS FD, ForestGALES must be tested against local knowledge and adjusted where necessary. Furthermore, the use of the model in the district needs to be investigated and refined.

3. Research target

The goal of this thesis is reducing wind damage in IRS FD. The basis for this research is ForestGALES. During the thesis, the model's applicability will be tested for the IRS FD. Using ForestGALES, an assessment of the stability throughout the district at this point in time will be carried out. Recommendations will then be made for refining ForestGALES for country-wide use

3.1 Research question

What adjustments can be made to ForestGALES to optimise its value and reduce wind damage in IRS FD?

3.2 Sub-questions

- How is ForestGALES used in land management planning in IRS FD at this point in time?
- How can ForestGALES be refined for application in the district?
    - Does the ForestGALES prediction compare to reality in recently blown stands?
    - What local factors have influence on stability?
    - Can manual adjustments be made to the in- and output as a result of local factors and knowledge?
- In what ways can ForestGALES be applied in the different layers of the district as a tool to minimise wind damage?

4. Method

The prediction and prevention of wind damage within Inverness, Ross and Skye was done according to the sub-questions presented earlier. First off, current usage was examined. Secondly, the model was perfected for use in the district. Thirdly, an assessment was done to see where in the district ForestGALES could be applied to reduce wind damage most effectively.

4.1 Current use of ForestGALES

To determine the current use of ForestGALES, the following 3 steps were taken:

1. An inquiry of users of ForestGALES in IRS FD was done.
2. A research on what aspects of ForestGALES are used and how this is implemented in the decision-making process was done.
3. An inquiry on previously used methods of determining the likelihood of wind damage was done to compare different models.

1. To determine usage the planning forester (Bob Chester) was interviewed on who uses the program within IRS FD.
2. The users of ForestGALES were interviewed in one on one sessions on how ForestGALES has been used in their decision-making process. They were also asked what version of GALES was used and which inputs and outputs are preferable.
3. To get a broad view of wind damage management in the IRS FD the users of ForestGALES were asked in what way they had previously taken wind damage into account. Because the number of users of ForestGALES in the district was limited other planners have also been asked how they take stability into account. Their opinions combined with a desk-research on previous methods give a reliable basis for determining pros and cons of ForestGALES.

4.2 Refining the model

To find out how ForestGALES could be refined the errors in the model have been researched and resolved. After the model had been updated, the output received an update as well. This has been done according to the following steps.

1. Comparing windblown stands to ForestGALES's prediction
2. Considering local influences on recently blown stands
3. Increasing quality of the modelling for IRS FD by making sure the input is correct
4. Calculating stability at this point in time and determining how to present that in the right way
5. Considering other variables, their relationship with stability and adjusting the model accordingly

1. First off an investigation has been carried out on recently blown stands. On the Black Isle and in Boblainy & Battan, Meall Morr and Shenval 27 stands had been damaged in recent years. The blocks are marked in Figure 3. Measurements of these stands were taken to determine whether ForestGALES calculated them to be unstable.

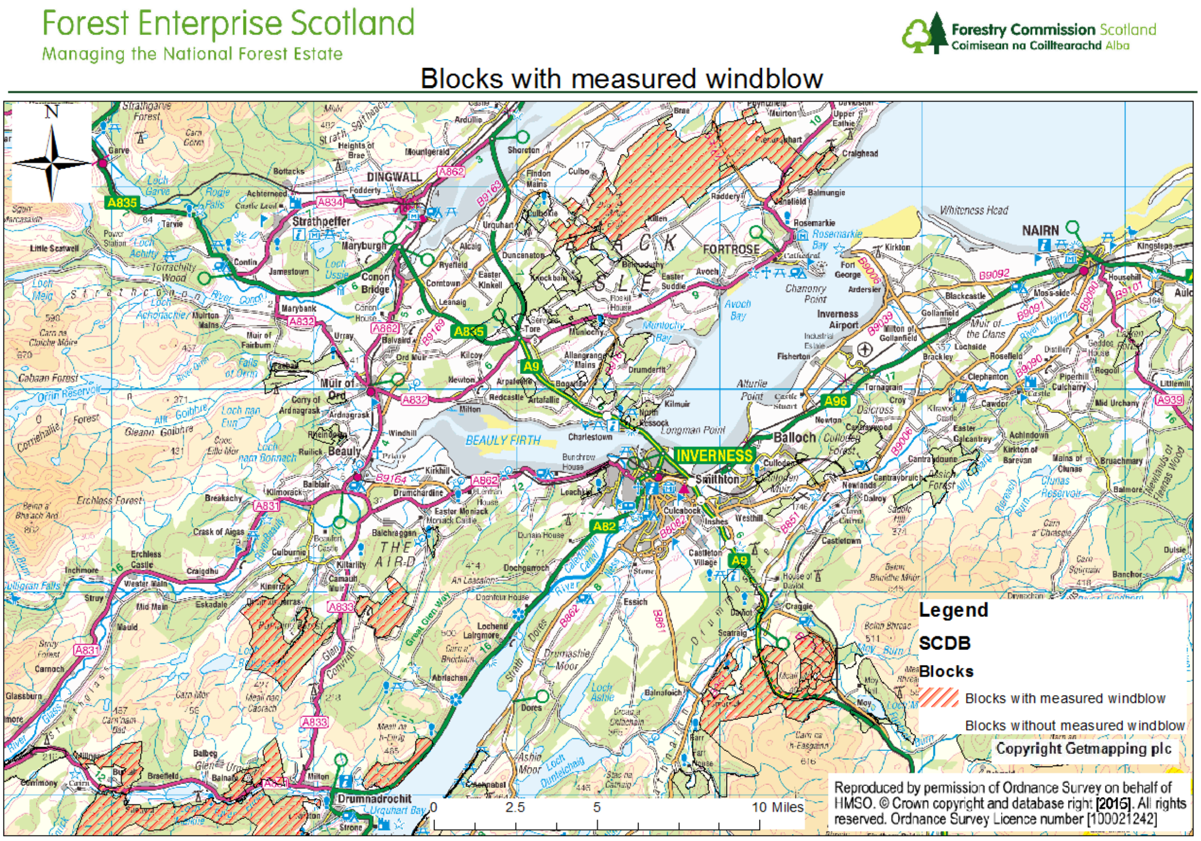


Figure 3: Blocks in which windblow was measured and analysed (Source: FCS)

The sub-compartments with damage were determined with the help of Bob Chester and were then confirmed in the field. If damage had occurred the measurements were looked up in the sub-compartment database (SCDB) in Forester (the GIS module of FC) (Forestry Commission, 2017). If this data was not available, the stand was measured in the field. The following data was gathered according to Forest Mensuration for Practitioners (Matthews & Mackie, 2006):

- Location
- Tree species
- Average DBH (cm)
- Average height (m)
- Basal area (m2)
- Soil type/Rooting depth (if applicable)

Some of the damaged stands had already been felled and stand data was no longer in the SCDB. The measurements of these stands were found in an old version of the SCDB (Chester, 2017). By combining this and old work plans, which showed volumes of all tree species in that coupe, a estimate of the volume and size of trees in the blown stands could be made.

These stand parameters were then run through ForestGALES to determine return periods of damaging winds. The results can be found in Appendix 2. ForestGALES also has the option of basing the stability on yield class, management regime and age. The yield class is based on the height and age of the stand using FC yield models (Forestry Commission, 1971). Consequentially the right management regime was selected using the Thinning Coupe Map (Forestry Commission, 2017).

The stand data is used by ForestGALES to model the tree and determine the force needed to damage it. For the damage to happen a wind speed is required that could exercise such a force. For the analysed stands, it would be most useful to know the wind speed from the moment the trees blew over. Sadly, the exact date and speed of damage in the researched stands could not be discovered. Therefore, wind speeds from the past 5 years measured by weather stations in the district (Skye/Lusa, Aviemore and Inverness Airport) were gathered.

Table 2: Location details weather stations, DAMS based on the Forest Research Decision tool (Forest Research, 2017)

Location	**Coordinates (N)**	**Coordinates (W)**	**Altitude**	**DAMS estimate**
Aviemore	57.206	-3.827	228m	11
Inverness Airport	57.54	-4.057	8m	11
Skye/Lusa	57.257	-5.809	18m	17

All hourly average speeds were collected by WeatherOnline (WeatherOnline Ltd., 2017).

The return periods of the different wind speeds were visualized using Excel and compared to the data in Appendix 3. This way the predicted DAMS and the actual DAMS could be compared (Appendix 4).

2. In the recently blown stands, an assessment was carried out to determine the cause of the instability. Literature suggests several possible variables influence stability such as shallow rooting, forest operations in the vicinity, disease or just a terminal height for the location and species being reached (Quine, et al., 1995) (Schelhaas & Vos, de, 2011). An aspect taken into consideration was the wind direction. Local sources and literature mentioned that non-prevailing winds are the more dangerous as trees are not sufficiently adapted to them (Schelhaas & Vos, de, 2011). Therefore, the assessment also looked at the direction of the damaging wind.
   Literature and local knowledge suggests that deep ploughing, especially single board ploughing has a negative impact on stability (Quine, et al., 1995) (Hay, 2017)(Figure 4&5). Therefore, the ground preparation at the moment of forest establishment was noted when this could be discovered.

   The direction of the damaging wind was discovered by determining which way the trees blew. The ground preparation was analysed by inspecting the planting direction and soil morphology. Rooting depth could be discovered by measuring the roots of blown trees and rounded off to a decimetre (10 trees per stand), if water was visible on the surface this was noted. Exposed edges were noted in the field and confirmed by coupe designs of the past years. Tree health was assessed visually by inspecting the timber on rot and insect damage. These factors have been noted and a map with the situation in each stand was made (appendices 5,6,7,8 and 9).

Figure 4: Deep drain ploughing in 1919, possibly in Glen Creran (Source: Forestry-memories.org.uk)

Figure 5: A stand of Sitka spruces blown along the plow lines (Source: Forestry Commission)

3. When using ForestGALES to calculate stability throughout the district, data for every stand was required. The smallest reliable spatial map for these data is the sub-compartment database (SCDB) (Forestry Commission, 2017). By using the SCDB, stability is calculated per sub-compartment. By leaving out all irrelevant sub-compartments the comprehensibility of the maps increases. The new maps are made for major productive coniferous species; Douglas fir (DF), European larch(EL), Hybrid larch (HL), Japanese larch (JL), Lodgepole pine (LP), Sitka spruce (SS) and Scots pine (SP) planted from 1920. This is because these are economic areas and wind damage would have a negative effect on their objective. The year 1920 was chosen because this was the year the Forestry Commission was established. From this moment on the planting years are recorded. Before this time the planting years are estimates and are not relevant because the areas with a planting year before 1920 tend not to be designated as production areas.

The decision was made to base stability on yield class, management regime and age. The other option is to base stability on current stand parameters acquired through mensuration. The advantage of the yield class based method is the option of predicting future progression of stability, opposed to only being able to calculate the current stability. The other advantage of using yield classes is that they are all recorded in the SCDB. However, when measured stands were compared to the data in the SCDB it was discovered that many yield classes and had a tendency to be conservative. Prior to mensuration, the yield classes are determined by the Forest Management Forester (FM Forester) at the time of planting. The FM forester does this based on soil type, previous crop and/or adjacent crop. FM Foresters tend to be on the safe side for production forecasting; this means that they generally predict a lower yield class. But a lower yield class means a longer rotation period according to ForestGALES. Choosing a conservative prediction for the yield class means that the modelling will think the trees grow slower and will be stable for longer.

In 1762 out of 6627 stands, mensuration has been done. This gave validated data for basing yield classes on. Per tree species and per block the validated stands (stands in which mensuration has taken place conform standards (Matthews & Mackie, 2006)) were compared to the invalidated stands. The difference in average between the invalidated and validated stands was added to the invalidated stands. Every species has a maximum modelled yield class; this was used as the upper limit for a stand.

In some blocks, there were very little or no validated stands, others had large variations in fertility. In these instances, the estimated yield class and the yield class in the Ecological Site Classification (ESC) program were added and divided by two to get the average. By doing so an approximation of the truth was made.

The second variable, the management regime, was also checked. In general, the management regimes are as follows (Chester, 2017):

Table 3: Management regime planning guideline

DAMS >16:	No thin
DAMS 13-16:	Maybe thin
DAMS <13:	Thin

As this is not always the case, the districts thinning coupe map (Forestry Commission, 2017) was used to verify which stands are or will be thinned. The thinning coupe map shows the regime that is currently in place. Some sub-compartments that had been thinned are shown as non-thin regimes in this database. Because a stand is unstable until canopy closes current non–thin stands which were thinned in the last 10 years were considered as thin stands (Schelhaas & Vos, de, 2011) (Quine, et al., 1995).

On average, the district does intermediate thinnings and has a delay of at least 10 years. That is why, for the thinned stands, the management option of 'Intermediate thinning with a 10-year delay' is most applicable.

4. Step four in the process consisted of using the updated input data to show stability in the most comprehensible and accessible way. To solve the problem of accessibility it was decided that the new model should be incorporated in ArcGIS. This had several advantages over the current model. Everyone with the need for stability data has access to and experience with ArcGIS, the stand parameters would not have to be manually entered and the stability could better be visualised through ArcGIS.

All possible ways of showing stability based on ForestGALES were done. The following maps were created:

- Rotation periods per stand
- Number of years until instability
- Current stability in WDRS based on management regime, yield class and DAMS
- Map with current damaging wind return period

For the first two of these a bottom limit for stability had to be put in place. Therefore, a decision had to be made on what the acceptable risk is. This was determined in cooperation with the planning manager Doug Mitchell. If the 'Return Period' is over 50 years this is acceptable to the district. Because the stability drops quickly in time, the 10 years after the threshold of 1:50 years is marked as 'likely to blow'. 10 years after the stand has reached the threshold of 1:50 years it will enter its next status: extremely likely to blow.

