JNCC Report
No. 701

Brecon Beacons Fire Risk Modelling Tool

Trippier, B., Jones, A., Jones, G., Harris, M., Woodcock, P., Hassall, I. and Wright, E.

June 2022

© JNCC, Peterborough 2022

ISSN 0963 8091

For further information please contact:
Joint Nature Conservation Committee
Monkstone House
City Road
Peterborough PE1 1JY
https://jncc.gov.uk/

This report should be cited as:
Trippier, B., Jones, A., Jones, G., Harris, M., Woodcock, P., Hassall, I. and Wright, E. 2022. Brecon Beacons Fire Risk Modelling Tool. *JNCC Report No. 701*, JNCC, Peterborough, ISSN 0963-8091.

This report is available from: https://hub.jncc.gov.uk/assets/7691fb4a-b77a-4f8e-8660-a06b567ba345

Acknowledgments:
JNCC would like to thank our partners at Natural Resources Wales and the Brecon Beacons National Park Authority for their valuable contributions to the project, as well as the Mynydd Du graziers and the Wildfire Advisory Group for sharing their knowledge of the area with us. We would also like to thank Ashleigh Harper for providing us with training data for developing the fire risk model.

JNCC EQA Statement:

This report is compliant with JNCC's Evidence Quality Assurance Policy
https://jncc.gov.uk/about-jncc/corporate-information/evidence-quality-assurance/

Summary

Brecon Beacons National Park Authority (BBNPA) and Natural Resources Wales (NRW) sought to understand if spatially targeting land management measures (such as grazing and prescribed burning) could have an effect in reducing wildfire risk. This technical report outlines the model development as part of the JNCC-led project, in which a spatially explicit tool was constructed to support scenario testing of the impact of land management measures in the Mynydd Du on wildfire risk.

The Mynydd Du in the Brecon Beacons National Park is a large common land manged by local graziers. Reductions in grazing levels have led to concerns as to the impact changes in habitat management has had on the landscape and especially to fire regime control and the increased risk to major wildfire events.

As part of this proof-of-concept approach, we have developed a multi-criteria analysis model informed by local expertise and Earth observation data to assess the role management practices of grazing and controlled burning has upon the likelihood a habitat is to burn. This incorporates key factors influencing how susceptible a habitat is to burn, including habitat type, climatic and topographic factors, as well as how accessible an area is to sources of ignition. This was combined into a decision support tool allowing users to run scenarios of land use change and explore how management factors influenced their relative burn risk in the region. The report also outlines the limitations of this approach and areas which could be further developed to help improve the accuracy of this analysis.

Contents

1 Introduction

In 2018, the dry summer conditions resulted in many significant moorland fires across the UK, having major ecological, environmental, and financial implications. A decrease in grazing levels on the Mynydd Du massif, located within the Brecon Beacons National Park in South Wales, has caused some concerns as to the impact this change in management is having upon fire risk. The Mynydd Du massif is the single largest extent of registered common land in Wales (BBNP 2020). Under future climate change scenarios, it is likely there will be a greater risk of major wildfires with prolonged periods of dry weather predicted to increase (Sinnadurai 2005). Further changes to the agricultural economy are likely to drive an increase in fuel load over the coming decade, especially if grazing rates continue to decrease in upland areas, increasing the fuel load, making catastrophic fire more likely.

Earth observation can provide a rapid valuable means of detecting and monitoring the spread of wildfires across the landscape at local, regional, and global scales, providing input data to models as factors that help us predict where wildfires are more likely to occur in future. There are three established and active fire detection systems which use thermal anomalies to locate potential fire hot-spots: (i) EFFIS (European Forest Fire Information System) which uses NASA FIRMS (Fire Information for Resource Management) calibrated to European forest conditions; (ii) the MODIS active fires product which uses the MODIS sensor present on the TERRA and ACQUA satellites; and (iii) the VIIRS (Visible Infrared Imaging Radiometer Suite) present on the NASA/NOAA Suomi National Polar-orbiting Partnership (SNPP) (Joint Research Centre (JRC) 2021).

Modelling is widely used to forecast fire risk, with multiple fire danger rating systems (FDSRs) established to estimate areas at greater fire of exposure to fires. In Canada, the Fire Weather Index (FWI) is a meteorologically based global index which has been developed to estimate fire intensity and likely danger accounting for the impacts fuel moisture and wind have on the behaviour of a fire (CWFIS 2020). In the UK, the Met Office Fire Severity Index (MOFSI) is based on this system however calibrated for the UK forestry types, providing a 5-day forecast of FWI (Met Office 2020; de Jong. *et al*. 2016). These two FDSRs are accurate in modelling the dynamics of wildfire, however, are only based on meteorological factors, whereas in the Mynydd Du, the aim is to investigate how land use changes may influence wildfire risk. Approaches such as McMorrow and Lindley (2006) and Trippier *et al*. (2020) have used risk-based approaches and machine learning techniques to estimate likely burn and ignition risks from wildfires using key factors of topology, climate, habitat and land management. McMorrow and Lindley (2006) also combined stakeholder knowledge in the weighting of important fire risk factors and the influence of human factors which would impact the accessibility of sites to sources of ignition. This combination of Earth observation data and land use centric approaches can provide a means for dynamically predicting wildfires the Mynydd Du region and calibrating risk based on local knowledge of factors and management influences to estimate how agricultural practices can impact risk.

This project aimed to create a proof-of-concept, user friendly decision support tool which could demonstrate the potential impacts of management decisions on fire risk on Mynydd Du. Working with partners from National Resources Wales (NRW) and the Brecon Beacons National Park Authority, as well as expert knowledge from local stakeholders, we have developed a model using Earth observation data to generate modelled predictions of burn risk in the Mynydd Du.

2 Burn Risk Modelling

2.1 Site description

The Brecon Beacons National Park located in South Wales consists of mostly bare grassy moorland, grazed by Welsh mountain ponies, sheep, and less frequently by cattle with scattered pasture and forestry plantations. The Mynydd Du massif is located to the west of the park and is the largest extent of common land in Wales (BBNP 2020). The study area is shown in Figure 1 covering an area of 151.53 km^2.

The Mynydd Du is dominated by *Nardus* and *Molinia* Grassland, covering 28.89% and 22.40% land cover respectfully. The remaining land cover is predominantly grassland and heathland habitats with inflammable surfaces such as rock, road and lake covering 4.41% of the total site area.

