Fire Danger Assessment of Scottish Habitat Types

Deliverable 2.3b for the

Project D5-2 Climate Change Impacts on Natural Capital

March 2023

Summary

This report is a product of the Scottish Government Strategic Research Programme project JHI-D5-2 'Climate Change Impacts on Natural Capital'. The purpose of this report is to provide an assessment of current wildfire danger conditions for the main habitat types in Scotland. The aim of this report is to present the components of a fire danger assessment framework that can be used to inform the development of a spatial model of fire danger for the main habitat types in Scotland. For this reason, we present findings related to fire occurrence patterns in Scotland derived from recent studies and from the combined analysis of burnt areas and land cover information that will be used to inform fire danger and risk assessments for Natural Capital assets in the context of the Risk and Opportunities Assessment Framework (ROAF) being developed in JHI-D5-2.

Key Messages:

- Wildfires are an intermittent hazard and exhibit clear seasonal patterns of occurrence, with the main fire season being in the spring when most of the larger wildfires occur in heather moorlands and peatlands.
- Fire danger depends on the presence of ignition sources and the interaction between weather, fuel type composition and characteristics and landscape that regulate the moisture of live and dead fuel material.
- Current fire danger systems fail to forecast fire occurrence in heather moorlands but can perform better for forest fire occurrence.
- Future climatic trends may increase fire danger in parts of Scotland, which when coupled with large scale land use change such as woodland expansion could also increase risks to Natural Capital assets and to people and infrastructure as well.

Advances in Technical Capabilities

This report has been developed through technical advances made in the JHI-D5-2 Project related to the combined analysis of spatial layers such as land use maps and burnt area polygons delineated from the analysis of satellite imagery, and the calculation of descriptive statistics for the assessment of wildfire danger indices for different fuel types.

Contents

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Introduction

The purpose of this report is to present the main components of fire danger assessments and a broad assessment of fire danger for the main habitat types in Scotland. This report is a Deliverable for the Strategic Research Programme project 'Climate Change Impacts on Natural Capital' (JHI-D5-2). The aim of this work is to provide insight on the current wildfire regime in Scotland and the information needed to conduct fire danger assessments for the main habitat or fuel types present in Scotland. In particular, the objective of this work is to use literature findings and results of a spatial analysis of land cover and burnt area layers to assess patterns of fire occurrence and of fuel type composition and assess the efficiency of fire danger indices for predicting fire occurrence in different habitat types.

Advancing analytical capability

A combined analysis of information on fire occurrence, land cover or fuel type and fire weather indices is necessary for identifying temporal and geographical patterns of fire occurrence and fuel type composition. In this context, work presented here has advanced our technical analytical capability by:

- Analysis of land cover data layers, translated to main fuel types, and layers of burnt areas mapped from remote sensing analysis to identify patterns of seasonality, fire magnitude and fuel type composition.
- Analysis of fire weather indices within the extent of the mapped burnt areas to assess variation of fire danger for main habitat or fuel types in Scotland.

The benefits of these technical developments are that report findings will inform the development of a spatial fire danger model (i.e., model structure/modules, input dataset requirements) with the ability to conduct fire danger assessments for different climatic scenarios, which will be used as inputs to ROAFF spatial assessments of projected wildfire danger and risk impacts on Natural Capital assets.

Technical Developments

Wildfires in Scotland

Fire is an integral part of the ecology of the British uplands. Traditional managed burning is used extensively for habitat management for red grouse (*Lagopus scoticus*) on heather (*Calluna vulgaris*) dominated moorlands and blanket bogs, and to rejuvenate moorland and grassland, principally dominated by purple moor grass (*Molinia caerulea*) for cattle, sheep and deer grazing (Davies and Legg, 2016). In forests, prescribed fire has also been used as a ground preparation tool prior to planting and to facilitate restoration in native woodlands. Land management such as clearing of vegetation and prescribed burning can also reduce fuel availability and prescribed burning has been used as a management tool for reducing wildfire risk, especially in highly flammable ecosystems as those found in southern Europe (Davim et al., 2022).