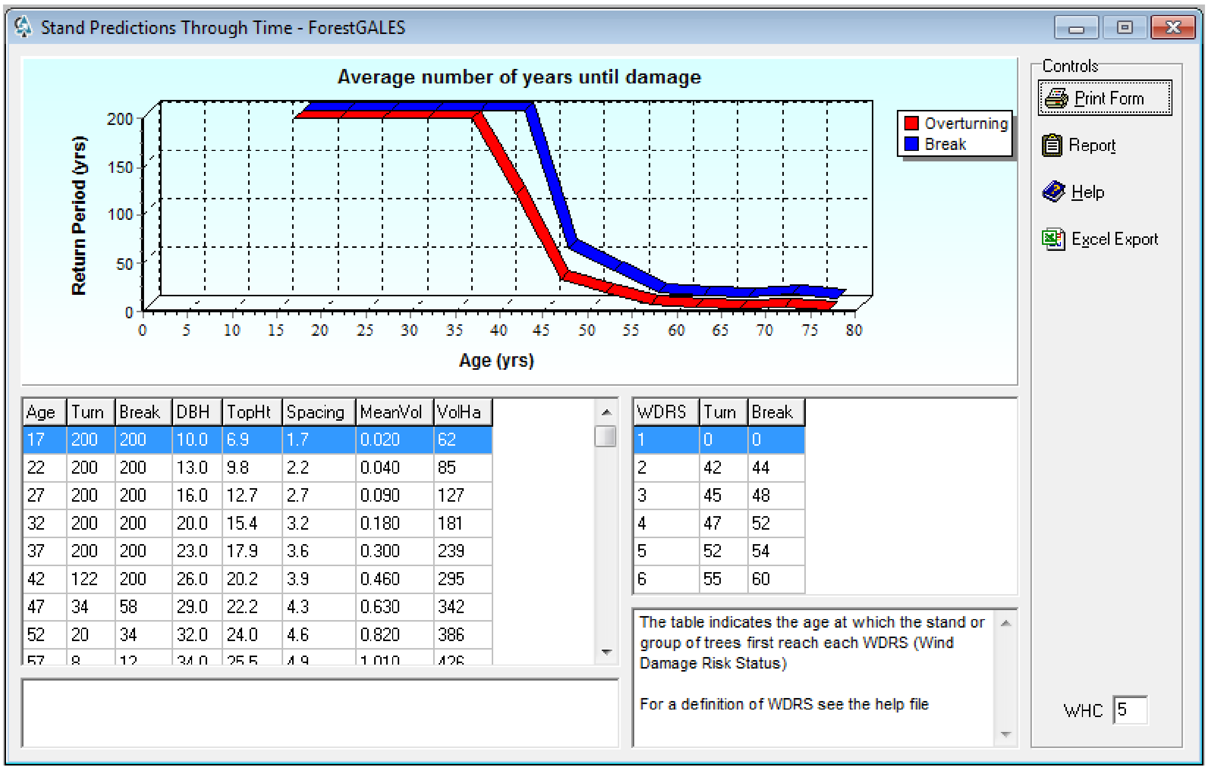


Figure 6: Screenshot ForestGALES showing the stability of a stand in relation to its age. The stand parameters for this example are; Sitka spruce, DAMS: 17, YC: 14, Management regime: 'Intermediate thinning no delay' and Spacing: 1.7m. The threshold of a return period of 1:50 years in this stand would be reached after 45 years (WDRS 3) (Source: ForesGALES).

The age at which a stand reaches the threshold was determined by using ForestGALES. As can be seen in Figure 6/Appendix 10, ForestGALES shows the stability in relation to age and the Wind Damage Risk Status (WDRS). The moment a stand enters status 3 the chance of wind damage is 1:50 years (Dunham, et al., 2000). Rotation periods based on this threshold for the productive species for all combinations of DAMS score, yield class and management regime were taken from the program to write a script (see Appendix 11 for an example). This script was then run through QGIS to calculate the rotation period per sub-compartment. The script makes use of the yield class, management regime and maximum DAMS score in a sub-compartment. It uses the maximum DAMS score because if part of the sub-compartment blows over, the rest of the sub-compartment is more likely to blow due to exposed edges. The maximum age for a stand was put on 100 years instead of the given 200 years because this is representative for productive forests.

The age of the stand was determined by subtracting the planting year by the current year.

The years to or after the threshold were then determined by subtracting age from rotation period

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5. To further analyse the relationship between windblow and other stand characteristics such as height, taper and the predicted rotation period, relevant stands were visually judged on damage. This was done by selecting all DG, EL, HL, JL, LP, SS and SP stands larger than 2ha and planted between 1920 and 2002. Larch data was taken out later in the process, resulting in 3519 visually checked stands. Small stands are less representative as they are subject to more external factors and young stands are highly unlikely to have blown and were therefore not taken into account. The selected stands were than visually judged on damage by using aerial photography (Figure 7).

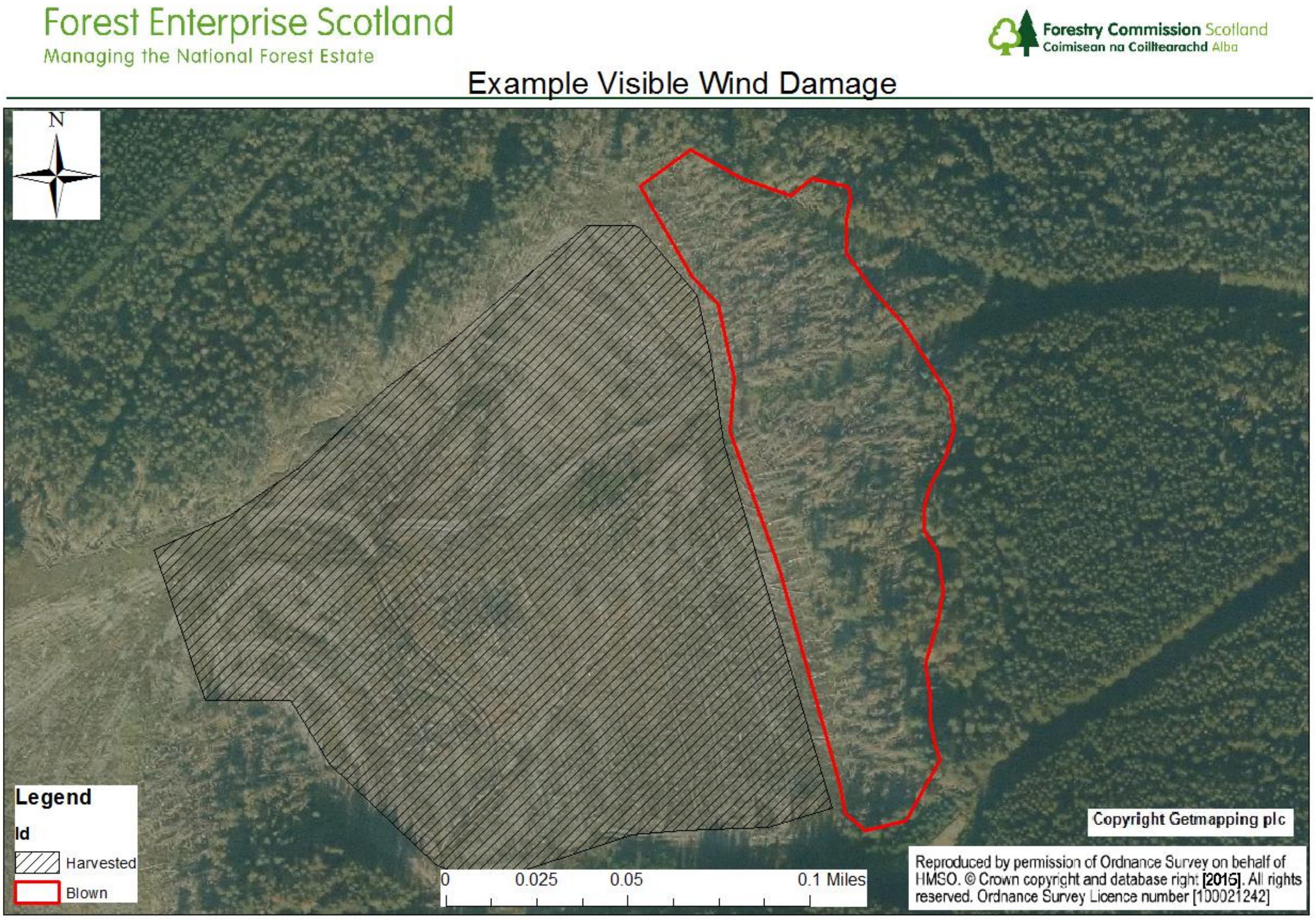


Figure 7: An example of visual wind damage starting from an exposed edge (Source: FCS)

Both windblow and exposed edges were noted. Windblow was defined as visible blown trees in part of the sub-compartment. Exposed edges were marked when the trees that blew over started at the exposed edges and blew in the direction away from the edge.

Hereby, a large dataset of stands with their age, ForestGALES's predictions, rooting, yield classes and actual damage was created. A similar method was used by Hale et al. (2015) and Välinger and Fridman (2011).

Damage was than compared to ForestGALES's predictions to see how representative the modelling per species is. Per species the stands were subdivided based on how far in their predicted rotation period they were. All stands that were more than 20 years past their predicted rotation were grouped together and all stands between 10 and 20 years past their predicted rotation period were grouped together etc. The percentage of damage was then calculated by dividing the damaged stands by the total stands in that group.

Taper and height, which are suggested to be related to stability, were cross-checked to look at the relation between the variable and damage.

Using this bigger dataset, it was possible to determine the relation between different soils and damage. Literature and experience suggest that rooting depth and soil type have influence on stability (Ray & Nicoll, 1998) (Blackwell, et al., 1990) (Blackburn, 1986). In the field, this was noticeable as well (Figure 8). On small scale, it was easily visible that waterlogged soils or peaty areas were blown prior to the rest of a stand with better rooting. Using the dataset created using aerial photography all stands still predicted to be stable were selected. The average rooting depth of the damaged stands was compared to the average rooting depth of the undamaged stands in this selection.

Another attempt to incorporate rooting in the maps was done based on the soil description. All stands that were predicted to be stable (not past rotation period) were selected. All soil polygons from the soil map overlapping these stands were then selected. The damaged and undamaged stands, determined using the aerial photography, could then be compared. Different soil types were selected to see if they matched up with wind damage. Selections of soil types suggested by the Forestry Commission soil guide (Kennedy, 2002) to have limited rooting were made; indurated, peaty surface water gleys, bogs and ranker complexes were selected.

Figure 8: Example of shallow rooting due to waterlogging of Douglas fir near Shenval, the root plate is on average less than 10cm thick (Source: Eelco de Jong)

4.3 Applying ForestGALES

There are different layers within the district which might have use of stability data, most prevalent of these is the planning department. By interviewing the planners and in particular, the planning manager, the different aspects of planning where stability is a major factor were identified.

In the previous part of the research 4 maps were made to show stability, in each of these, stability was shown using a different variable:

- Rotation periods per stand
- Number of years until instability
- Current stability in WDRS based on management regime, yield class and DAMS
- Map with current damaging wind return period

Feedback was asked from the potential users to see what they thought the maps might be useful for and why.

Complementary to that, other areas in need of stability data were identified. This was done by conversations with the planning department. For every area where stability data was needed the following questions were answered to make sure the result suited the demand:

- How is this problem tackled currently?
- What information could ForestGALES provide?
- How best to generate and show this information?

5. Results

The result of this report is, in essence, a series of maps showing stability in the Inverness, Ross and Skye forest district. The sub-questions were put in place to discover what and where the current model's weaknesses were and how to best improve these. Consequently, it has resulted in an advice to the district on how wind damage can be minimised using this updated model.

5.1 Current use of ForestGALES

Currently, ForestGALES is barely used in the district. Only the planning forester, Bob Chester, has experimented with it on a limited basis. Besides this, a map was made by Forest Research on stability in an area near the A82. Forest Research has also created a map with rotation periods but this has not been distributed to the planners and/because it contains a large margin of error.

The reason for the limited usage of ForestGALES is a lack of knowledge and a lack of trust. The planners have either not heard about it or have not been told how to use it. The only user of ForestGALES has, after several experiments, developed doubts about the current quality of the program.

Furthermore, ForestGALES is a program that must be installed separately on FC computers. Another option is using the Forest Research Decision Support Tool, which few have access to. For most employees who rarely use or wish to use the model this creates a barrier that they are not willing to overcome.

Opposed to that, a look was taken into previously used models and their accuracy compared to ForestGALES. Forest Research itself has done extensive research to this and has adapted the ForestGALES model based on this research. In a windblown Scottish upland conifer forest, different versions of ForestGALES and a statistical logistic regression model were tested and compared to the observed damage by Hale et al.(2015). This and other research suggests that previous models had bigger disadvantages and were generally more pessimistic and limited in their in and output (Gardiner, et al., 2008) (Miller, 1985) (Quine, 1994). Whilst other wind risk models have been developed at a comparable level of detail such as HWIND, ForestGALES has been developed particularly for the UK (Gardiner, et al., 2000) and is therefore likely to be more accurate in Scotland.

Currently, stability is not considered via any system by the planners. The WHC is still in the SCDB but not actively used. Local knowledge and experience are the main drivers of the decisions made on where to fell and what to preserve.

5.2 Refining the model

The first step in increasing the value of ForestGALES for the IRS FD was making sure the model is correct. To refine the model 27 stands with wind damage were assessed. The results are described below.

Out of the 27 damaged stands ForestGALES predicted 8 to be stable (a return period of 1:50 years or more)(Appendix 2). Out of these 8, 5 were found in the Meall Mor area, 1 in Shenval and 2 in Boblainy and Battan. The 2 stands in Boblainy and Battan turned out to have sustained little damage. Whenever ForestGALES predicted stable forests local circumstances explained instability (Appendix 5)

The wind data of Aviemore and Skye/Lusa connect seamlessly to the predictions by ForestGALES. Inverness Airport, DAMS 11, has wind speeds which correlate with a DAMS 17 site (Appendix 3).

The research to local influence of recently blown stands uncovered that the damaged stands that blew prior to expectation possessed one or more of the following aspects:

- Limited rooting depth (due to waterlogging, iron pans or bedrock)
- Exposed edges
- Delayed thinnings
- Deep ploughing (most likely single board)

All forests had blown whilst under influence of Westerly to Southerly winds.

When calculating district wide rotation periods, it was discovered that many yield classes were too conservative. Recalculations were done for all relevant sub-compartments and the result of this can be found in the shapefiles with the updated yield classes. Included in these shapefiles are all relevant data for stability; yield class, planting year, management regime, soil type, rooting depth, DAMS score, species and, if applicable, mensuration data.

This data was then run through the QGIS to determine rotation period per stands. This gave information on if a stand was passed its rotation period or not. The model predicted many larch stands to be past their rotation period. Out of 1107 larch stands, 178 were overshooting it. Two were past their expected rotation period by over 40 years and when entered in ForestGALES should be damaged every winter, when these sites were visited no damage was visible.

When all species were combined 615 stands were past their rotation period, 178 were larch species. Because the modelled data for larch was definitely far off the larch stands were taken out of the calculations from here on.