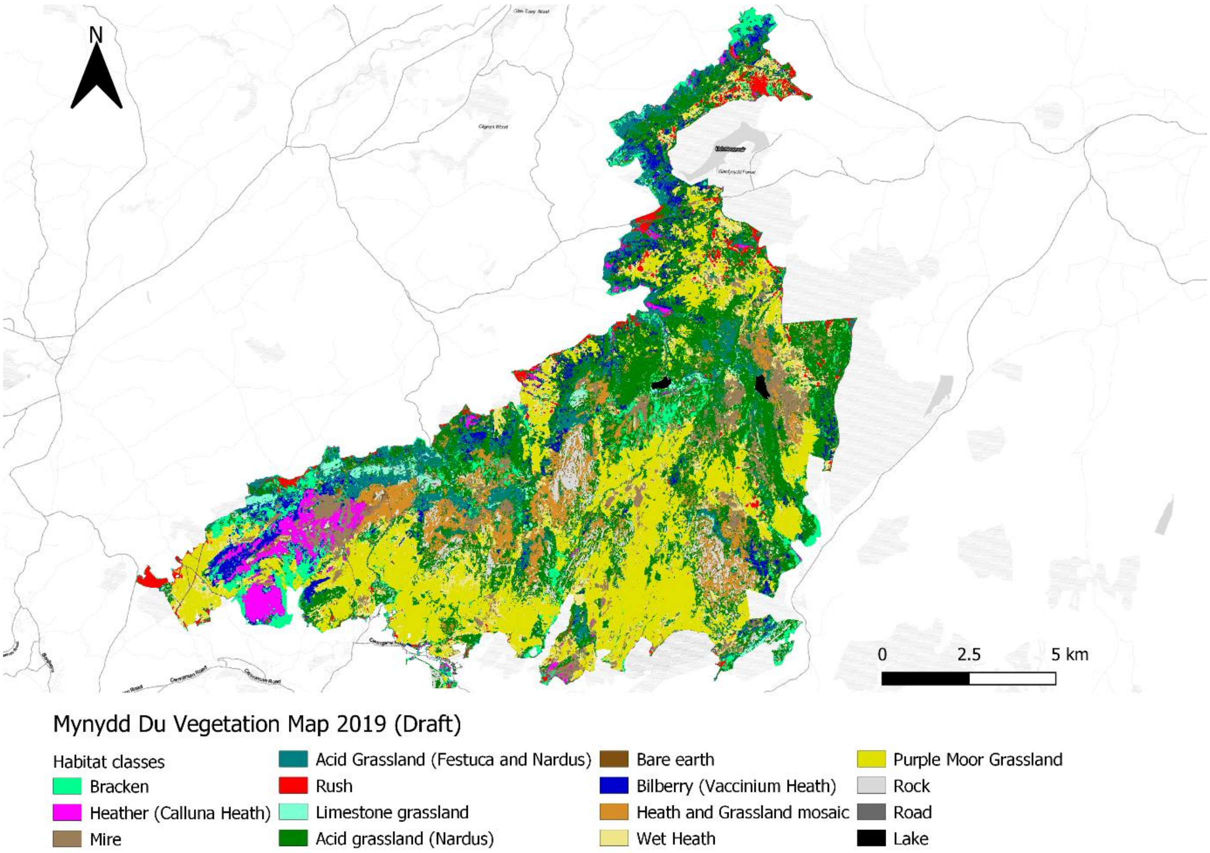

Figure 1: The 2019 habitat map of the Mynydd Du, provided by NRW. Contains Natural Resources Wales information © Natural Resources Wales and database right. All rights reserved. Contains Ordnance Survey data © Crown Copyright and Database Rights. Ordnance Survey Licence number 100019741. Sentinel-2 analysis-ready data processed by JNCC and supplied under the Open Government Licence v3 via the CEDA Archive (archive.ceda.ac.uk).

Commons and upland grazing with sheep and cattle constitute nearly 50,000 hectares of the Brecon Beacons National Park (BBNP 2021). Controlled burns are sometimes used as a management tool for maintaining natural habitats in the region by graziers in partnership with the National Park Wardens as part of the Meithrin Mynydd partnership, but if can be avoided then it is especially on areas of wet heath and deep pear. They are also being considered to create fire breaks in the landscape to limit the potential extent of future wildfires. Other restoration works which have been undertaken in the areas have included heather seed harvesting, bracken control and bare peat protection works to restore habitats in poor condition and help maintain grazing quality for livestock (BBNP 2020).

2.2 Model development

Fire risk encompasses the likelihood that a fire is to start (ignition probability), the likelihood a habitat is to burn (flammability) and the amount of damage caused when a fire spreads (fire severity). Both biotic and abiotic factors can influence these, by having an impact upon the vegetation moisture which will affect the amount of energy the fire needs in order to evaporate enough water to burn the vegetation, as well as the fuel load which is the amount of fuel available to the fire increasing the severity of the damage caused.

A literature review was carried out to assess the key abiotic and biotic factors which could affect fire risk, a summary of which is shown in Appendix 1. This informed the key factors affecting wildfire in the Mynydd Du to include in the fire risk model (shown in Figure 2), as well as the relationships between land management types and fire risk.

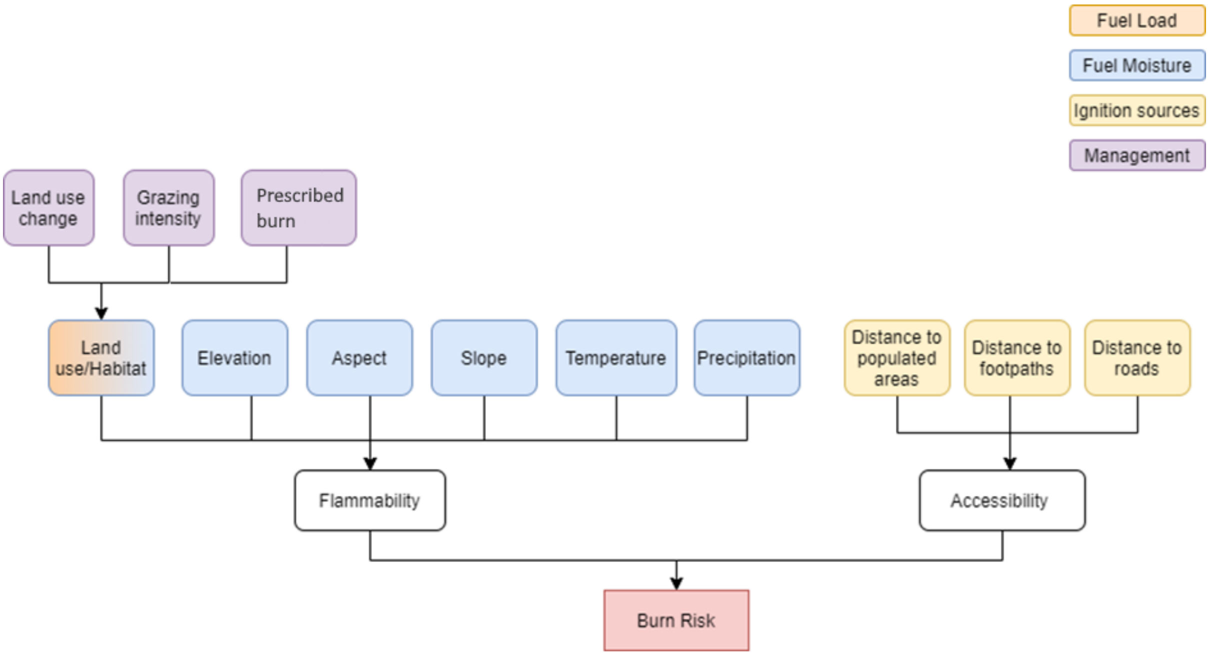

Figure 2: A diagram of the burn risk model.

Of particular interest in this project was considering how management practices varies fire risk. The review highlighted that the timing and intensity of grazing has an impact upon fire risk, affecting the fuel load and moisture available at certain times of the year. Davies *et al*. (2017) notes spring grazing having a notable increase on fuel moisture relative to autumn grazed or ungrazed grassland habitats. The type of grazing animal may also influence the intensity of grazing and trampling causing impacts upon the vegetation height and fuel loading. Expert input from the stakeholders (collected via questionnaire, Appendix 2) also highlighted that grazing helps to break up the vegetation continuity, preventing large fires from developing. Prescribed burning, a management practice aimed at reducing fuel load, can also help to reduce the intensity of fires and so preventing greater damage from large fires, although if not timed carefully can increase the risk of fire spread (Kalies *et al*. 2016). Grazing and prescribed burning practices were explored in the model along with peatland restoration measures, which have been of particular policy interest for lowering greenhouse gas emissions and enhancing biodiversity, with large peat reserves found in the upland moors.

As the majority of fires are started by people in BBNP (Mid and West Wales Fire and Rescue Service, South Wales Fire and Rescue Service, Incident call out records for BBNP 2015–2022), accessibility factors are used as a proxy for ignition susceptibility.