When the dataset of aerially judged stands was related to species and age and rotation period the following results were found (Graph 1):

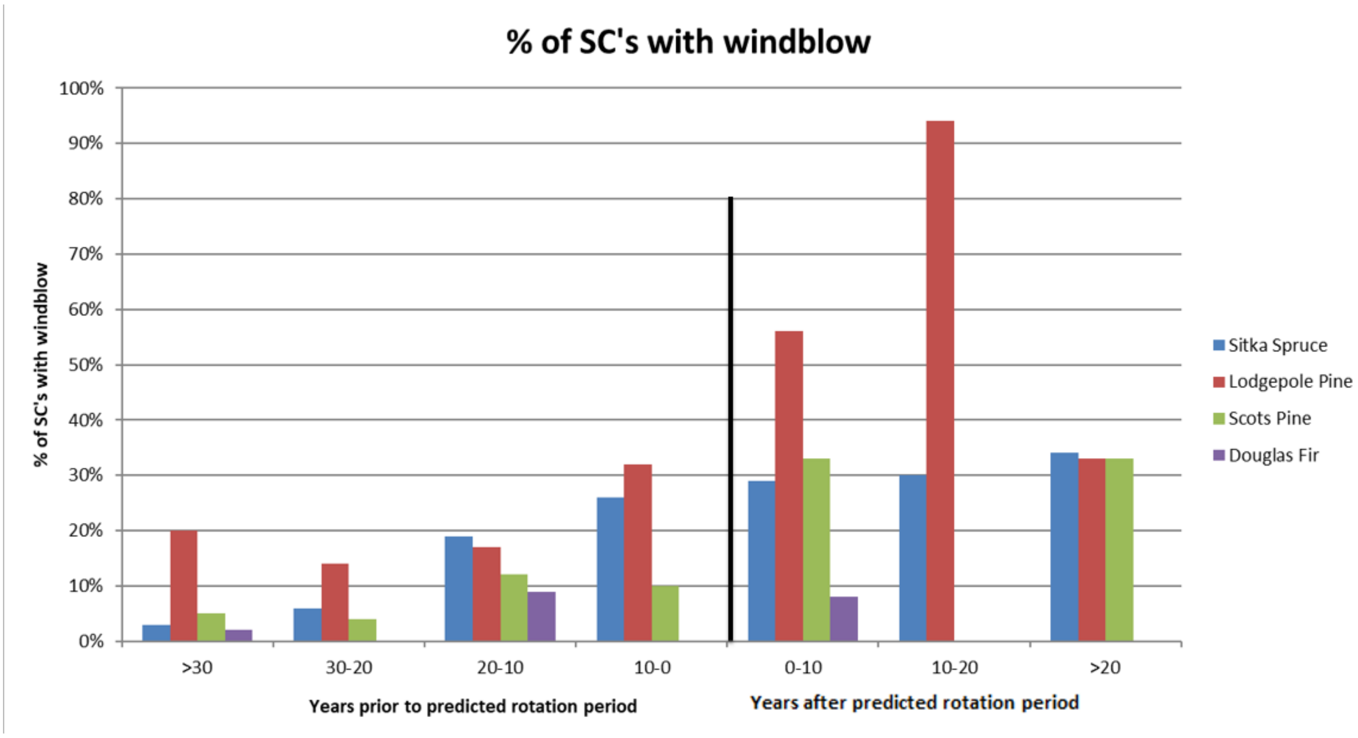
Sitka spruce stands that are past their predicted rotation period show a higher percentage of windblow. 30% as opposed to 10% but increasing the further past the rotation period a stand is.

Lodgepole pine stands that are past their predicted rotation period show a high percentage of windblow. The percentage of damage among stands that are expected to be stable is more than 10%.

Scots pine stands that are past their predicted rotation period show a higher percentage of windblow than stands that are still within their rotation period. About 30% of stands past rotation period are damaged opposed to 10% within rotation period.

Douglas fir can be far beyond its predicted rotation period but still be stable. However, the stand in Shenval demonstrates that it can blow far prior to its rotation period as well.

Graph 1: The percentage of damaged sub-compartments divided according to ForestGALES's prediction. In the bar '>30' all SC's more than 30 years prior to expected end of rotation period are included. The percentage shown is the percentage of SC's within that group that have sustained damage visible on aerial photography. Rotation period according to ForestGALES set at a maximum return period of 1:50 years.



Out of all 3519 stands judged using aerial photography, 430 (13%) had sustained wind damage in part of the sub-compartment which was visible on aerial photography.

25% of the windblown stands were predicted to be past rotation period and 45% was within 10 years of the predicted rotation period.

Out of the total stands, 20% has a thinning regime. Out of all windblown stands, 15% had a thinning regime of which 37% was past rotation period.

70 (17%) of the damaged stands had blown on exposed edges, damaging winds always came from South or West or something in between. On average the stands damaged on exposed edges were damaged 29 years prior to the end of their rotation period. Whilst stands that were not damaged on exposed edges were damaged 14 years prior to the end of their rotation period.

The average height of the damaged stands was 21m opposed to 20m in undamaged stands.

The taper (H/D ratio) in stands in which mensuration was done was in both damaged and undamaged stands on average 0.9. In stands with a thin regime, the average H/D is 0.84 respectively 0.86 for undamaged and damaged stands.

The above shown data gives no basis for adjusting the current model for the IRS district.

In Table 4 the relationship between rooting, soil description and damage is shown. Soil type and stability did not show a strong correlation. The only increase in damage can be found on soils with 'Indurated' in their description. Out of all the damaged stands that blew prior to expectation 80% are not on soils with 'Indurated' in their description. These results give no basis for adjusting the rotation period depending on the soil. Therefore, no adjustment was done.

Table 4: The relationship of the soil and the windblown stands which blew pematurely. The data was taken from the Stability Shapefile and Soil map.

	Undamaged stands (1577 soil polygons)	**Damaged stands (360 soil polygons)**
Average rooting depth	47cm	51cm
% 'Indurated' in description	9%	20%
% Peaty surface water gleys	45%	46%
% Ranker complexes	17%	17%
% Ironpans	16%	19%
% Bogs	58%	43%

5.3 Applying ForestGALES

The next part of the research focussed on where and how to apply ForestGALES in the district. The maps made in the previous part of the research were discussed with the planning department to see which information and which map is valuable for them during a part of the planning process. The maps received the following feedback:

Rotation periods (Appendix 12) > Would be useful for planning and FM especially if both management regimes are available. This way a choice in management regime can be decided on with more background knowledge.

Years until threshold (Appendix 13) > Would be useful for the planning department to get a view of current stability and the degradations of that in the coming years. This could be especially useful when planning coupe designs where stability is a limiting factor.

WDRS based maps (Appendix 14) > Gives very little information, only shows current status and is hard to comprehend. One would need knowledge of the program, the statuses and how to interpret that for management issues.

Return periods (Appendix 15) > Similar problem as with the previous map. Only gives information about the current status and not about the progression of stability in the future. It is the most accurate map because it directly gives the chances calculated by ForestGALES and is not converted to a rotation period

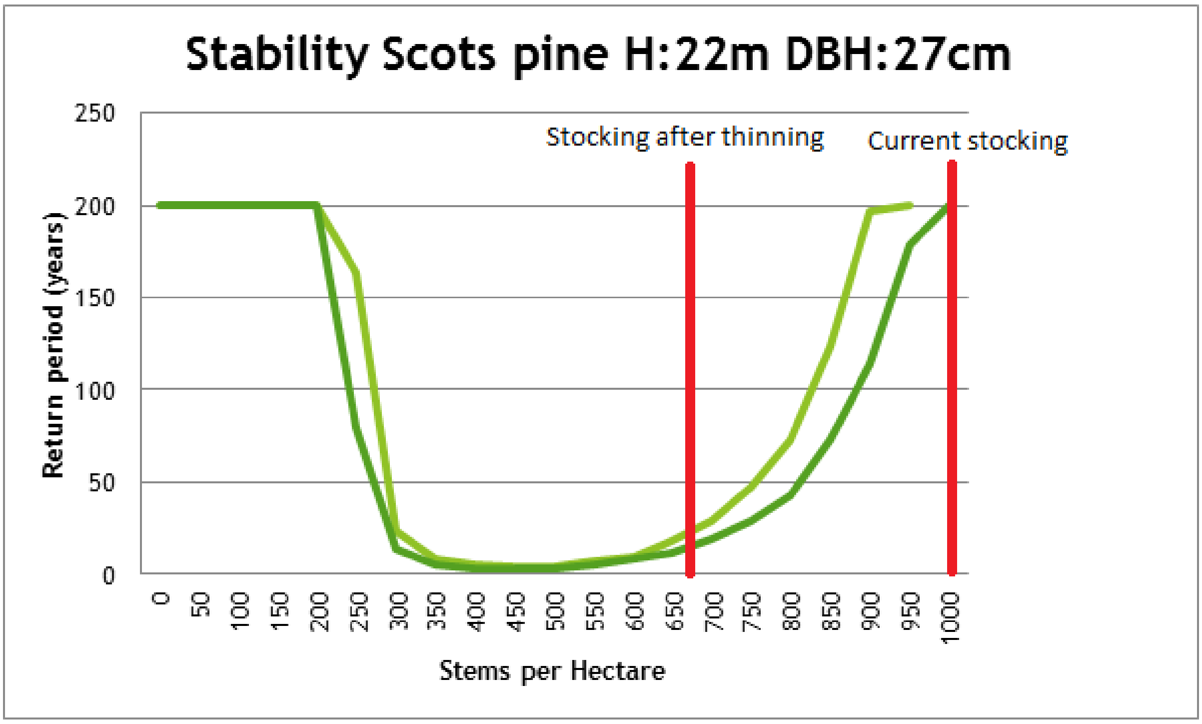
Based on the current issues the IRS district has with wind damage done by the inquiry, the implementation of the new format of ForestGALES can be used in the following places.

- Planning of fellings to determine which stands are prone to blow
- Planning of thinnings to determine how much can be taken away before the forest becomes too instable
- Planning of management regimes, currently this is based on just the DAMS score. With the help of ForestGALES this can be based on DAMS and the Yield Class, thereby giving more information and a better substantiation of the choice.
- Planning operations where wind damage might result in considerable problems such as the A82 fellings now.

Per situation, the relevant in and output has been discovered. For the first issue, planning needs to able to foresee which stands will be at risk. The most relevant information is the stability in relation to age. Because of this, the maps need to be able to model the growth, which can be done using yield classes. As mentioned in the feedback on the maps made, the preferable map in this case, is the one with the age subtracted from the expected rotation period. This then gives the number of years until instability.

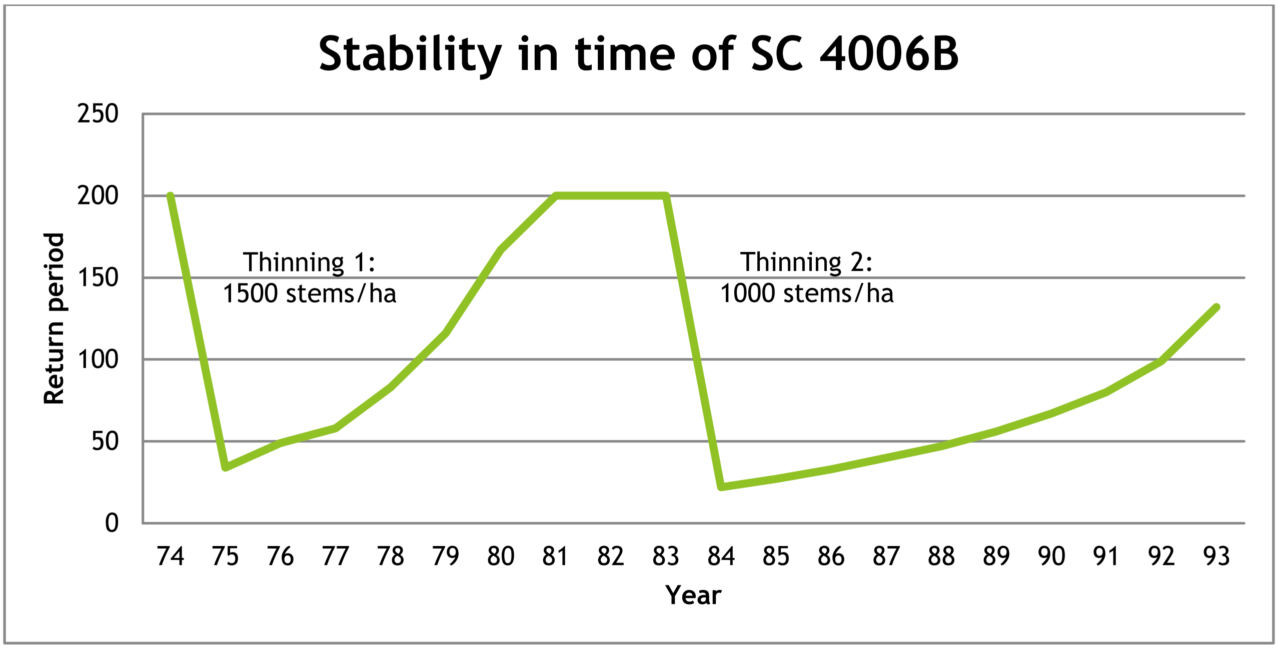
For the second issue, when planning thinnings, the stability in relation to the stocking is more important. Thinnings reduce the number of trees per hectare and thereby reduce stability for a while (Quine, et al., 1995). Knowing how many trees can be taken away without destabilizing the crop is valuable for planning the thinning (graph 2).

Graph 2: Predicted stability of a stand of Scots pine with similar height and diameter but a variable stocking, now done manually. The return period gives the likelihood of wind damage; 200 relates to a 1:200-year event. Lower return period means lower stability. If current stocking is 1000 the return period is 1:200. When a thinning reduces the stocking by a third the stability will drop significantly to a return period of about 1:25.



In addition to that, it is relevant to know the recovery in terms of stability after a thinning. This has been shown as the return period in relation to years (graph 3) The dimensions of the trees were predicted using yield models (Forestry Commission, 1971)

Graph 3: Progression of stability in relation to age after two thinnings of sub-compartment 4006B a Scots pine stand in Inshriach starting with a stocking of ±2000



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Currently, these graphs can only be calculated by entering the dimensions manually. For every year the tree properties have to be looked up in the yield models and thereby the risk is calculated. The data is useful but the usability of the model for this case could use improving.

The third issue revolves around rotation periods. Deciding whether a site is suitable for thinning is now based on exposure only. To further substantiate this decision, maps with rotation periods were created that combine exposure and yield classes. Per sub-compartment the expected rotation period in case of a thinning regime and a non-thin regime is shown. If the expected rotation period with a thinning regime is shorter than the desired rotation period, the non-thin regime can be chosen.

Some high-risk operations require more detailed knowledge about the coupes to fell. Currently, IRS FD is doing fellings on the slope above the A82, a major road connecting Fort William and Inverness. Wind damage in these coupes would result in high risk for the contractors and traffic on the road. Knowing which stands are prone to blow can help planning the operation so as not to create exposed edges where it might result in wind damage. According to the manager of this operation, the current stability shown as a return period is most valuable (Macleod, 2017). This gives the most accurate information of which stand is most likely to blow and what that chance is. An example is given below in Figure 9.