To implement the fire risk model, an approach combining factors was taken following McMorrow and Lindley (2006), using a multi-criteria evaluation model to weight different factors impacting fire risk against each other to produce an overall risk score across the landscape. This type of approach allows for the incorporation of management factors, particularly where quantitative data for this is limited, as well as incorporating stakeholder expertise in assessing the scoring and weighting of layers with characteristics they know to influence burn risk.

2.3 Data Sources and processing

For observations of where wildfires had occurred at the Brecon Beacons National Park (BBNP) site, polygons of burn scars identified using Landsat and Sentinel-2 imagery at 30 m and 10 m spatial resolution between 2007 to 2018 were obtained from a PhD study by Harper (2020). These provided reliable detections of large-scale fire events (>25 ha) based on detections from NASA's FIRMS Viewer within the park during these dates, however small fire events and cloud cover have meant not all fires taking place within this date range would have been captured.

A local habitat map of the Mynydd Du was supplied by NRW for use in this project. This was developed from Sentinel-2 imagery taken from 2019, trained with classified segments digitised from aerial photography. The boundary of this map defined the area of interest.

For topographic factors, a Digital Terrain Model (DTM) was obtained from Environment Agency's Integrated Height Model (IHM) using Lidar data (Bluesky International Ltd/Getmapping PLC) at 10 m spatial resolution. Slope and Aspect were calculated 'using the Zevenbergen Thorne algorithm (Asher Greenberg & Mattiuzzi 2018). Climatic data were obtained from the Met Office (2019), using their HadUK gridded 1 km monthly product available through CEDA's archive. These were combined to calculate an average total annual rainfall and average annual mean temperature using data from 1999 to 2018. Windspeed was also considered, however comparisons with burnt and non-burnt areas didn't show any significant differences and therefore this factor was not included in the final model.

For the accessibility layers, vector data containing the location of roads were obtained from Ordnance Survey (2020) OpenMap and the location of footpaths were obtained from OpenStreetMap through the 'osmdata' R package (Padgham *et al*. 2020). These data were clipped to the BBNP site boundary and then rasterised at 10 m spatial resolution, giving the road or footpath at value of 1. Populated areas were assessed using data from Worldpop (2020) which is an open geospatial data on population distributions at 1 km spatial resolution. The population density data for 2018 were cropped to the site boundary and reclassified, with all areas with a population over 1,000 considered as populated. To calculate the distance from each grid cell to the highlighted feature (road, footpath or populated area), the 'gdal_proximity' function was used which calculated the distance from the centre of each pixel to the centre of the nearest target pixel in meters.

All data were georeferenced to British National Grid (EPSG:27700) with data processing conducted in R version 3.6.1 (R Core Team 2019) and QGIS v. 3.4.5-Madeira (QGIS Development Team 2020).

2.4 Methods

2.4.1 Risk scoring the climatic, topographic and accessibility factors

Each of the layers were scored based on the relationship between the factor and the burnt areas data, analysed through mechanisms derived from McMorrow and Lindley's (2006) methodology.

Firstly, the continuous climatic, topographic and accessibility data layers were assessed using a distance decay approach. The observed burnt area polygons were extracted from the data layers and the values were plotted onto a histogram, using bin widths determined using the Freedman-Diaconis rule for optimised ranges. The bin thresholds were then used to categorise the data. These were then scored using an area-weighting principle, whereby the category classes were extracted for all cells falling within the observed burnt polygons and then summarised to calculate the total observed number of burnt cells per habitat class. This was compared to an expected number of burnt cells per habitat class, which assume that all categories are equally likely to burn, and therefore the expected area of burn per category is equal to the proportional area of each category, calculated using the equation:

$$Expected \ = \frac{pcntCov * totalBurnt}{100}$$

where $pcntCov$ is the percentage cover of a given habitat class across the total area, and $totalBurnt$ is the total number of burnt cells observed in the area of interest.

Comparisons of the expected and observed number of burnt cells can be used to calculate a residual (R) value for each class, using the equation:

$$R = Observed - Expected$$

The residual (R) values were used to score the layer by normalising the values between 1 to 10, giving the maximum residual ($maxR$) value a score of 10, the minimum residual ($minR$) value a score of 1, and values falling between these were scored using the equation:

$$Score = (10 - 1) * \frac{(R - minR)}{(maxR - minR)} + 1$$

Areas where no burns were observed (lake, road and rock) were given a risk score of 0.

2.4.2 Risk scoring habitat and management factors

For assessing the risk and the impact of land management on the modelled burn risk for each of the habitat types, stakeholders were asked to complete a questionnaire to help inform how this was scored in the model. Appendix 2 shows an example questionnaire that was circulated to local experts, in both English and Welsh, alongside descriptions of each habitat type (Appendix 3) to capture their knowledge of how wildfire in the Mynydd Du is affected by practices such as grazing, prescribed burning and peatland restoration. The classes of Acid Grassland (Festuca and Nardus) and acid grassland (Nardus) were combined in the analysis for ease in communicating the habitat types. The stakeholder groups engaged included a mixture of local active graziers, staff from the Brecon Beacons National Park Authority, NRW, and the Wildfire Advisory Group. They were asked questions about the levels of grazing and burning currently undertaken in the Mynydd Du and the types of habitats which these took place on. They were also asked for their perspectives and experience on whether this increased or reduced risk from wildfire, which was collated into a pairwise weighting shown in Table 1, following McMorrow and Lindley (2006). Scores were derived independently, but there were no conflicting views on directionality of weighting across any habitats (i.e. disagreement whether management practices would make the habitat more likely or less likely to burn). Where weighting responses were not unanimous, a mean weighting was used of all responses per habitat.

Table 1: Pairwise weighting table.

Less Likely to burn			**Equally likely**	**More likely to burn**		
1/4	1/3	1/2	1	2	3	4
Four times less likely	Three times less likely	Half as likely	Equal likelihood	Twice as likely	Three times as likely	Four times as likely

From the results the relative risk due to habitat/management type were calculated by first extracting the observed burnt area polygons from the habitat map and calculating a total number of burnt cells across the entire site ($Burn_{total}$). For each habitat class, the number of burnt cells were summarised ($Burn_{obs}$), with those where habitats where noted as not being susceptible to wildfires such as lakes, rock, and roads recorded as 0.

For grazing practices, the average proportion of grazed habitat estimated by stakeholders ($pCov$) was used to calculate the percentage of each class which was grazed ($prop_{Grazed}$) and non-grazed ($prop_{NonGrazed}$):

$$prop_{Grazed} = (\frac{pCov}{100}) * pcntCov$$

$$prop_{NonGrazed} = \frac{1 - pCov}{100} * pcntCov$$

An expected density (Exp) of fires occurring throughout the site was calculated from the total number of burnt cells and the total number of cells in the whole site:

$$Exp = \frac{Burn_{total}}{\sum n}$$

The observed density of fires occurring in grazed (Obs_{Grazed}) and non-grazed ($Obs_{NonGrazed}$) habitats was calculated by comparing the proportion of observations to the total habitat area. Since there is no spatial data available of grazed and ungrazed land, this was estimated from the stakeholder response questionnaire, with a mean of responses taken where there was not consensus. The grazed observations were also adjusted by the average weighting (ω) indicated by the stakeholders using the pairwise scoring described in Table 1. This was indicative of how influential they would expect grazing to be on the likelihood a habitat was to burn compared with ungrazed habitats:

$$Obs_{Grazed} = \frac{\left(Burn_{obs} * \frac{pCov}{100}\right)}{\left(n * \frac{pCov}{100}\right)} * \omega$$

$$Obs_{NonGrazed} = \frac{\left(Burn_{obs} * \frac{1 - pCov}{100}\right)}{\left(n * \frac{1 - pCov}{100}\right)} * 1$$

Residual values were calculated for each class by comparing the observed and expected values as with the other risk layers, and the values were normalised between 1 and 10.

The same process was carried out on the stakeholder estimates for the influence of prescribed burn on the likelihood of a habitat to burn. As both grazing and burning are independent of each other, a mean score was then calculated for the unmanaged habitat types, by comparing the non-burned and non-grazed scores. Finally these were all compiled into the look-up table shown in Table 2 and used to create a habitat risk layer from the Mynydd Du habitat map and was incorporated into the application (see Section 3).

Table 2: Habitat scoring table. Higher scores indicate habitats at higher risk of burning.

Habitat class	Score	Habitat class	Score	Habitat class	Score
Bracken	2.29	Grazed Bracken	1.70	Burned Bracken	1.54
Heather	4.66	Grazed Heather	3.05	Burned Heather	2.7
Mire	3.09	Grazed Mire	2.15	Burned Mire	1.91
Acid grassland	2.13	Grazed Acid grassland	1.46	Burned Acid grassland	1.47
Rush	1.4	Grazed Rush	1.21	Burned Rush	1.14
Limestone grassland	1.12	Grazed Limestone grassland	1	Burned Limestone grassland	1
Bilberry	1.29	Grazed Bilberry	1.14	Burned Bilberry	1.09
Heath and grassland mosaic	2.81	Grazed Heath and grassland mosaic	1.99	Burned Heath and grassland mosaic	1.93
Wet heath	4.66	Grazed Wet heath	3.43	Burned Wet heath	2.71
Purple Moor Grassland	10	Grazed Purple Moor Grassland	5.91	Burned Purple Moor Grassland	5.45
Bare earth	2.89				
Rock	0				
Road	0				
Lake	0				

2.4.3 Calculating burn risk

The risk layers were combined using a similar equation to McMorrow and Lindley (2006), however including climatic and topographic factors alongside habitat to assess flammability (F_{lm}). This was carried out using the equation:

$$F_{lm} = (H \cdot W_1) + (E \cdot W_2) + (S \cdot W_3) + (A \cdot W_4) + (P \cdot W_5) + (T \cdot W_6)$$

where H = habitat, W_1 = habitat weighting factor, E = elevation, W_2 = elevation weighting factor, S = slope, W_3 = slope weighting factor, A = aspect, W_4 = aspect weighting factor, P = precipitation, W_5 = precipitation weighting factor, T = temperature, and W_6 = temperature weighting factor.

The accessibility (A_{cc}) layers were combined using the following:

$$A_{cc} = (F \cdot W_7) + (R \cdot W_8) + (Pop \cdot W_9)$$

where F = distance to footpaths, W_7 = footpath weighting, R = distance to roads, W_8 = roads weightings, Pop = distance to populated areas, and W_9= populated area weighting.

The overall burn risk (B_r) was calculated by:

$$B_r = (F_{lm} \cdot \alpha) + (A_{cc} \cdot \beta)$$

Where α and β are weighting factors.

The optimum values for the weightings were assessed through a sensitivity analysis. Randomly distributed points were sampled from the observed burnt area polygons and used as training data, with 20% held back for evaluating the performance of the model. The training data were used to calculate the risk layers and run through the burn risk equations. The overall burn risk at the training point locations were then compared to the burn risk at the test point locations using a Mann-Whitney U test. Higher differences in their significance values indicated the means of the datasets were strongly correlated and therefore the predictions accurately reflected the observed dataset. Ideally this would have used points from independent burn events, however, due to the limited number of burn polygons available within the Mynydd Du, the sample size was too small.

Different relative weightings of parameters α and β, and the weightings used for each layer parameter were trialled to see which yielded the best performance. Details of the full sensistivity analyses are provided in Appendix 3. The optimum weightings are shown in Table 3 which demonstrated the strongest agreement with a Mann-Whitney significance of 0.997. These values were used to weight our final model of burn risk.

Table 3: The optimum weightings established from the sensitivity analysis.

Parameter	Weighting layer	Weighting value
$\boldsymbol{\alpha}$	Flammability	0.8
$\boldsymbol{W_1}$	Habitat	0.65
$\boldsymbol{W_2}$	Elevation	0.05
$\boldsymbol{W_3}$	Slope	0.05
$\boldsymbol{W_4}$	Aspec	0.1
$\boldsymbol{W_5}$	Precipitation	0.1
$\boldsymbol{W_6}$	Temperature	0.05
$\boldsymbol{\beta}$	Accessibility	0.2
$\boldsymbol{W_7}$	Distance to footpath	0.25
$\boldsymbol{W_8}$	Distance to populated area	0.615
$\boldsymbol{W_9}$	Distance to road	0.135

Finally, the overall burn risk (B_r) was categorised into risk categories based upon equal quantile ranges of probabilities between 0 and 1. These categories are shown in Table 4.

Table 4: The probability ranges used for categorising burn risk.

Category	Risk probability range
Very low	0 – 0.2
Low	0.2 – 0.4
Moderate	0.4 – 0.6
High	0.6 – 0.8
Very high	0.8 – 1.0

2.4.4 Validation

Fire point records not used in the model development were used as an initial validation of the fire risk model. Fire point data was downloaded from https://firms.modaps.eosdis.nasa.gov/ for the period 2000–2020, which included data sourced from MODIS and VIIRS, and clipped to the area of interest. Locations were then used to extract the risk category associated with each of the underlying points, to calculate the proportion of the fire records over the 20-year period which fell into each of the fire risk categories (very low to very high). This could then be compared to the proportion of the total area which was mapped as each of the risk categories.

2.5 Results

The resulting burn risk when no management is applied is shown in Figure 3: The modelled burn risk The model was integrated into an R shiny application to explore how the varying the management applied across the landscape would influence the burn risk, described in Section 3.

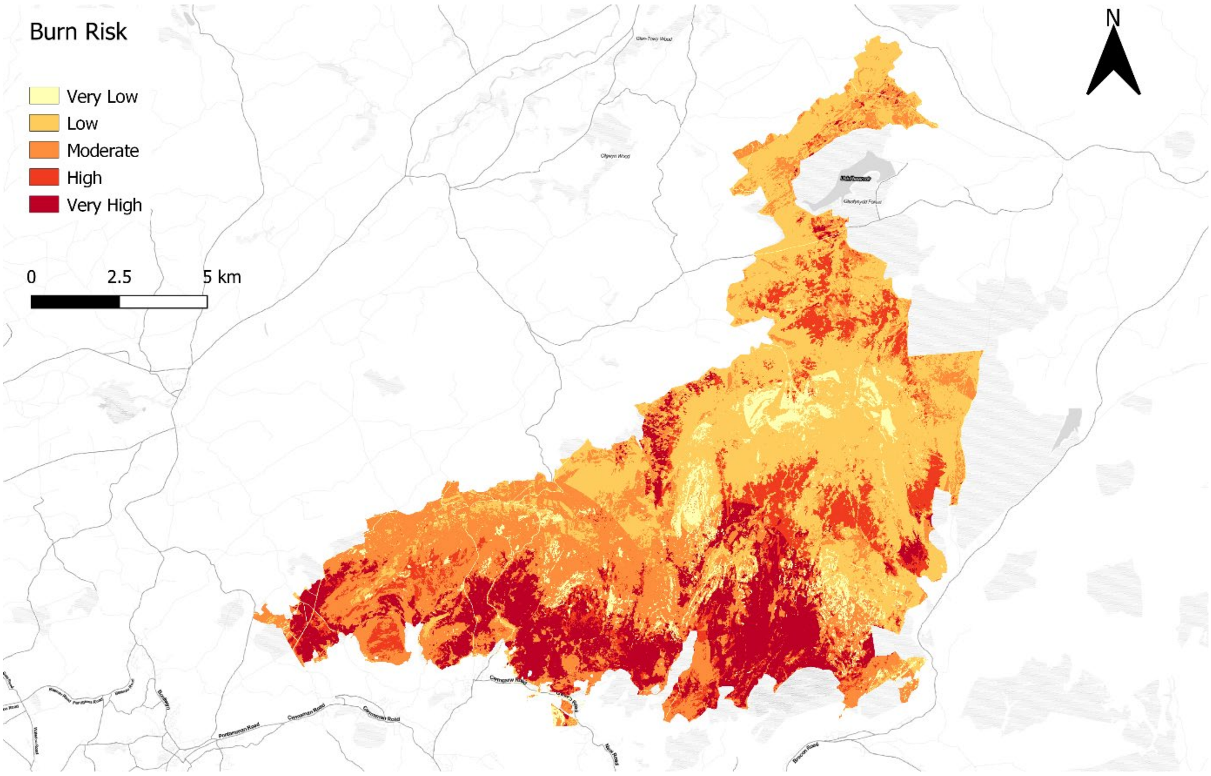

Figure 3: The modelled burn risk in the Mynydd Du when no management options were applied.