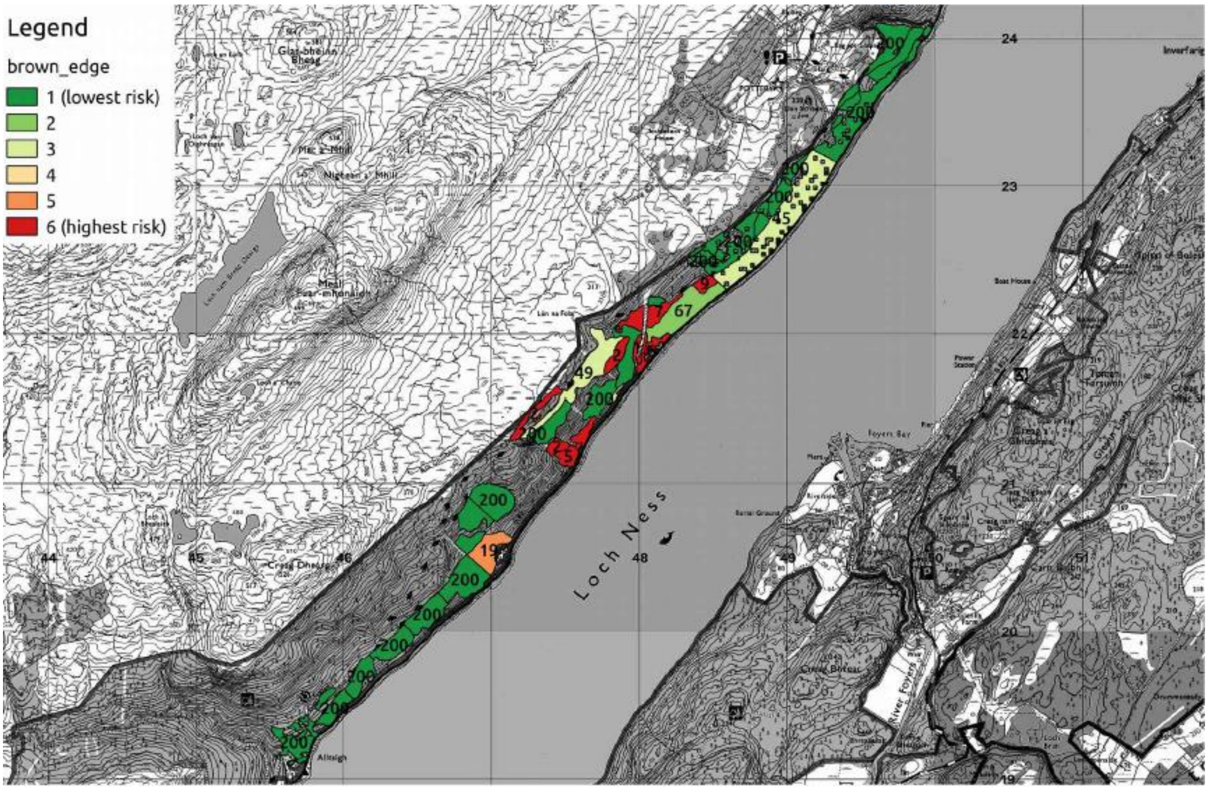

Figure 9: Map with return period of damaging wind speeds near the A82 (Source: Forest Research)

6. Discussion

In this discussion, reflection on the method will take place. Furthermore, the results taken from the research will be cross-checked with reality. When possible the answers will be related to previous research done in this field. Limitations and further research will be listed and lastly, the impact of the research on sustainability will be demonstrated.

6.1 Methodology

The methodology chosen was the most appropriate given the time and data available. Looking back there are some points of improvement which could be used for future research.

To test ForestGALES, 27 recently damaged stands were measured and modelled. Ideally all variables would be entered in the model exactly to see if the model predicts trees of that size to blow with the exercised force. The major flaw in this research was that one variable could not be discovered; the wind speed. It is possible that all stands are of similar stability and the only reason the researched stands blew over is a very local exceptional wind speed. Because of the variability in forest blocks and the unpredictability of wind speed no control group could be set up either, the sheer number of different variables would result in no valid data. Without the means to discover the wind speed at the time of damage there was no way of justifying any changes to the internal part of the model for the IRS FD. The only conclusion that could be drawn from this part of the research was that most damaged stands were predicted to be vulnerable to windblow. The ones that were predicted to be stable either did not have damage or possessed characteristics related to instability.

In this research the stability was converted to a rotation period. The damage was than related to how far an SC is in its rotation period. There is another, more direct, way of checking ForestGALES. Likelihood of damage can also be given as a percentage. This can then be related to the percentage of actual damage between SC's. Determining the relationship between these would give more accurate data. However, this would limit usability as it only gives current stability. For the planning department the most valuable information is stability in relation to age and therefore the decision was made to work with the rotation periods. The value of this rotation period was higher than the loss of accuracy for this research.

6.2 Interpretation of results

In this chapter the results will be reflected upon using local knowledge and literature. Likely explanations will be provided and substantiated.

To try and confirm the wind speed prediction, DAMS was researched to its maximum extend. This only enabled the confirmation of DAMS at three specific locations. Research on this subject has been done and is ongoing so the assumption was made that DAMS does give valid information (Hale, et al., 2015). The low score given by DAMS for Inverness Airport could be explained by the fact that DAMS was created for upland forests (White & Quine, 1993). Besides this, Inverness airport is unusually exposed. The weather station is right

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next to the runway and close to sea (Bathgate & Locatelli, 2017). Because there is no other data available within the district which would justify changing DAMS, the scores were kept the same in this research.

The larger dataset based on aerial photography gives a good basis for relating ForestGALES predictions to actual damage. The sample size is of such extent and throughout the entire IRS FD that the data is representative.

As opposed to conclusions in several previous studies to windblow (Schelhaas, et al., 2003) (Lohmander & Helles, 1987) stand height was not an important factor to overall risk in the SC's assessed in IRS FD. The average height of damaged stands was not significantly higher than that of undamaged stands. A possible explanation for this is the terrain of the district. Previous studies were done in largely homogenous terrain. In this district, there is an enormous variety in exposure and elevation, impacting terminal height. Within the district are some of Europe's tallest trees, sheltered in a valley, as well as areas were tree growth is hardly possible due to elevation and exposure. Furthermore, there is a range of coastal to continental climates. This directly shows the value of ForestGALES's predictions which combine exposure and growth rate in detail.

The percentage of damage in stands past their rotation period is higher than of stands prior to the end of their rotation period. This shows the relationship between actual damage and the prediction of ForestGALES. Lodgepole pine stands more than 20 years past their predicted rotation period gave a slightly lower percentage of damage than stands between 10-20 years past their rotation period (Appendix 17). Probable causes for this could be that stands >20years past rotation have withstood damage for a long time and have reached their top height. Furthermore, the last thinning was done in such stands many years ago and the trees have been able to adapt to mechanistic forces acting on them. This idea was formulated in previous research by Välinger and Fridman (2011).

As this study proves as well, exposed edges decrease stability. This is further supported by the studies of Lohmander and Hellis (1987) and Quine et al. (1995).

The dataset showed that thinned stands were less susceptible to blow prior to their predicted rotation period than unthinned stands. This gives the image that thinned stands are more stable than predicted in comparison to unthinned stands. The predictions for thinned stands were however made using the 'intermediate thinning with a 10-year delay' models, resulting in pessimistic rotation period. With these pessimistic rotation periods overshooting the rotation period is more likely. Any thinning done in time would result in forests being more stable than predicted. When thinnings are done in time they are predicted to be stable for at least 10 years more than when thinnings are delayed (Forestry Commission, 2015).

In other studies, (Välinger & Fridman, 2011) (Albrecht, et al., 2010) there was a relation between species and damage. Especially Norway Spruce was found to be vulnerable to windblow. Pines were considered more stable than Spruce species and Douglas was associated with higher probability of damage. Within the IRS district, a different image is visible. Lodgepole pine is most susceptible to windblow even from an early age on. Sitka spruce does have shorter rotation periods than pine species but this is most likely due to the higher growth rate. Douglas stands seem to surpass the predicted rotation period more often than all other species researched. The most likely explanation for this is the soils the different species are grown upon. Lodgepole pine does relatively well in the wet, water-logged and more exposed places which limit anchorage. The IRS district has a substantial amount of these soils and often this is planted with Lodgepole pine. Douglas fir is generally only planted on brown earths which are optimal locations for rooting.

When comparing stability and soil maps no relationship could be found. Multiple site visits and interviews with foresters demonstrated that soil impacts stability. Waterlogged areas within a stand demonstrated wind damage whilst the rest of the stand was still stable on several occasions. Previous research is unanimous about the fact that soil affects stability (Gardiner, et al., 2013). Anchorage is reduced by water-logging, heavy rain and poor drainage (Gardiner, et al., 2010).

One last factor that has, in previous research, been related to stability is taper (Wood, 1995) (Gardiner, et al., 2013). In the IRS district, this does not seem to affect stability as on average the H/D ration is 0.9 in both damaged and undamaged stands. The explanation for this could well be the management strategy. Within the district the thinning program is small, most (80%) of the stands have non-thin regimes. These rely heavily on mutual support for stability and on average have a high H/D ratio. When thinnings are done, trees rely less on mutual support and more on their own strength and anchorage. A small increase in average H/D ratio was found in damaged stands opposed to undamaged stands with thinning regimes.

The most important result of this research is the relation between the prediction of ForestGALES and actual percentage of damage in the field. However, there is still a large percentage of the stands which are past rotation period but do not show signs of windblow and the other way around. This has to do with the research being probability based. The moment a stand is at the end of its rotation period there is a 2% chance of damage predicted by ForestGALES. The years after, the chance of damage increases rapidly. If the thinning regime was done in time, if anchorage is exceptional at that location or if the exposure is inaccurate the chance of damage can be much lower. On the other hand, limited rooting or exposed edges can decrease rotation periods drastically. All these variables have influence but need further research or higher quality data to be quantified for the district.

6.3 Limitations

The work done on ForestGALES in this research was as diligent as possible but still limited by time, resources and knowledge. Therefore, not all aspects of the model could be researched and perfected to the full extent. In this paragraph, the main limitations of the research will be presented.

When considering the different models and their pro's and con's, literature suggested that ForestGALES would be the most applicable model for the district. Because of limited time and more importantly, limited knowledge on this complex subject of wind modelling, the decision was made to only use ForestGALES. Previous research compared different models with observed damage to determine the accuracy of the modelling (Hale, et al., 2015). The choice of only using the most recent version of ForestGALES was based on this previous research.

It was beyond the scope of this study to research the climatic part of the model (DAMS) to full extend. This is because redesigning wind speeds would take more data, time and knowledge than available at this point. For this research the assumption was made that wind speeds behaved largely as DAMS predicts, the limited investigation of DAMS did back this decision. Another major factor which impacts exposure but is not researched is climate change. The subject of climate change is a complex one, a diligent research into the effects of climate change on wind speeds without a major error margin was not possible within this timeframe and with current knowledge.

The scientific basis of the model for some of the species is extensive. For others, it is rather limited. Especially for Douglas fir and the larch species, the number of trees pulled is minimal (see Table 5). It should always be considered that the smaller the scientific basis the higher the risk of inaccuracy. This is most likely the reason for the predictions of all larch species being far off. Douglas fir stands seem to surpass their expected rotation periods by a considerable amount of years as well but the likely explanation for that is the soil choice (Savill, 1991).

Table 5: Number of trees pulled per species

Tree species	No. pulled
Douglas fir	40
European larch	24
Japanese larch	44
Lodgepole pine	244
Scots pine	137
Sitka spruce	1155

The research to soil in relation to stability was very much limited by the level of detail of the soil map. There were clear signs that soil influences stability but the soil map is generated to give only a general indication of soil properties. The level of detail necessary to accurately predict stability in relation to the soil is not present. A similar issue arises when using the SCDB, the research and the maps are limited by the level of detail and the quality of the data of this database as well.

One of the new ways of applying ForestGALES would be in the planning of thinnings. It would have been valuable to make sure this would be possible using batch calculations for the district. Due to limited knowledge of computing and limited time, this could not be done during this research.

6.4 Further Research

As mentioned in the limitations there are several areas were the research was limited by the available data. To continue to guarantee and improve the quality of the model some recommendations on further research are essential to make.

First off, a recommendation will be made that was made 17 years ago for the first time (see Figure 10). The sub-compartment database comprises all necessary information for ForestGALES to make a prediction on stability. A script encompassing all this which automatically updates when changes are made to the sub-compartment database would be ideal.

What to expect in future versions of ForestGALES

In future versions of ForestGALES the following features are planned:

- Seamless integration with a Geographical Information System (GIS), allowing easy data extraction.
- Integration with the latest FC yield models.

Figure 10: Prediction on future versions in 2000 (Dunham, et al., 2000)

Fields of study with the highest priority for getting more accurate predictions of wind damage are:

- In-depth research of thinnings and its effect on stability. Currently, the predictions of stability are based on the yield models. These only include the aboveground tree measurements. The effect of a delayed thinning is suggested to result in limited rooting and therefore more instability as well. The centre of gravity also moves up quickly when thinnings are delayed resulting in a lever effect, reducing the force necessary to blow a tree over (Rayner, 2010) (Schelhaas & Vos, de, 2011).
- For the IRS district, more tree pullings of Scots pine in shallow soils and with different management regimes would be valuable. The number of tree pullings done in Scots pine sub-compartments with a rooting depth of <40cm is very limited (5 sites) (Nicoll, et al., 2006).
- More tree pullings of larches and Douglas fir in general.
- Creating a batch mode in ForestGALES with which the stability in relation to stocking and the recovery after thinning can automatically be calculated.

- Concerning rooting, it would be a large improvement of the model if it adjusts for the soil quantitively. Perhaps connections between rooting and stability can be found in other places than were looked for in this research or the soil mapping should be done in more detail. More research to tree anchorage would be extremely valuable for ForestGALES's calculations. The relationships between stability and moisture levels, rooting depths and soil fractions are rather unexplored. If this were to be quantified one would have a stability model based on the belowground, aboveground and climatic data which would improve the model drastically.
- With recognition software, all damaged stands throughout the United Kingdom could be identified. As yield classes and ages are known the scripts could be run on them. Thereby the model could be calibrated using the largest possible dataset.

6.5 Sustainability

The main objective of the Forestry Commission Scotland is expanding and preserving Scottish forests. It does this for three, equally important, reasons. Historically the sustainable resource production for local markets was the most important. Nowadays, the environmental and recreational values are protected and enhanced with as much vigour. At the end of the day the Forestry Commission has a finite number of resources. The main income still comes from the timber production. With the money made, the production, environmental and recreational values are sustained. Wind damage causes a serious budget cut as mentioned in the introduction. This results in lower quality forests or less budget to increase quality or land. Considering FC's strategy, money saved on an avoidable expense will be put to good use. A higher budget will enable FC to increase sustainable resource production, increase recreational values and increase habitat quality throughout the UK

7. Conclusions and Implications

Based on this report, it is advisable for the district to undertake steps to continue decreasing wind damage. A subdivision in conclusion and direct implications has been made.

7.1 Conclusion

The goal of this research was minimising wind damage making use of ForestGALES. Current use of the model has, up until now, been very limited in IRS FD. The reason for this being lack of usability and lack of trust in the modelling. This gave the two major areas of improvement for the model.

The lack of usability was due to IT barriers and lack of knowledge of the model's existence. Furthermore, the model could not do batch calculations and the output gave a limited amount of information.

The lack of trust was due to errors in the input and modelling. These shortcomings were a result of incorrect yield classes, limited adjustment for management regimes and little to no adjustment for soils. Updating these has increased quality and trustworthiness of the model. The influence of soil however, could not be quantified in the model.

Different ways of applying the model were found and for each, the most relevant format was used to give the information.

The new maps and models calculate a rotation period based on a bottom limit on the stability of 1:50 years return period. If stands blow before this point in time it is either due to extremely unlikely wind speeds or other circumstances such as delayed thinnings, waterlogged soils or mistakes in coupe design. These last three can all be avoided through diligent silvicultural and civil measures. The maps can substantiate decisions of rotation periods, management regimes and coupe designs.

The new maps show that wind damage can, to a certain extent, be predicted. Stands predicted to be unstable show a high rate of wind damage. However, there are sites that are predicted to be very unstable which show no sign of damage and the other way around. The problem here is that wind, soils and growth cannot be calculated to exact detail with the existing mapping and knowledge. The new maps are however valuable tools for sequencing the timing of crop removal, planning management regimes, planning high-risk operations and planning thinnings.

ForestGALES and the maps must, therefore, be tools to <u>support</u> decision-making not make the decision. Local knowledge should always be considered.