Note that the inclusion of risk weightings by stakeholder assessment is following previously used methods but should be considered crude and indicative. The risk map has not been verified within the limits of this project, but stakeholder feedback was positive that this map appears to reflect perceived risk. Habitat type is a major factor in considering burn risk, but the model helps to combine this with other spatial factors, so that for instance many of the habitat types are at higher risk in southern parts of the area of interest, but also picking out areas of higher and lower risk at high resolution throughout the area due to the combination of factors.

2.5.1 Validation

Over half (62%) of all MODIS and VIIRS fires were recorded from areas modelled as high or very high risk of fire (Table 5). This was despite only 26% of the area being classed as either of those categories. The largest category by area was 'Low' at 37%, but only 7% or recorded fires came from these areas.

Table 5: The proportion of total area, and of fire records, that fall into each of the fire risk categories.

Category	Percentage of area	Count (and percentage) of fire records
Very low	6%	5 (2%)
Low	37%	14 (7%)
Moderate	31%	61 (29%)
High	10%	35 (17%)
Very high	16%	94 (45%)

3 Managing Fire Risk Tool

The fire risk model was integrated into an R Shiny application, pictured in Figure 4, developed using R version 3.6.1 (R Core Team 2020), and the application was built using the package's 'shiny' version 1.4.0 (Chang *et al*. 2020) and 'shinydashboard' version 0.7.1 (Chang *et al*. 2018). This software is open source and provides a flexible interface in both its design and functionality to let users interact with the data spatially and run models in a user-friendly way, without requiring prior technical knowledge.

The application is available to users both in Welsh and English with a language switch available in the top right corner of the interface. It lets users explore the predicted burn risk for the Mynydd Du with the interactive map plotted against Esri World imagery integrating using 'leaflet' version 2.0.3 (Cheng *et al*. 2019). The user can filter to a habitat type and view where the habitats are located on the map with clickable polygons. Polygons smaller than 1 km^2 were excluded from selection in the application for processing ease.

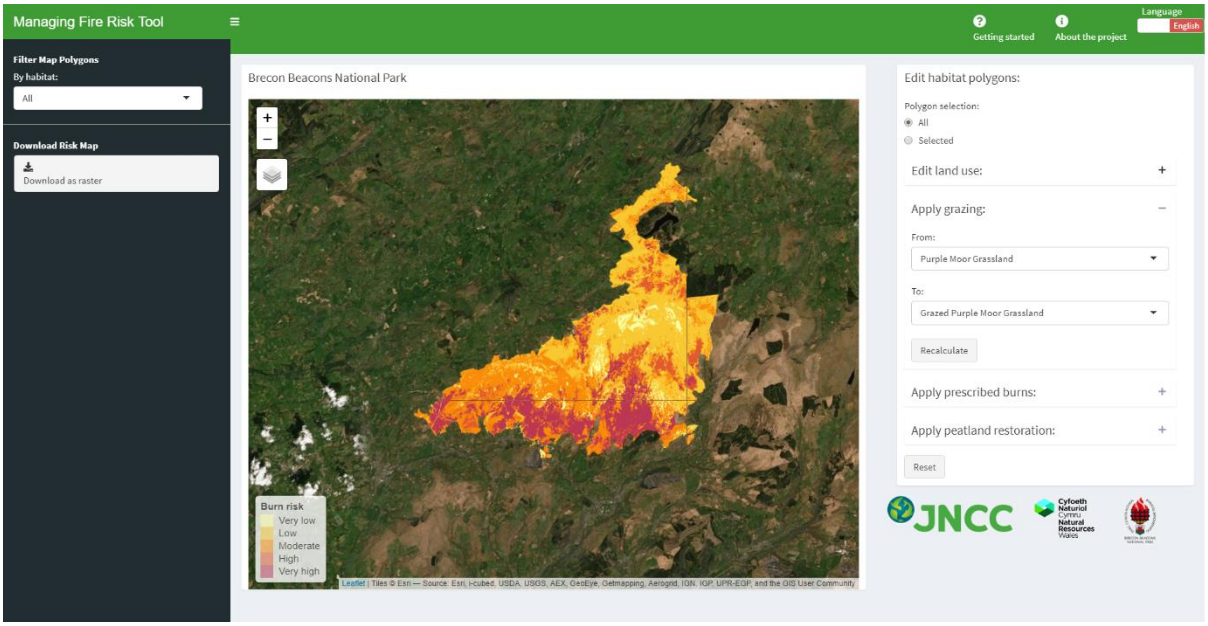

Figure 4: The application interface.

They can then select to run a management scenario, where they change the land use either on the selected polygon or on all polygons of that habitat type. This will recalculate the habitat risk layer in the background and recalculate the overall fire risk with this changed layer. The new burn risk map will then be plotted on the map and the user can assess how their burn risk has changed. They can then download the risk map to their local machine. An example scenario has been run with the results displayed in Figure 5 where grazing has been applied to all the Purple Moor Grassland in the site, demonstrating a notable decrease in burn risk.

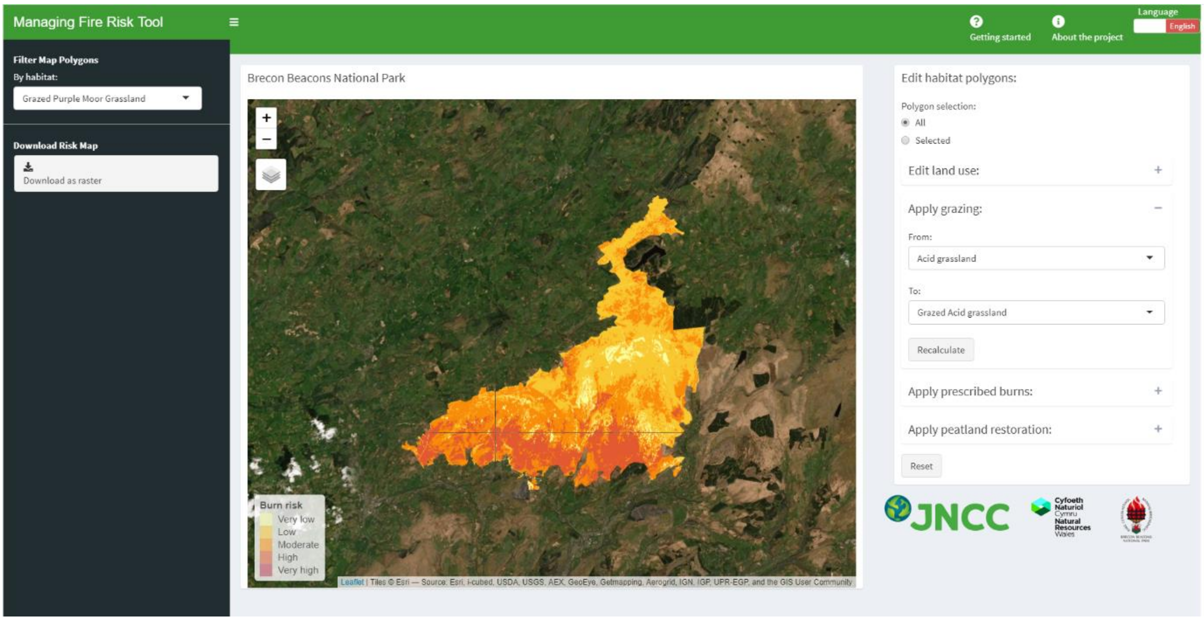

Figure 5: The recalculated burn risk run with a scenario where all the Purple Moor Grassland in Mynydd Du has had grazing applied.