7.2 Implications

The following implications for forest management can be drawn from the research:

- Do not create brown edges on the West- or Southside of the forest. Fell from North-East to South-West.

- Do not delay thinnings. Delayed thinnings have a drastic impact on stability because as trees are forced to grow up quicker and lose lower branches, their centre of gravity moves up rapidly. The competition also results in limited rooting. Every year a thinning is delayed stability drops significantly. When it comes to thinnings they should be done in time, moderately and often. When the thinning is put off for too long it is advisable to not thin at all as stability will never fully recover from the thinning. (Gardiner, et al., 2013).

- Consider draining waterlogged areas to increase stability.

- Use the stability maps when planning land management plans to spot high-risk areas and get an idea of stability for the coming rotation.

- Use the stability maps for substantiating the decision on management regime.

- Decrease rotations of Lodgepole Pine to minimise damage drastically.

- When starting high-risk operations such as the A82 operation make sure stand data is accurate so that accurate stability predictions can be made.

- Keep improving quality of the model by staying in contact with FR. When new data is available rerun the scripts using this new data to get the most accurate stability predictions.

The work on ForestGALES has resulted in a product which makes it easier to predict wind damage. However, the model itself does not prevent wind damage. When the model is perfect but unused wind damage can still be a significant problem. In the end, it is up to the users of the model to take the appropriate measures by taking the predictions of the model into account.

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Appendices

Contents

Appendix 1 – Example yield loss windblown site

Shenval calculation								
DBH	26cm							
Height	19m							
Ha	9.5ha							
M3	2000m3							
Age	33years							
	Windblow					**Not windblow growing until mature**		***60yrs (9000 tons)***
	Tons	Price per ton	Total			Tons	Price per ton	Total
Logs	1482	£ 45.00	£ 66,703.50		Logs	7290	£45.00	£328,050.00
Pallet	408	£ 28.00	£ 11,424.00		Pallet	1505	£28.00	£42,134.40
Chips	549.7	£ 28.00	£ 15,391.60		Chips	205	£28.00	£5,745.60
Haulage	2440	-£ 8.00	-£ 19,520.00		Haulage	9000	-£8.00	-£72,000.00
Harvesting	2440	-£ 14.00	-£ 34,160.00		Harvesting	9000	-£11.00	-£99,000.00
Total	2440	£ 16.33	£ 39,839.10		Total	9000	£22.77	£204,930.00
	Not windblow			**Restock site like this**				
	Tons	Price per ton	Total			Amount	Price	Total
Logs	1976	£ 45.00	£ 88,938.00		Mounding (ha)	9.5	£ 700.00	£ 6,650.00
Pallet	408	£ 28.00	£ 11,424.00		Planting (ha)	9.5	£ 300.00	£ 2,850.00
Chips	55.6	£ 28.00	£ 1,556.80		Plants (pcs)	2800	£ 0.10	£ 280.00
					Beat up planting (h	9.5	£ 110.00	£ 1,045.00
Haulage	2440	-£ 8.00	-£ 19,520.00		Beat up plants (pcs	420	£ 0.10	£ 42.00
Harvesting	2440	-£ 11.00	-£ 26,840.00					
					Total			£ 10,867.00
Total	2440	£ 22.77	£ 55,558.80					

Figure 11: Data gathered through: (Forestry Commission, 1971) (Manson & MacPherson, 2017) (Baranski, 2017)

Appendix 2 - ForestGALES predictions for recently blown stands

Determining Damage IRS FD																				
							Overturn			Breakage										
Block	Compartment	Subcomp.	Height (m	DBH (cm)	Stems/Ha	Spec.	Speed (km/h)	Return (yr)	Status	Speed (km/h)	Return (yr)	Status	Rooting (cm)	Direction	DAMS	PLYR	YC	H/D	Return period YC based
Black Isle	1080		22	31	410	SP	69.2	2	6	83.8	29	4	60	W	16	1949	10	0.709677	1
20m gap	1081		22	29	432	SP	61.8	1	6	73	4	6	70	W	16	1949	10	0.758621	1
	1082		24	32	388	SP	57.3	1	6	68.1	2	6	70	W	16	1950	10	0.75	1
	1083		23.5	31	352	SP	59.2	1	6	70.4	3	6	60	W	16	1949	10	0.758065	1
B&B	1403	a	22	27	359	SP	59.8	3	6	67.8	13	5	50	SW	14	1951	10	0.814815	6
20m gap		b	20.5	27	563	SP	68.2	2	6	76	7	6	40	SW	16	1951	10	0.759259	1
		c	19.5	25	775	SP	75.2	17	5	82.8	89	2	50	SW	15	1951	8	0.78	51
		d	32	28	975	SS	38.6	1	6	32.9	1	6	40	SW	15	1951	18	1.142857	1
		e	32	28	975	SS	39.3	1	6	30.6	1	6	40	SW	14	1951	18	1.142857	1
	1418	b	20.5	30	397	SP	77.8	29	4	98	200	1	40	SW	15	1955	10	0.683333	2
	1419	a	19	28	469	SP	82.2	21	4	104	200	1	50	SW	16	1955	8	0.678571	6
		b	18.5	23	1125	SP	84.2	124	1	91.8	200	1	60	SW	15	1955	8	0.804348	16
		c	20.5	23	1020	SP	72.5	36	3	75	200	1	40	SW	14	1955	10	0.891304	7
		e	20	29	525	SP	74.7	16	5	95.1	200	1	50	SW	15	1955	10	0.689655	3
	1421	a	18	23	1010	SP	84.7	35	3	93.7	200	1	40	SW	16	1955	8	0.782609	6
	1428	a	18.5	24	941	SP	82	21	4	91.1	130	1	50	SW	16	1956	8	0.770833	6
		b	18.5	24	941	SP	82	21	4	91.1	130	1	50	SW	16	1956	8	0.770833	6
	1429	a	18.5	25	730	SP	78.5	11	5	88.9	81	2	60	SW	16	1954	8	0.74	5
	1430	a	21	26	943	SP	77.2	112	1	83.3	200	1	60	SW	14	1954	10	0.807692	6
	1436	a	19	24	583	SP	67.1	4	6	76.3	22	4	60	SW	15	1955	8	0.791667	15
Shenval	1550		19	26	565	DF	76.9	200	1	103	200	1	20	W	13	1984	20	0.730769	200
Meall Mor	3305	a	YR: 1963	26	YC: 12	SP	78.8	200	1	83.9	200	1	-	W	13				200
20m gap		b	YR: 1963	21	YC: 10	LP	61.9	12	5	54.4	3	6	-	W	13				3
	3307	b	18	21	1610	SP	90.7	200	1	96.1	200	1	-	W	13	1963	10	0.857143	36
		c	18	20	938	SP	68.7	200	1	71.5	200	1	-	W	12	1963	10	0.9	36
	3311	a	18.5	25	790	SP	80.2	200	1	90.7	200	1	-	SW/W	13	1963	10	0.74	36
	3312	a	19	24	972	SP	81.4	200	1	89.1	200	1	-	W	14	1963	10	0.791667	36

Appendix 3 – Return periods of wind speeds per DAMS Score according to ForestGALES

DAMS 17 return periods		
km/h	return period	chance in 1 year
99.9	200	0.50%
98.6	155	0.65%
97	114	0.88%
95.5	84	1.19%
93.9	62	1.61%
92.4	46	2.17%
90	35	2.86%
89.3	26	3.85%
87.8	20	5.00%
86.2	15	6.67%
84.5	11	9.09%
82.8	9	11.11%
81.1	7	14.29%
79.6	5	20.00%
77.9	4	25.00%
76.2	3	33.33%
74.3	3	33.33%
72.4	2	50.00%
70.8	2	50.00%
68.9	1	100.00%

DAMS 11 Return periods		
km/h	return period	chance in 1 year
59.6	200	0.50%
58.6	161	0.62%
57.3	106	0.94%
56.1	70	1.43%
54.9	47	2.13%
53.6	32	3.13%
52.4	22	4.55%
51.2	15	6.67%
49.8	10	10.00%
48.4	7	14.29%
47.1	5	20.00%
45.5	4	25.00%
44.1	3	33.33%
42.7	2	50.00%
41	2	50.00%
39.4	1	100.00%

Appendix 4 – Validated meteorological data

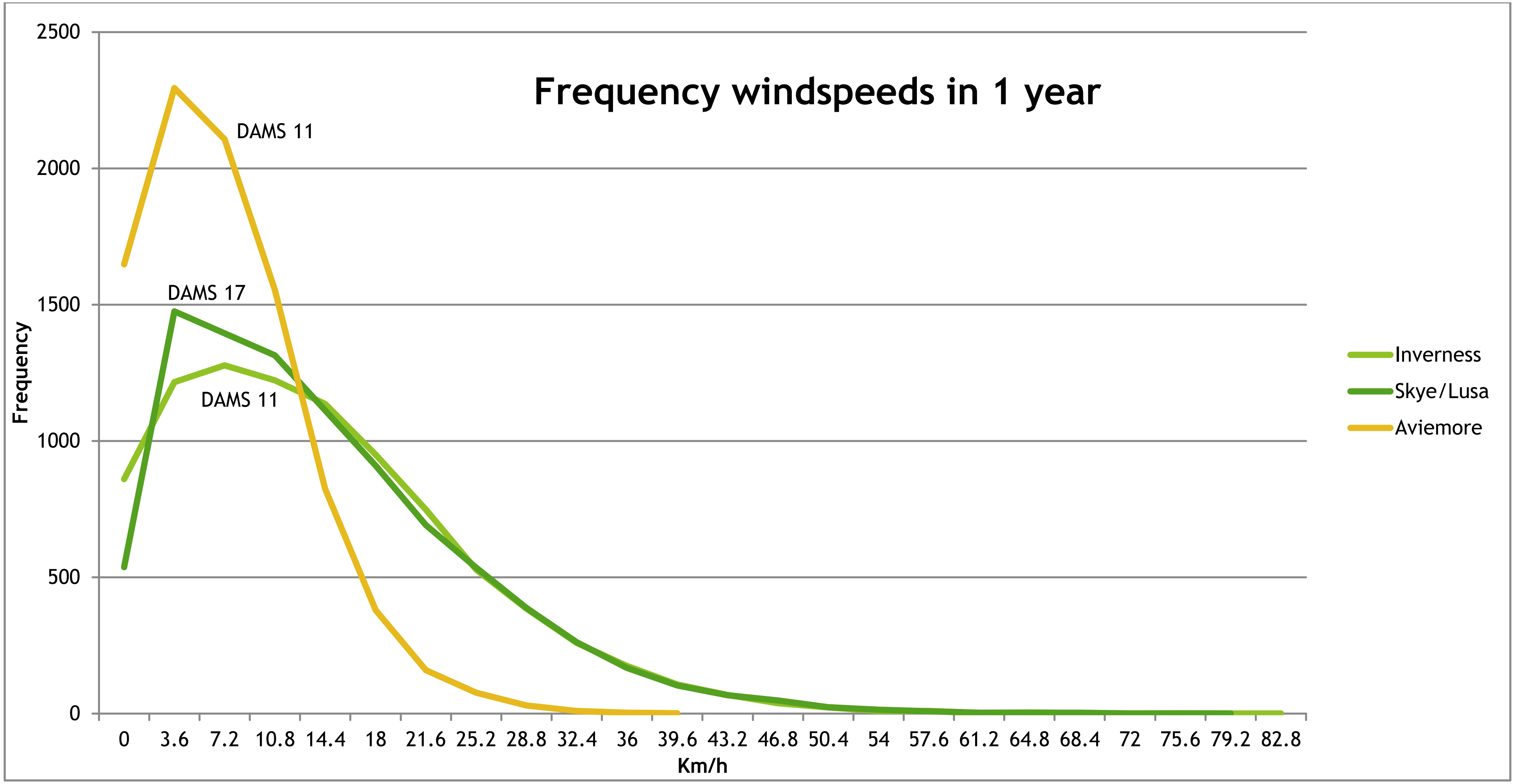


Figure 12: Frequency of different wind speeds in one year (WeatherOnline Ltd., 2017)

Appendix 5 – Descriptions windblown stands

To calibrate ForestGALES four locations were picked which recently experienced windblow. Of all the locations, the predictions of ForestGALES are given (appendix 6) and the situation is described.

Black Isle (appendix 3)

Mature Scots Pine stand, can be described as natural thinning, reasonable rooting but at the point where forest is unstable according to GALES. Damaging wind came from the West. Method of ground preparation could not be discovered, most likely ploughed.

Boblainy & Battan(appendix 4)

Similar to the black isle only with smaller trees. Higher wind exposure. In this case thinnings were delayed which is reflected by the higher H/D ratio. Rooting is reasonable, approximately 40 cm at the least. Damaging wind came from the South-West. Method of ground preparation could not be discovered but is most likely ploughed again.

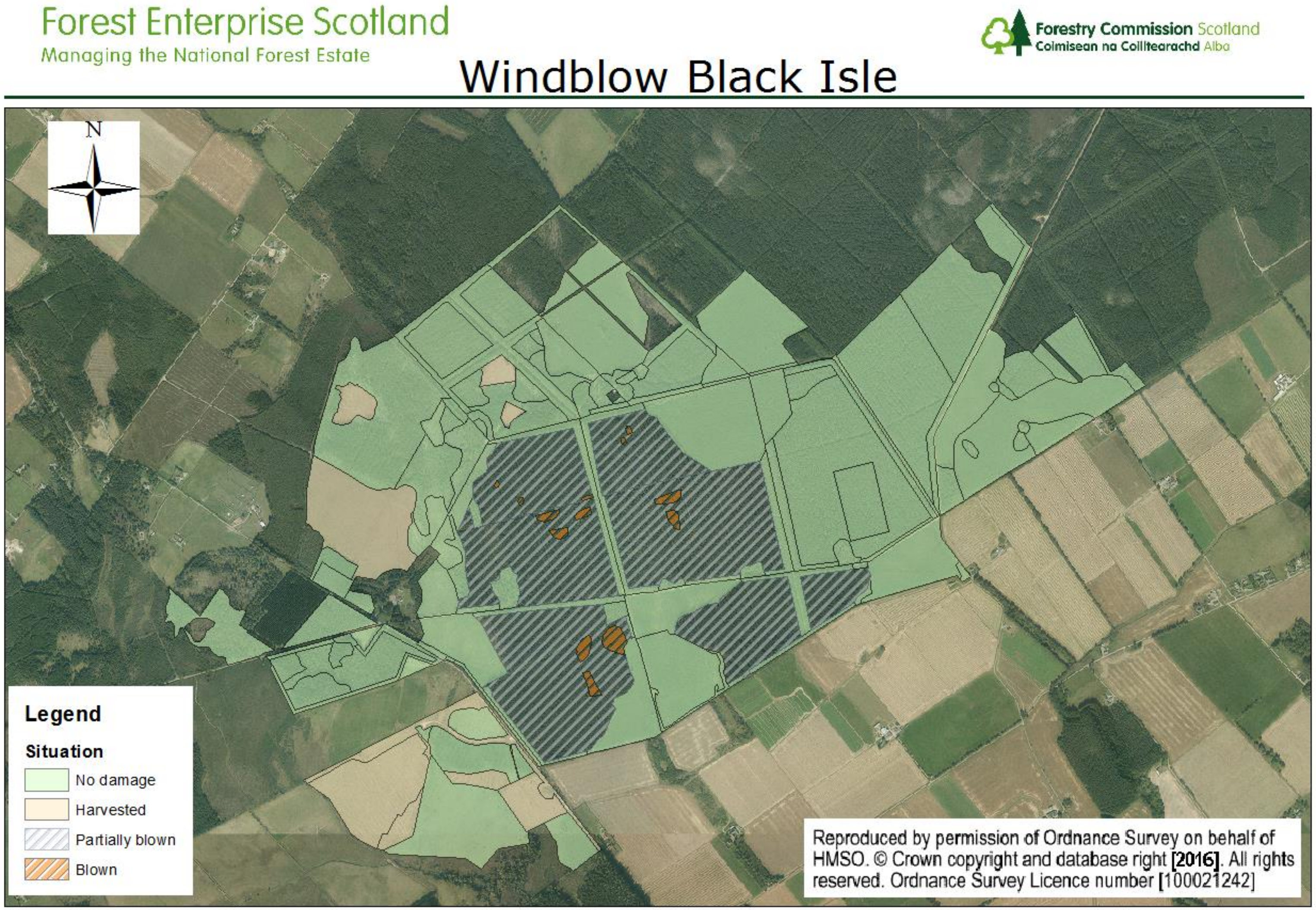
Meall Mor (appendix 5)

According to ForestGALES based on mensuration this stand should be stable. There were however three major aspects influencing the stability. Several pockets with high water tables (especially in peaty surface water gleys) caused areas of shallow rooting. These were blown over first by westerly winds.
Around 2001 the Forestry Commission issued an increase in thinnings. For IRS FD, this meant they had to do thinnings in windy and marginal sites (Chester, 2017). Meall Mor was one of these sites were a non-thin regime was originally planned but due to change in policy a thinning was scheduled. Consequently, the first thinning was years too late. The stability in these stands was largely dependent on mutual support. When removing this support, the forest became more unstable.
Thirdly operations in the vicinity of the stand resulted in large brown edges. The already unstable forest could not handle that level of exposure and blew over.
Anecdotal evidence furthermore suggests that the wind that damaged Meall Mor was exceptionally fast.

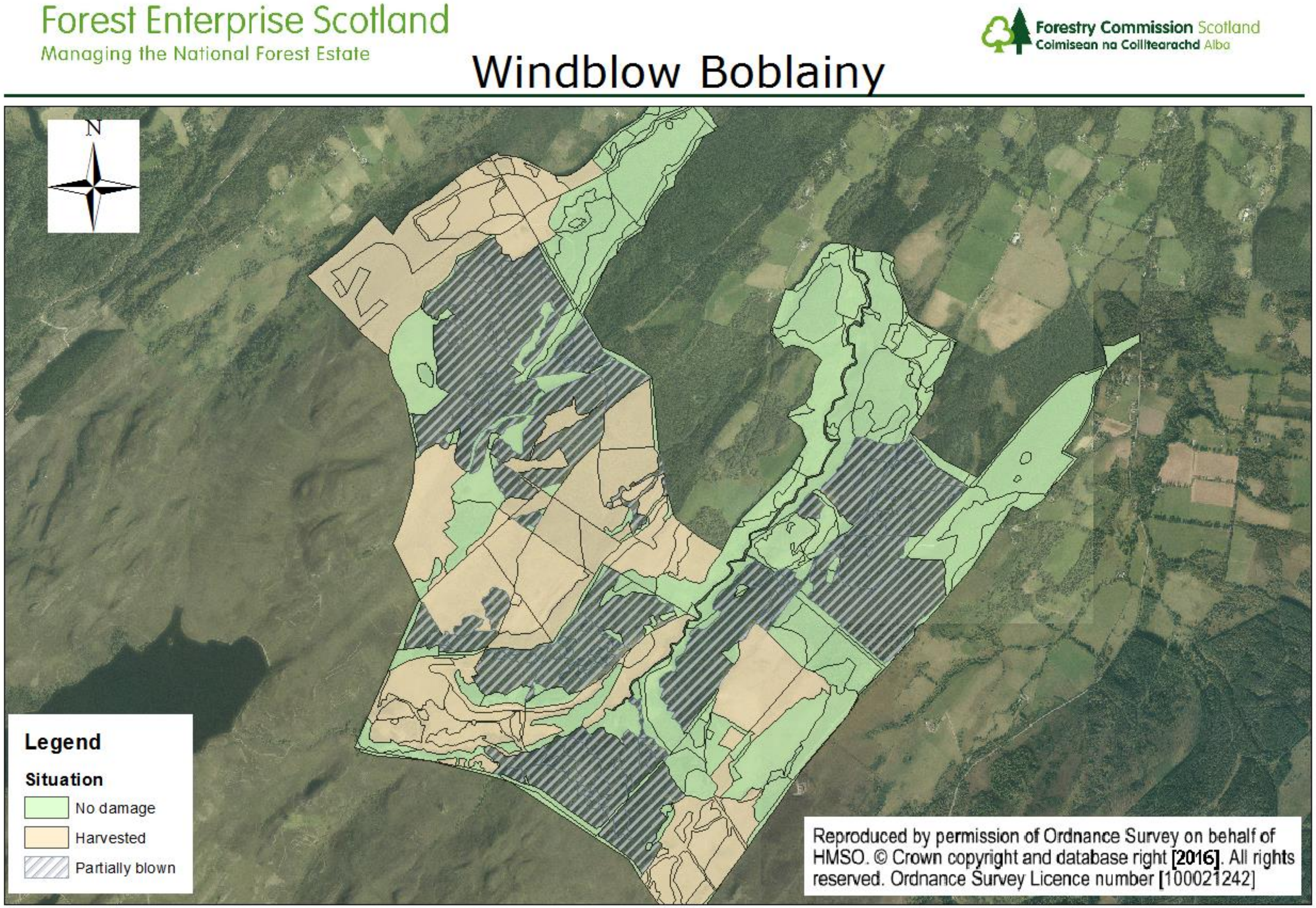
Shenval (appendix 6)

Young Douglas stand, deeply ploughed with a high water table resulting in very shallow rooting (<20cm) It blew along plough lines. DAMS 13 (it is noted that DAMS 13 for Douglas is not very suitable (Rayner, 2010)). Douglas fir is one of the least tolerant species grown in Britain to the anaerobic conditions resulting from high water tables (Savill, 1991).