To guide the user, a pop-up menu containing a walkthrough of the application's functionality and further information about the project, the method for calculating risk and a disclaimer for using the outputs were also integrated in the top right-hand corner of the application.

4 Limitations and next steps

The modelling approach was designed to inform landowners of land management decisions and demonstrate how activities such as grazing and controlled burns can help to reduce their wildfire risk. It is a dynamic model which can be updated with new more up-to-date data and uses open-sourced tools. However, it is not a model of fire dynamics and should not be used for such purposes to predict when wildfires will occur, as it is based on historical burn and climatic data. The historical burns are based upon data from Sentinel-2 and Landsat imagery, and while these spatial resolutions are able to detect major fires, they perform poorly when detecting smaller fires, and so some events will not have been captured. Other limitations in the input data were that an average was estimated for the climatic variables of temperature and precipitation, rather than assessing the individual records observed on the burn date, as this information was unavailable. This annual average means that our predictions do not account for seasonal variability in climate and so instead provides a static snapshot of relative risk, as opposed to varying temporally. Furthermore, land use management data was limited for the area and so the model was based upon estimates provided by the stakeholder questionnaires as to the proportion of habitats used for grazing and controlled burns. In reality, the spatial and temporal occurrence as well as information such as the type for grazing and intensity would help to further refine these predictions and better understand the influence these practices have upon wildfire risk. Risk here refers to the likelihood a habitat is to burn should a wildfire start and is a relative risk across the Mynydd Du rather than a quantitative measure. Further work could help to expand the analysis in order to compare how wildfire risk in the region compares with other areas of the Brecon Beacons National Park.

This project has provided a working fire risk model, and a first look at how this type of analysis can be used to inform future agricultural land management and ecosystem service provision. The initial validation based on point localities of fire records suggest the underlying model is a good spatially relevant reflection of fire risk. Until further validation of the model and in particular the tool, the results presented should be considered indicative. The results from a user-testing component have not been included here as an insufficient number of responses could be gathered within the timeframe of this project, and any further development of the tool would need to complete this in order to review how well the tool in particular met stakeholder expectations and needs. However, the partners and stakeholders have given positive feedback that it represents their understanding well, appreciate the spatial resolution it brings to that understanding, and highlighted its use in making local land use decisions and other key management practices which could be further explored.

The model and application could be further developed to include more management options, as well as temporal seasonal impacts of practices and further scenarios which may be of interest to stakeholders, such as climate change scenarios. The condition of habitats could also be further considered in this approach and spatial management data could provide a more accurate picture of what is happening on the ground to inform more accurate predictions. Further ecosystem services could also be modelled within the region such as regulating water quality or biodiversity, to make this a more useful tool in assessing the trade-off between local land-use decisions.

References

Albertson, K., Aylen, J., Cavam, G. & McMorrow, J. 2009. Forecasting the outbreak of moorland wildfires in the English Peak District. Journal of Environmental Management 90(8): 2642-2651.

Asher Greenberg, J. & Mattiuzzi, M. 2018. Package 'gdalUtils'. Wrapper for the Geospatial Data Abstraction Library (GDAL). Version 2.0.1.14. Available from: https://cran.rproject.org/web/-packages/gdalUtils/gdalUtils.pdf [Accessed on 21/01/2021].

Brecon Beacons National Park Authority (BBNPA) 2021. Available from: https://www.beacons-npa.gov.uk/the-authority/press-and-news/archive/2015-2/february-2015/controlled-burning-to-protect-against-wildfires/ [accessed 01/04/2021].

Brecon Beacons National Park Authority (BBNPA) 2020. National Park Management Plan 2015-2020. Available from: https://www.beacons-npa.gov.uk/wp-content/uploads/BBNP-Management-Plan-PROOF-03-03-16-English.pdf [accessed 01/04/2021].

Bluesky International. 2019. APGB: Aerial Photography for Great Britain. Available from: https://www.apgb.co.uk/ [Accessed on 21/01/2021].

Parliamentary Office of Science & Technology (POST) 2019. Climate change and UK wildfires. POST Note Number 603. June 2019.

Chas-Amil. M.L., Touza, J. & García-Martíneza, E. 2013. Forest fires in the wildland-urban interface: A spatial analysis of forest fragmentation and human impacts. Applied Geography 43: 127-137.

CWFIS Canadian Wildland Fire Information System | Canadian Forest Fire Weather Index (FWI) System. Retrieved 9 June 2020, from https://cwfis.cfs.nrcan.gc.ca/background/summary/fwi

Davies, G.M., Legg, C.J., Smith, A.A. & MacDonald, A.J. 2009. Rate of spread of fires in Calluna vulgaris-dominated moorlands. Rate of spread of fires in *Calluna vulgaris*-dominated moorlands. Journal of Applied Ecology 46: 1054-1063.

de Jong, M.C., Wooster, M.J., Kitchen, K., Manley, C., Gazzard, R. & McCall, F.F. 2016. Calibration and evaluation of the Canadian Forest Fire Weather Index (FWI) System for improved wildland fire danger rating in the United Kingdom. Natural Hazards and Earth System Sciences 16: 1217–1237. https://doi.org/10.5194/nhess-16-1217-2016.

Grau-Andrés, R.G., Davies, G.M., Gray, A., Scott, E.M. & Waldron, S. 2015. Fire severity is more sensitive to low fuel moisture content on Calluna heathlands than on peat bogs. Science of The Total Environment 616-167: 1261-1269

Harper, A. 2020. Correspondence.

Joint Research Centre (JRC) 2021. Active Fire Detection. Available from: https://effis.jrc.ec.europa.eu/about-effis/technical-background/active-fire-detection [Accessed 08/03/2021].

McMorrow, J. & Lindley, S. 2006. Modelling the spatial risk of Moorland wildfire. The University of Manchester. Final report - Moors for the future, Dec 2006.

Met Office. 2020; UK Fire Severity Index - Met Office. (2020). Retrieved 9 June 2020, from https://www.metoffice.gov.uk/public/weather/fire-severity-index/

Met Office; Hollis, D.; McCarthy, M.; Kendon, M.; Legg, T. & Simpson, I. 2019. HadUK-Grid Gridded Climate Observations on a 1km grid over the UK, v1.0.1.0 (1862-2018). Centre for Environmental Data Analysis, 14 November 2019. doi:10.5285/d134335808894b2bb-249e9f222e2eca8

Ordnance Survey. 2020. OS OpenMap – Local. Available from: https://www.ordnancesurvey.co.uk/business-government/products/open-map-local [Accessed 02/11/2020].

Padgham, M., Rudis, B., Lovelace, R., Salmon, M., Smith, A., Smith, J., Gilardi, A., Spinielli, E., Kalicinski, M., Noam, F. & Lukasz, B. 2020. Package 'osmdata'. Import 'OpenStreetMap' Data as Simple Features or Spatial Objects. Version 0.1.4. Available from: https://cran.r-project.org/web/packages/osmdata/osmdata.pdf [Accessed 12/12/2020].