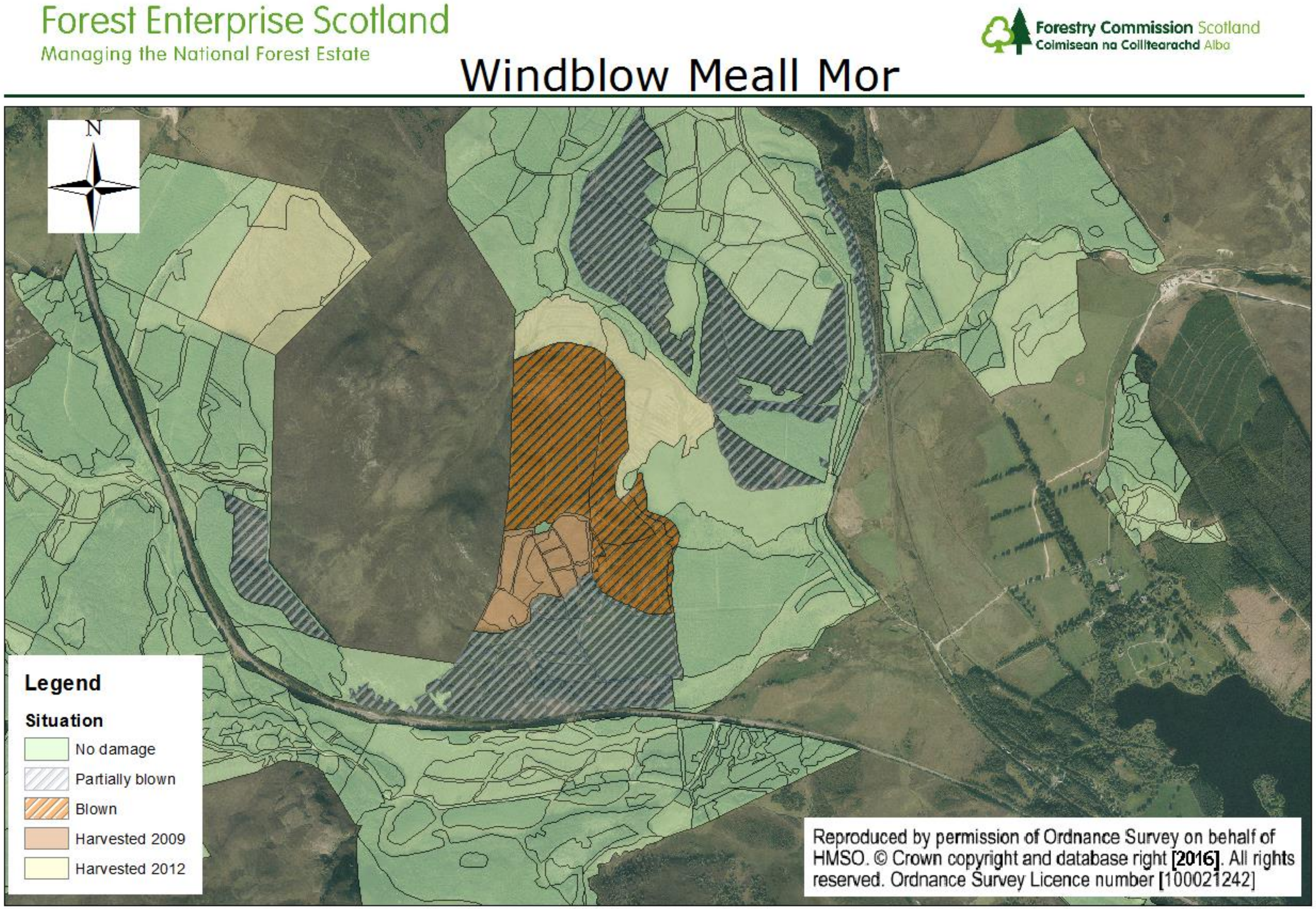
Appendix 6 – Situation Black Isle



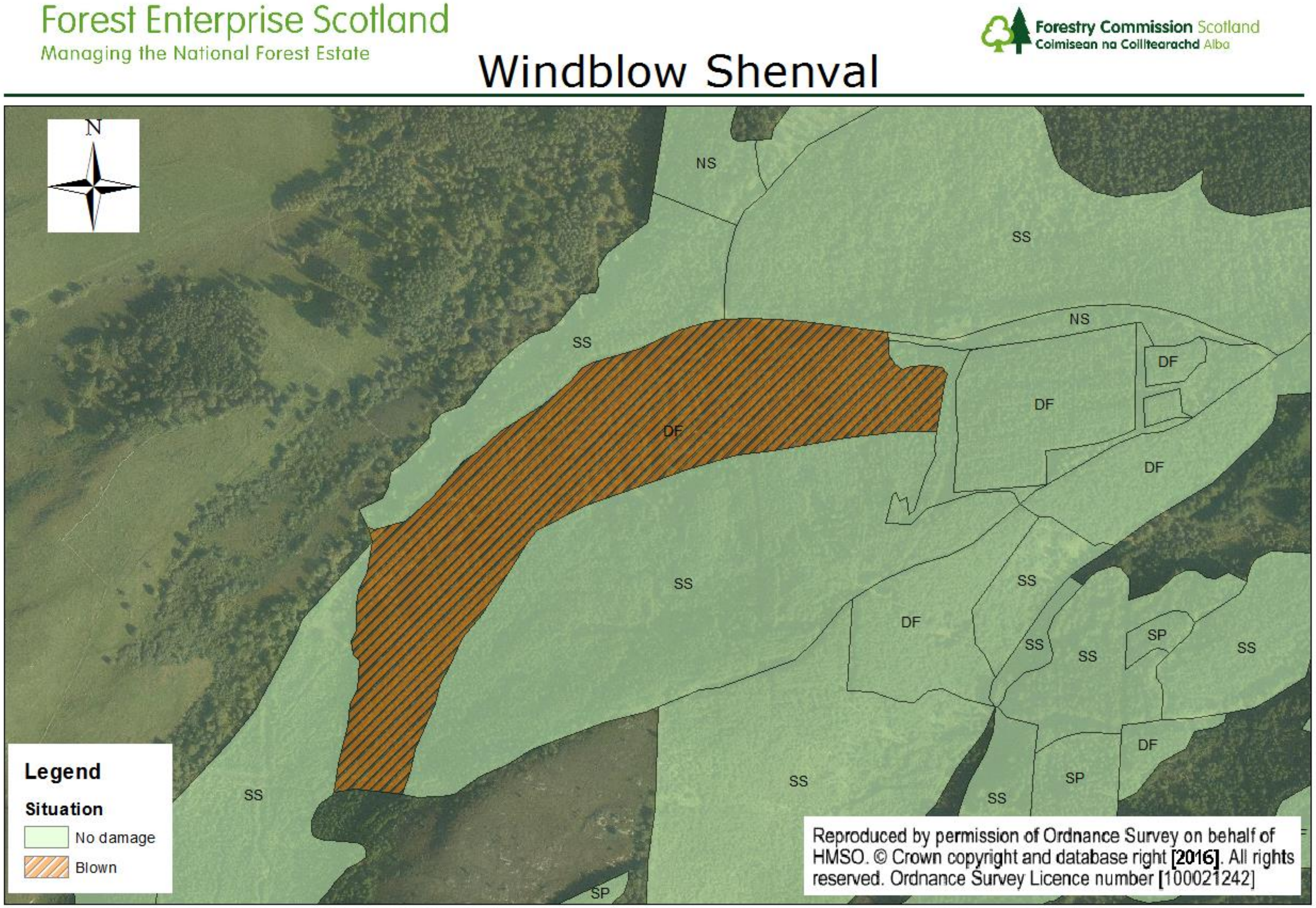
Appendix 7 – Situation Boblainy



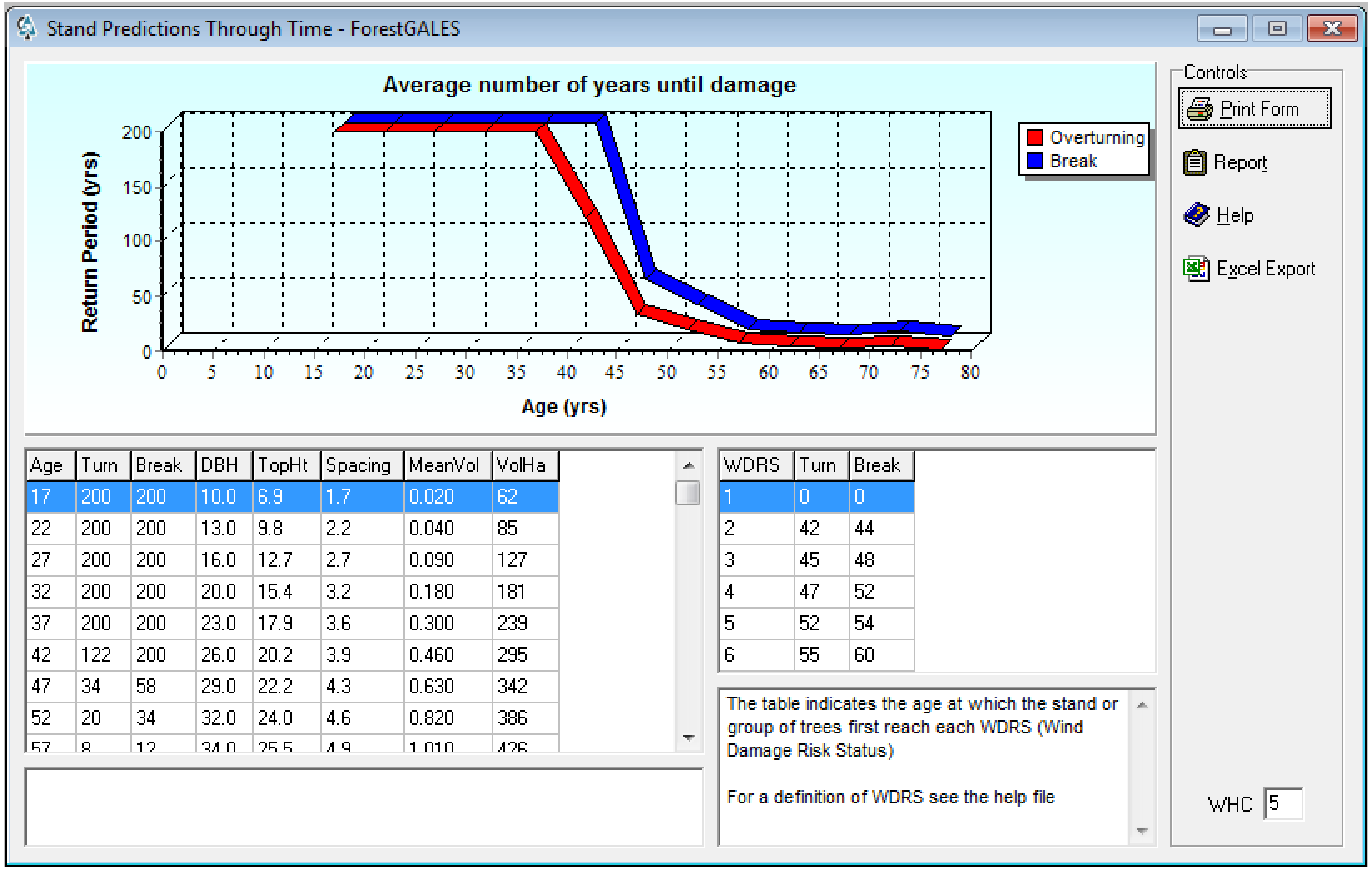
Appendix 8 – Situation Meall Mor



Appendix 9 – Situation Shenval



Appendix 10 – Screenshot ForestGALES



Age	Turn	Break	DBH	TopHt	Spacing	MeanVol	VolHa
17	200	200	10.0	6.9	1.7	0.020	62
22	200	200	13.0	9.8	2.2	0.040	85
27	200	200	16.0	12.7	2.7	0.090	127
32	200	200	20.0	15.4	3.2	0.180	181
37	200	200	23.0	17.9	3.6	0.300	239
42	122	200	26.0	20.2	3.9	0.460	295
47	34	58	29.0	22.2	4.3	0.630	342
52	20	34	32.0	24.0	4.6	0.820	386
57	8	12	34.0	25.5	4.9	1.010	426

WDRS	Turn	Break
1	0	0
2	42	44
3	45	48
4	47	52
5	52	54
6	55	60

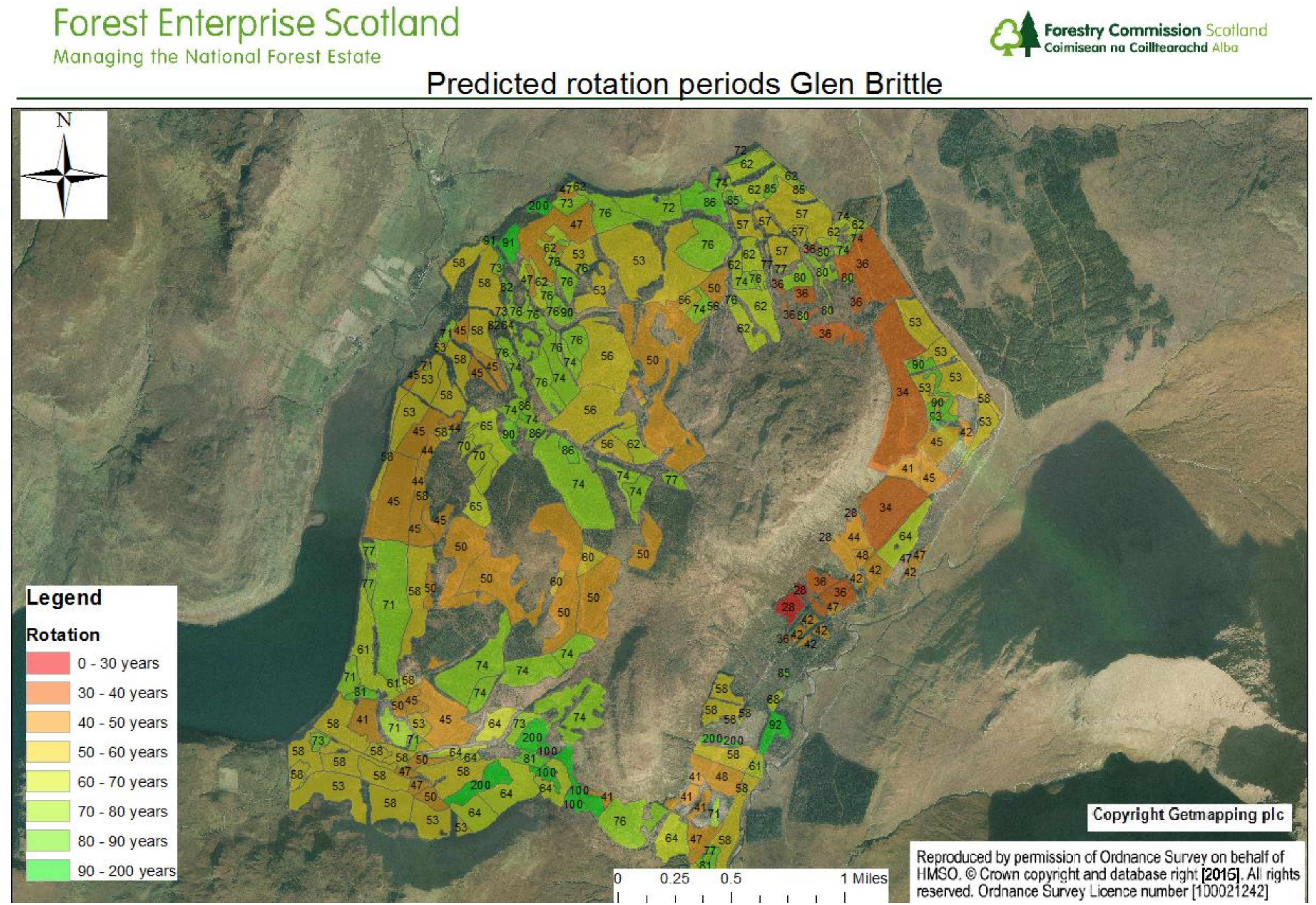
Sitka spruce, DAMS: 17, YC: 14, Management regime: ‘Intermediate thinning no delay’ and Spacing: 1.7m.

Forestry Commission Scotland

Appendix 11 – Example script for rotation periods (shortened)

```
CASE
WHEN ("MAX_DAMS" <=10 AND "MAX_DAMS">=0 )THEN 100

WHEN ("MAX_DAMS" >10 AND "MAX_DAMS"<=11 AND "YLDC" >=0 AND "YLDC"<=10) THEN 100
WHEN ("MAX_DAMS" >10 AND "MAX_DAMS"<=11 AND "YLDC" >10 AND "YLDC"<=12) THEN 68
WHEN ("MAX_DAMS" >10 AND "MAX_DAMS"<=11 AND "YLDC" >12 AND "YLDC"<=14) THEN 50

WHEN ("MAX_DAMS" >11 AND "MAX_DAMS"<=12 AND "YLDC" >=0 AND "YLDC"<=8) THEN 100
WHEN ("MAX_DAMS" >11 AND "MAX_DAMS"<=12 AND "YLDC" >8 AND "YLDC"<=10) THEN 58
WHEN ("MAX_DAMS" >11 AND "MAX_DAMS"<=12 AND "YLDC" >10 AND "YLDC"<=12) THEN 41
WHEN ("MAX_DAMS" >11 AND "MAX_DAMS"<=12 AND "YLDC" >12 AND "YLDC"<=14) THEN 35

WHEN ("MAX_DAMS" >12 AND "MAX_DAMS"<=13 AND "YLDC" >=0 AND "YLDC"<=6) THEN 100
WHEN ("MAX_DAMS" >12 AND "MAX_DAMS"<=13 AND "YLDC" >6 AND "YLDC"<=8) THEN 58
WHEN ("MAX_DAMS" >12 AND "MAX_DAMS"<=13 AND "YLDC" >8 AND "YLDC"<=10) THEN 37
WHEN ("MAX_DAMS" >12 AND "MAX_DAMS"<=13 AND "YLDC" >10 AND "YLDC"<=12) THEN 35
WHEN ("MAX_DAMS" >12 AND "MAX_DAMS"<=13 AND "YLDC" >12 AND "YLDC"<=14) THEN 30

WHEN ("MAX_DAMS" >13 AND "MAX_DAMS"<=14 AND "YLDC" >=0 AND "YLDC"<=4) THEN 100
WHEN ("MAX_DAMS" >13 AND "MAX_DAMS"<=14 AND "YLDC" >4 AND "YLDC"<=6) THEN 65
WHEN ("MAX_DAMS" >13 AND "MAX_DAMS"<=14 AND "YLDC" >6 AND "YLDC"<=8) THEN 40
WHEN ("MAX_DAMS" >13 AND "MAX_DAMS"<=14 AND "YLDC" >8 AND "YLDC"<=10) THEN 31
WHEN ("MAX_DAMS" >13 AND "MAX_DAMS"<=14 AND "YLDC" >10 AND "YLDC"<=12) THEN 26
WHEN ("MAX_DAMS" >13 AND "MAX_DAMS"<=14 AND "YLDC" >12 AND "YLDC"<=14) THEN 27

WHEN ("MAX_DAMS" >14 AND "MAX_DAMS"<=15 AND "YLDC" >=0 AND "YLDC"<=4) THEN 100
WHEN ("MAX_DAMS" >14 AND "MAX_DAMS"<=15 AND "YLDC" >4 AND "YLDC"<=6) THEN 53
WHEN ("MAX_DAMS" >14 AND "MAX_DAMS"<=15 AND "YLDC" >6 AND "YLDC"<=8) THEN 35
WHEN ("MAX_DAMS" >14 AND "MAX_DAMS"<=15 AND "YLDC" >8 AND "YLDC"<=10) THEN 28
WHEN ("MAX_DAMS" >14 AND "MAX_DAMS"<=15 AND "YLDC" >10 AND "YLDC"<=12) THEN 25

END
```

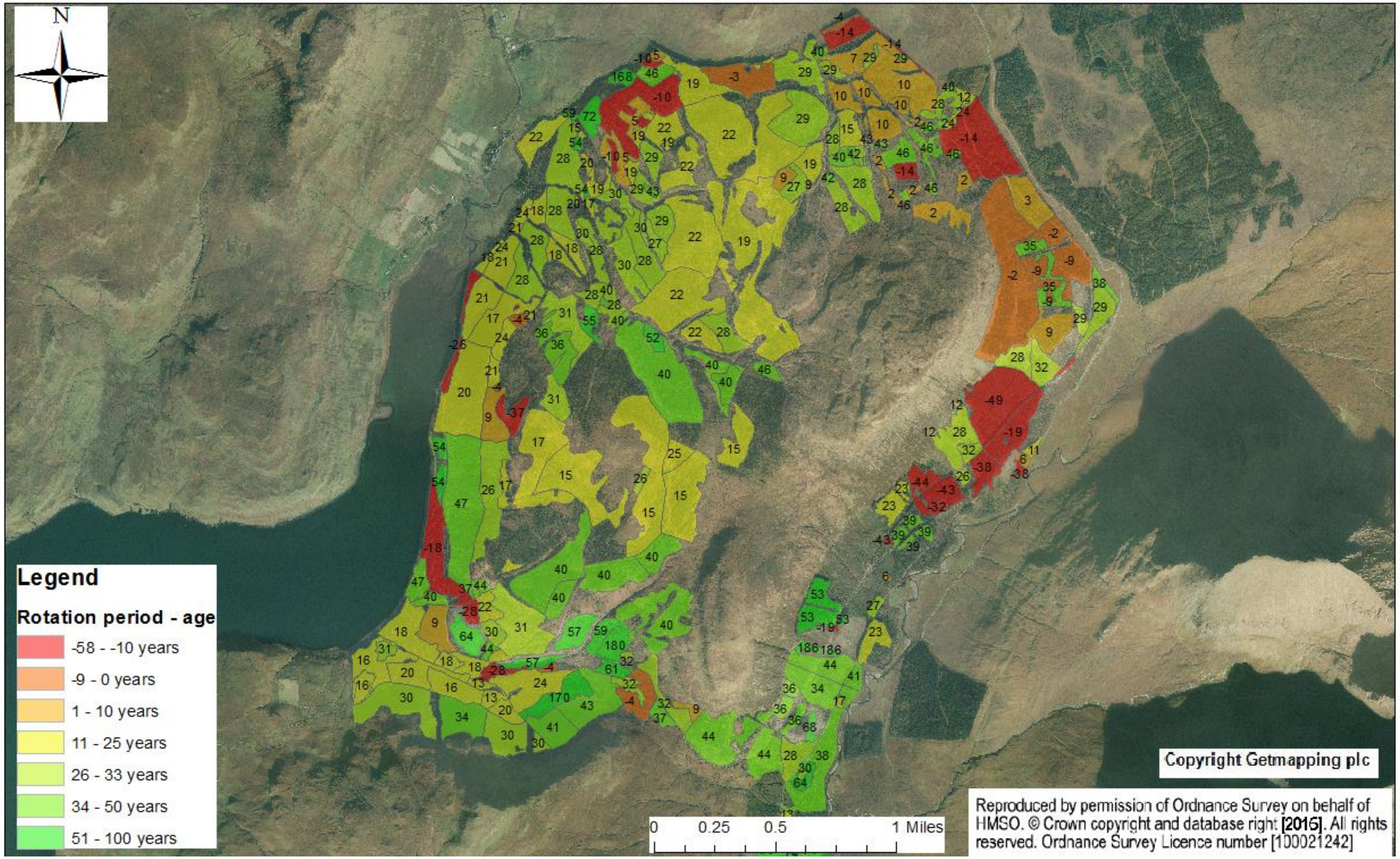
Appendix 12 – Estimated rotation periods