QGIS Development Team (2020). QGIS Geographic Information System. Open Source Geospatial Foundation Project. http://qgis.osgeo.org.

R Core Team. 2019. R: A Language and Environment for Statistical Computing. Vienna, Austria. Available from: https://www.R-project.org/.

RStudio, PBC. 2020. Shinyapps.io by RStudio. Available from https://www.shinyapps.io/ [Accessed 12/12/2020].

Santana, V.M. & Marrs, R.H. 2014. Flammability properties of British heathland and moorland vegetation: Models for predicting fire ignition. Journal of Environmental Management 139: 88-96

Sinnadurai, P. 2005. A review of current literature on the evidence for climate change and its implications for the Brecon Beacons National Park. Climate change implications for the Brecon Beacons National Park. An occasional report. December 2005. Available from: https://www.beacons-npa.gov.uk/wp-content/uploads/oldsite/environment/climate-change/bbnpclimatechangeinfonote_updateddecember05.pdf [Accessed 01/04/2021].

Worldpop. 2020.Open Spatial Demographic Data and Research. www.worldpop.org. [Accessed 21/01/2021].

Appendix 1. A review of biotic and abiotic factors affecting fire risk

A time-limited literature review was conducted with defined search parameters (habitat type, management interventions, recreational use, biotic and abiotic factors, available tools), and a focus on UK and Ireland initially but with a limited consideration for other regions with similar climates and vegetation. This review is primarily based on previous reviews and grey literature and is not considered a comprehensive literature review.

Factor		**Impact on…**			**Possible metrics**
		Ignition Susceptibility	**Flammability**	**Fire Severity**	
Climatic	Increased temperature	+ Reduces fuel moisture + Increases recreational use - New vegetation less fire prone than older, drier plants (Albertson *et al.* 2009, 2010)	+ Reduces fuel moisture	+ Reduces fuel moisture + Increases fuel load by stimulating plant growth (POST Note 603; Albertson *et al*. 2010)	Maximum, minimum, and average temperatures over defined periods
	Increased precipitation	- Increases fuel moisture - Reduces recreational use	- Increases fuel moisture	+ Increases fuel load by stimulating plant growth (POST Note 603) - Increases fuel moisture	Precipitation e.g. over defined time periods Soil moisture
	Increased wind speed	+ May dry vegetation (reduce fuel moisture)	- Increase fire spread		Wind speed data
Human accessibility	Increased proximity to urban areas	+ Increased number of potential ignition sources (Jollands *et al*. 2011)	- Fires in areas used by people may be detected more quickly, and easier to mobilise to control	- Fires in areas used by people may be detected more quickly, and easier to mobilise to control	Population density, Distance to road, Proximity to footpath, Distance to urban area, Proximity to fire service
	Increased recreation	+ Increased number of potential ignition sources	- Fires in areas used by people may be detected more quickly, and easier to mobilise to control	- Fires in areas used by people may be detected more quickly, and easier to mobilise to control	Recreational use
	Increased deprivation	+ The most socially deprived communities may have a higher risk of arson attack (Jollands *et al*. 2011)			

Factor		**Impact on…**			**Possible metrics**
		Ignition Susceptibility	**Flammability**	**Fire Severity**	
Topographic	Increased slope		- Fires tend to spread more quickly and burn more intensely uphill	- Fires tend to spread more quickly and burn more intensely uphill	Slope angle
Vegetation	Plant species	Differences between individual plant species due to e.g. moisture and volatile content (Wyse *et al*. 2016)	Differences between individual plant species due to e.g. moisture content, surface area:volume	Differences between individual plant species due to e.g. moisture content, volatile content, surface area:volume (Wyse *et al*. 2016)	

Appendix 2. Example questionnaire

The stakeholder groups engaged included a mixture of local active graziers, staff from the Brecon Beacons National Park Authority, Natural Resources Wales, and the Wildfire Advisory Group. These groups were approached by adding agenda items to regular meetings (e.g. Wildfire Advisory Group and Active Grazier meetings) or via email correspondence. There was a total of 17 responses (see breakdown of affiliation in Figure A1). As this is a proof-of-concept, this approach was considered appropriate for demonstration purposes. Future development work would require more robust models for gaining expert knowledge with more confidence.

Figure A1: Summary of the number of responses to the questionnaire.

An example questionnaire is available at: https://hub.jncc.gov.uk/assets/7691fb4a-b77a-4f8e-8660-a06b567ba345#jncc-report-701-appendix-2.pdf.

Appendix 3. Habitat descriptions

An information document was created to accompany the questionnaire to aid stakeholders with understanding of habitats being considered for this proof-of-concept. These included a short description and photographs of habitats. These were provided in English and Welsh.

An example is available (in English) at: https://hub.jncc.gov.uk/assets/7691fb4a-b77a-4f8e-8660-a06b567ba345#jncc-report-701-appendix-3.pdf.

Appendix 4. Sensitivity analysis results

Test mean	Train mean	MannWhitney	Flammability	Access.	Habitat	Aspect	Elevation	Slope	Prec.	Temp	Footpath	Poparea	Road
0.700	0.700	0.997	0.8	0.2	0.65	0.1	0.05	0.05	0.1	0.05	0.25	0.615	0.135
0.697	0.698	0.984	0.9	0.1	0.65	0.05	0.1	0.05	0.1	0.05	0.25	0.615	0.135
0.698	0.699	0.974	0.8	0.2	0.65	0.1	0.05	0.1	0.05	0.05	0.25	0.615	0.135
0.701	0.701	0.946	0.85	0.15	0.65	0.05	0.1	0.05	0.1	0.05	0.25	0.615	0.135
0.696	0.696	0.934	0.85	0.15	0.65	0.1	0.05	0.05	0.1	0.05	0.25	0.615	0.135
0.694	0.695	0.932	0.85	0.15	0.65	0.1	0.05	0.1	0.05	0.05	0.25	0.615	0.135
0.696	0.696	0.904	0.9	0.1	0.65	0.05	0.1	0.1	0.05	0.05	0.25	0.615	0.135
0.696	0.696	0.894	0.9	0.1	0.65	0.05	0.05	0.1	0.1	0.05	0.25	0.615	0.135
0.690	0.691	0.861	0.9	0.1	0.65	0.1	0.05	0.1	0.05	0.05	0.25	0.615	0.135
0.700	0.701	0.846	0.8	0.2	0.65	0.1	0.1	0.05	0.05	0.05	0.25	0.615	0.135
0.705	0.705	0.842	0.8	0.2	0.65	0.05	0.1	0.05	0.1	0.05	0.25	0.615	0.135
0.700	0.700	0.842	0.85	0.15	0.65	0.05	0.1	0.1	0.05	0.05	0.25	0.615	0.135
0.699	0.700	0.832	0.85	0.15	0.65	0.05	0.05	0.1	0.1	0.05	0.25	0.615	0.135
0.696	0.697	0.775	0.85	0.15	0.65	0.1	0.1	0.05	0.05	0.05	0.25	0.615	0.135
0.703	0.704	0.773	0.8	0.2	0.65	0.05	0.1	0.1	0.05	0.05	0.25	0.615	0.135
0.703	0.703	0.752	0.8	0.2	0.65	0.05	0.05	0.1	0.1	0.05	0.25	0.615	0.135
0.692	0.692	0.741	0.9	0.1	0.65	0.1	0.05	0.05	0.1	0.05	0.25	0.615	0.135
0.692	0.693	0.700	0.9	0.1	0.65	0.1	0.1	0.05	0.05	0.05	0.25	0.615	0.135

Appendix 5. Summary note of the updated version of the habitat map

In the closing phase of the project, an updated version of the habitat map was made available from NRW. This is displayed in Figure A2 with notably several land classes having been either separated from the broader term of 'Acid Grassland' or new classes having been created as a result of the mixed vegetation present. A comparison table with the older version of the habitat map is shown in Table A1.

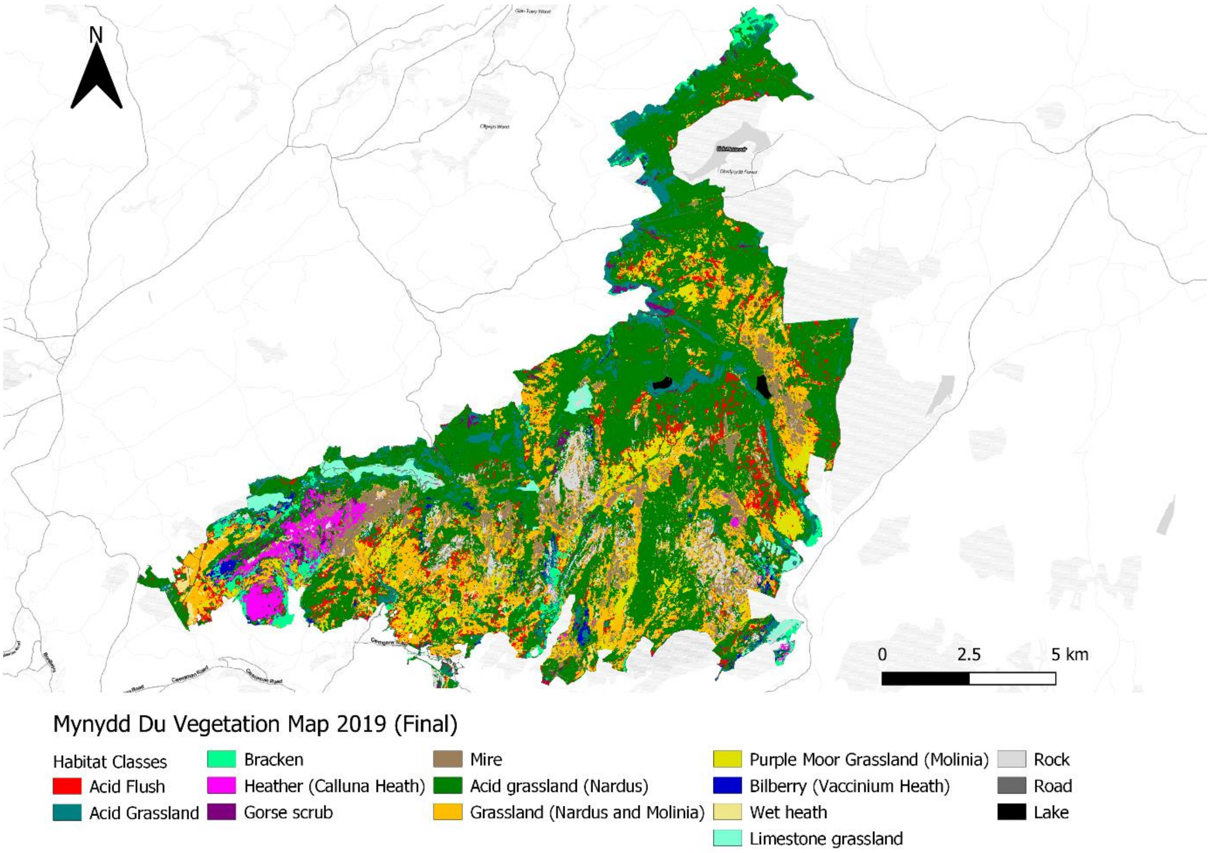

Figure A2: The updated habitat map from NRW. Contains Natural Resources Wales information © Natural Resources Wales and database right. All rights reserved. Contains Ordnance Survey data © Crown Copyright and Database Rights. Ordnance Survey Licence number 100019741. Sentinel-2 analysis-ready data processed by JNCC and supplied under the Open Government Licence v3 via the CEDA Archive (archive.ceda.ac.uk).

The main changes with the final version of the habitat map were with the addition of two new classes, '*Gorse scrub*' and '*Nardus and Molinia grassland*', and the separation of the 'Acid grassland' areas into 'Acid grassland' and '*Nardus grassland*'. For our analysis, we combined two classes of '*Festuca and Nardus*' and '*Nardus*' into one 'acid grassland' class for the stakeholder assessment of the management risks. The division of the acid grassland areas need to be carefully considered when making comparisons across the maps and comparing relative burn risks. In the later version, the proportion of Purple Moor Grassland has greatly decreased by 18.33%, with much of this being classified as a mixture of *Nardus* or *Nardus* and *Molinia* grassland and acid flush.

Table A1: A comparison table of the habitat classes classified in the different versions of the habitat map.

Habitat class (draft version)	Area cover of total site – draft version (%)	Area cover of total site – final version (%)	Difference
Bracken	5.65	2.50	-3.15
Heather (*Calluna Heath*)	2.62	4.07	1.45
Mire	6.13	7.30	1.17
Acid grassland - combined *Festuca* and *Nardus* and *Nardus* (draft habitat map)	35.7	-	-
Acid grassland (final map)	-	5.63	-
Nardus grassland	-	49.3	-
Rush / Acid Flush	2.36	4.78	2.42
Limestone grassland	1.59	1.59	0
Bare earth	0.258	0	-0.258
Heath and grassland mosaic	6.47	0	-6.47
Wet heath	8.09	1.09	-7
Purple Moor Grassland	22.4	4.07	-18.33
Rock	3.54	3.54	0
Road	0.687	0.687	0
Lake	0.191	0.191	0
Nardus and *Molinia* grassland	-	15.4	-
Gorse scrub	-	1.07	-

Comparisons of the relative habitat risk scores indicating how susceptible each habitat class was to fire based on where fires had previously occurred (using the area weighting principle documented in 2.4.1. unadjusted with management) are shown in Table A2.

The habitats display largely similar risk score, with the main exception being the shift of purple moor grassland from a score of 10 to 5.58 in the final version of the map. This can be explained by the significant decrease in the amount of habitat classified as purple moor grassland from 22.4% of the site to 4.07%, as mentioned previously. This has meant much of the burnt area is now reclassified however with some burns still recorded on this habitat, giving it a comparatively higher susceptibility score in the final map in comparison with other classes. *Nardus* and *Mollinia* Grassland is noted to be the most susceptible habitat in the final habitat map. This new class along with gorse scrub was not assessed during the stakeholder survey and therefore we cannot use the final version of the habitat map in our analysis without further guidance from stakeholders to assess the relationships of these classes with management practices.

Table A2: Comparison table of habitat risk scores between the draft and final versions of the habitat map.

Habitat class (draft version)	Habitat map (draft) susceptibility score	Habitat map (final) susceptibility score	Difference
Bracken	3.88	3.71	0.17
Heather (*Calluna Heath*)	4.42	4.36	0.06
Mire	4.05	3.38	0.67
Acid grassland -combined *Festuca* and *Nardus* and *Nardus* (draft habitat map)	1	-	-
Acid grassland (final map)	-	1.08	-
Nardus grassland	-	1	-
Rush / Acid Flush	-	3.93	-
Limestone grassland	4.15	3.14	1.01
Bare earth	4.36	-	-
Heath and grassland mosaic	3.96	-	-
Wet heath	4.51	5.23	-0.72
Purple Moor Grassland	10	5.58	4.42
Rock	0	0	0
Road	0	0	0
Lake	0	0	0
Nardus and *Molinia* grassland	-	10	-
Gorse scrub	-	3.51	-