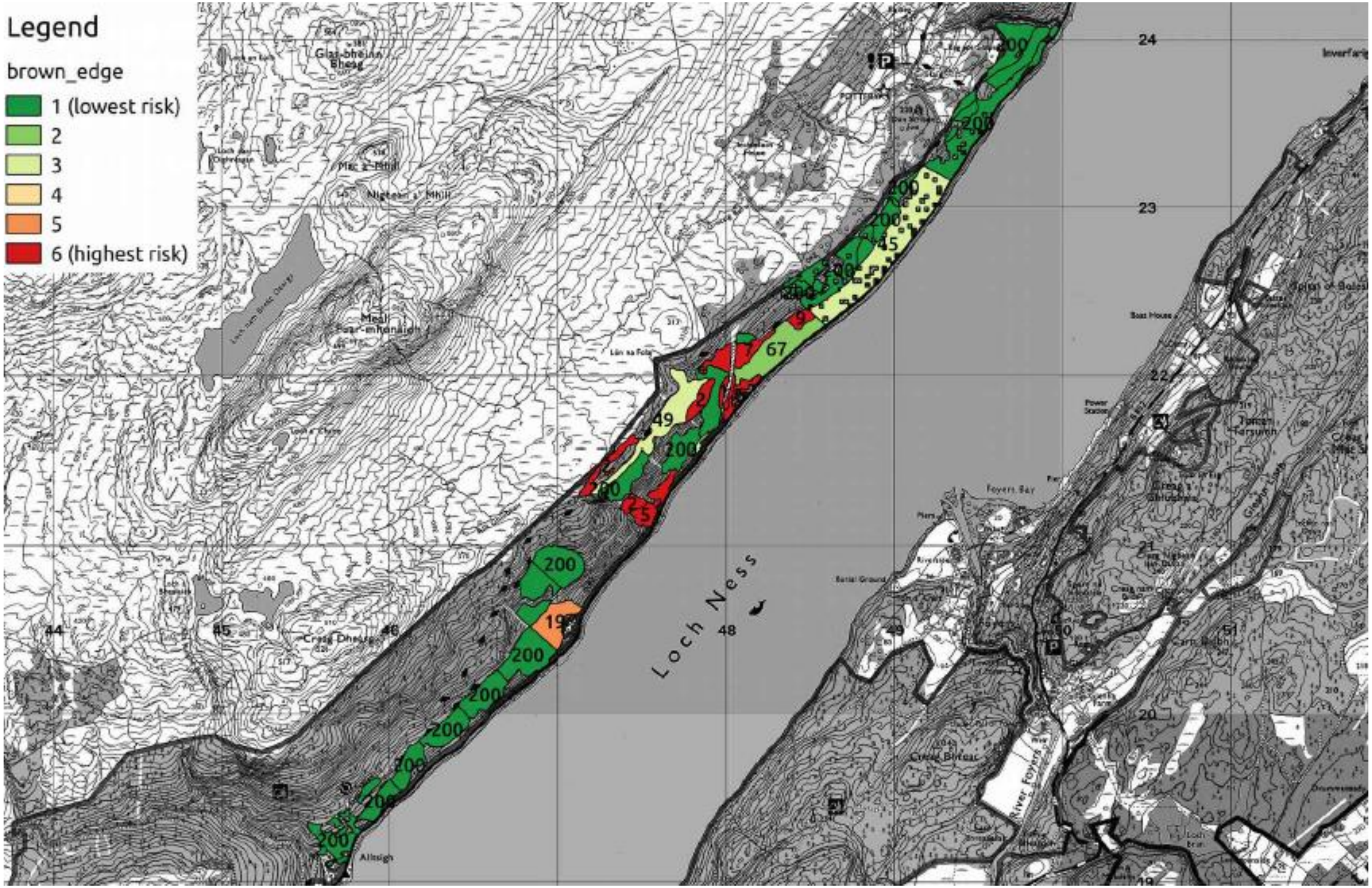
Forest Enterprise Scotland

Managing the National Forest Estate

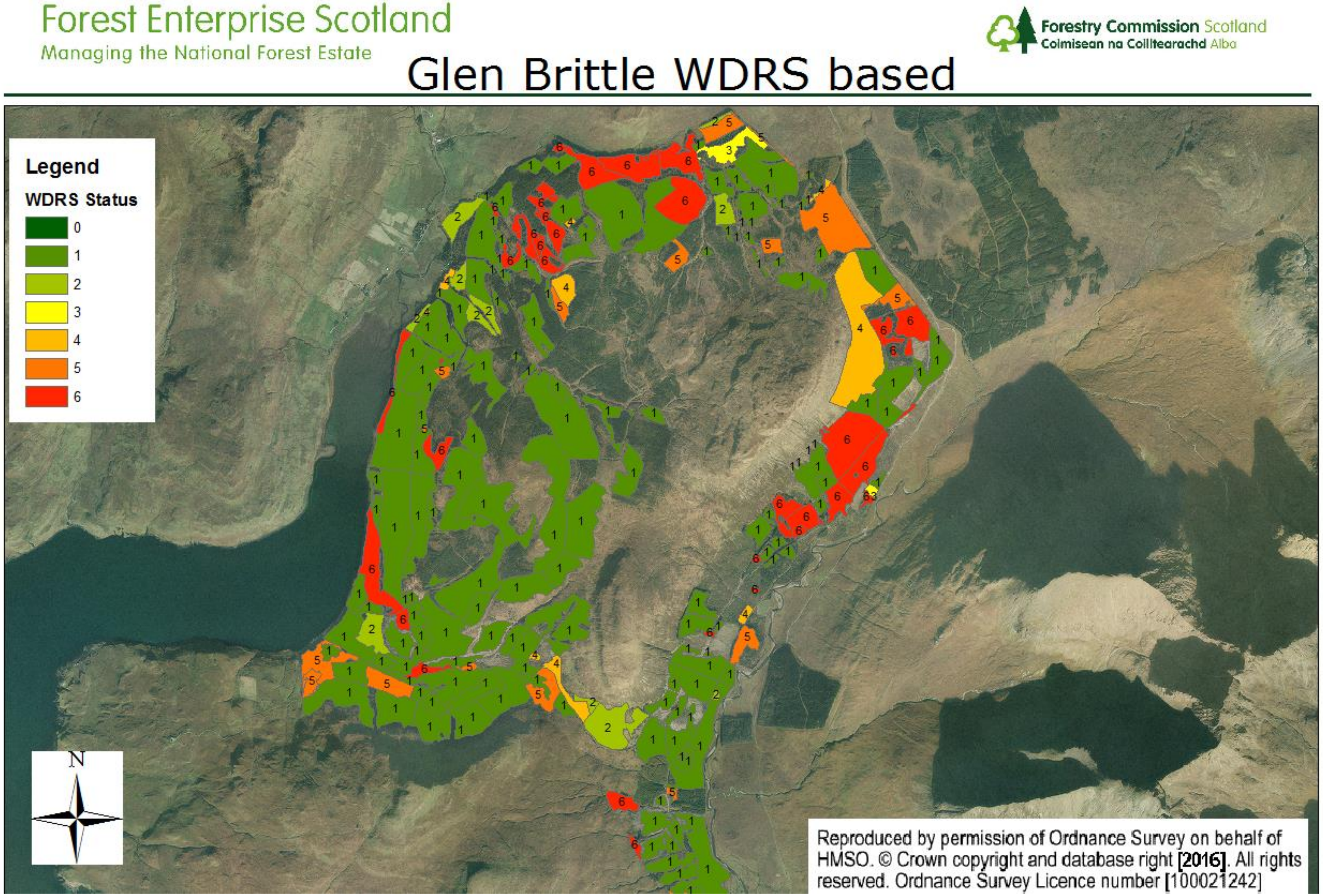
Stability Glen Brittle in years until predicted instability



Appendix 14 – Stability shown with current return period



Appendix 15 – Stability shown as current WDRS



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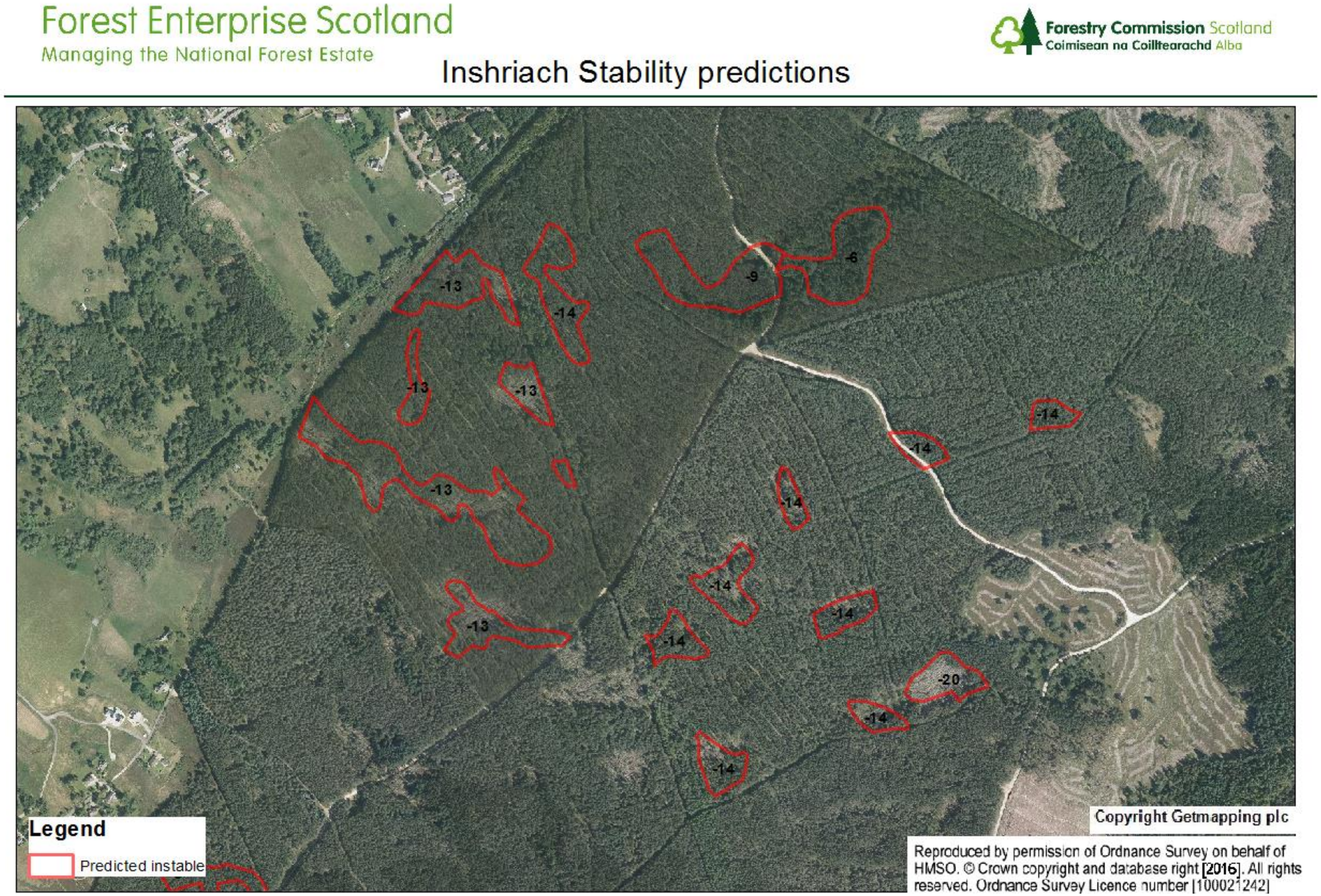
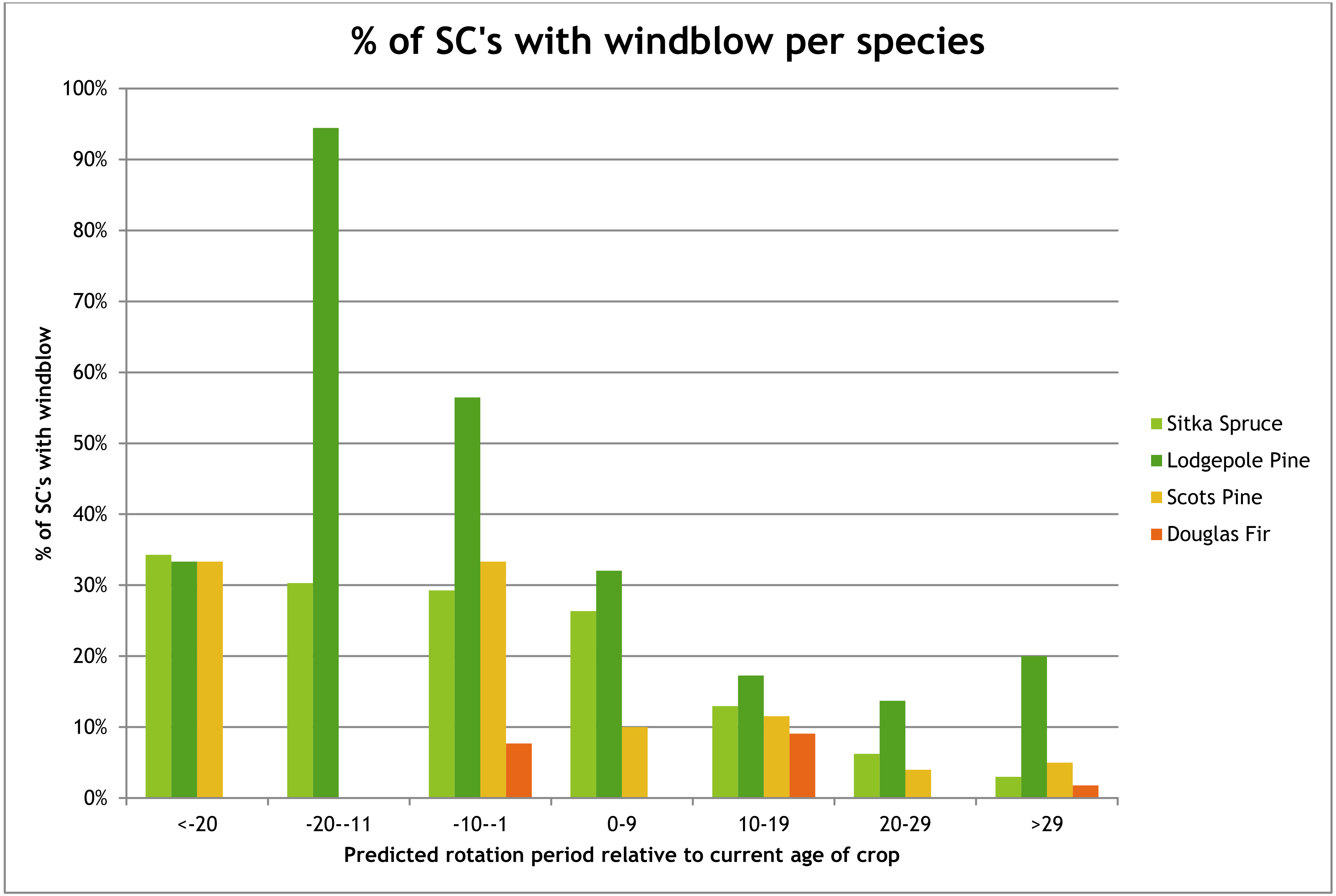
Appendix 16 - Prediction stability Inshriach



Appendix 17 – Witnessed damaged in relation to ForestGALES's prediction per species



Forestry Commission Scotland