However, wildfires, defined in Scotland as “any uncontrolled vegetation fire which requires a decision, or action, regarding suppression” (Scottish Government, 2013), are increasingly an important topic of discussion across the UK due to an increasing awareness of wildfire occurrence, as well as concerns about how wildfire incidents could alter the landscape and potentially damage property and infrastructure (Arnell et al, 2021). Wildfires can be destructive for seminatural habitats (Whitehead et al, 2021); they can cause peatland degradation and reduction of carbon storage and extensive damage of sensitive habitats such as *Sphagnum* vegetation communities (Grant et al, 2012). Wildfire activity is expected to increase across the British uplands due to fuel accumulation associated with changes in sheep stocking rates, pressure to reduce the extent of, or even ban, managed burning, warmer and drier conditions with more frequent droughts due to climate change and increased ignition frequencies associated with widening public land access (Belcher et al., 2021). An analysis of climate trends and future projections in Scotland (developed within the D5-2 Project) shows a likelihood of drier conditions (Rivington and Jabloun 2022). Therefore, it is expected that increased occurrence of wildfires, especially on remote upland areas and peatlands, will be costly to fight, cause damage to freshwater catchments and other ecosystem services and require costly restoration (Albertson et al, 2010).

Wildfire occurrence is likely to be determined by a combination of environmental and climatic influences i.e., temperature and amount of rainfall, but are most often caused by deliberate or accidental human influences (Arnell et al, 2021). In addition, the distribution of wildfires in Scotland is believed to be non-random in both time and space; in particular, fuel hazard in spring, with abundant dead herbaceous and aerial shrub fuels, is quite different from that in summer where most above-ground fuel is alive, while grass fuels are more abundant in the north-west of Scotland (Davies and Legg, 2016). Severe wildfire is considered an intermittent hazard as the most serious incidents are concentrated in a few dry years. Wildfire incidents are most prevalent in the spring because of the availability of dead and dry fine vegetation as fuel, but widespread wildfires have also occurred in some hot, dry summers (Perry et al., 2022).

According to Gazzard et al. (2016), most small wildfires in the UK occur at the rural-urban interface or on arable land, as this is where fires are most likely to be ignited by human activity; however, many of the larger wildfires occur in more remote areas, especially moorland, forests, and peatland bog. Drier moorland community types appear to be at greater risk of severe burns than blanket bog communities (Grau-Andrés et al., 2018). Wildfires are a common occurrence in grass and shrub dominated moorland vegetation and in gorse (*Ulex europaeus*) stands close to urban areas. Wildfires within forests in Scotland are much less common, though they do occur during exceptional weather conditions and in young plantations of conifers, especially where these are adjacent to heather or grass-dominated vegetation, or where heather has re-invaded older stands after thinning.

Recent analysis of fire incidents from the Scottish Fire and Rescue Service (SFRS) Incident Reporting System (IRS) (Gagkas et al., 2022) identified three main types of fires occurring in Scotland that affected seminatural vegetation: a) Wildfires caused in very remote and remote rural areas affecting mainly heathlands and bogs and peatlands that seem to be caused mainly by accidental ignitions; b) Wildfires in accessible rural areas and smaller urban centres that affected grasslands and woodlands; and c) Small fires close to settlements and urban centres affecting mainly grasslands that seemed to be caused by deliberate ignitions. Wildfires in remote areas tended to be larger and were mainly caused by bonfires or other intentional burns that got out of control, which might be associated with traditional land management practises or tourism/recreational activities.

Framework for Fire Danger Assessments

Overview

Fire danger is a general term used to express an assessment of both fixed and variable factors of the fire environment that determine the ease of ignition, rate of spread, difficulty of control, and fire impact (Taylor et al., 2022). In this study, we present a framework of fire danger assessment that is based on a pan-European framework of fire risk assessment proposed in the context of the European Forest Fire Information System (EFFIS[1]) by San-Miguel-Ayanz et al. (2019) and Oom et al. (2022) (Figure 1). Within this quantitative framework, wildfire risk is conceptually defined as the product of the probability of a wildfire occurring or/and propagating (hazard), and the damage that it may cause (exposure and vulnerability). Hence, this involves three main fire research areas:

- Fire ignition/occurrence.
- Fire behaviour/propagation (and intensity at which they might occur).
- Fire effects (potential loss of resources as a result of wildfires and exposure of assets located in wildfire-prone areas).

The focus of this study is on wildfire danger that is influenced by the factors related to the probability of ignition and those affecting fire behaviour. It is therefore composed by the likelihood/possibility of having a fire ignition, and the behaviour (propagation and intensity) of a fire once it is ignited. All these factors are represented by the upper branch of the scheme presented below in Figure 1. The aspect of vulnerability[2] of Natural Capital assets, which when combined with fire danger gives the assessment of fire risk, will be assessed separately in future work as part of the development of the Risk and Opportunities Assessment Framework (ROAF). The following sections provide a brief description of the respective fire danger components.

[1] https://effis.jrc.ec.europa.eu/

[2] The project uses the concept that Risk to Natural Capital assets is a function of an asset's Vulnerability and Exposure to a range of Threats (primarily climate driven, including fire).

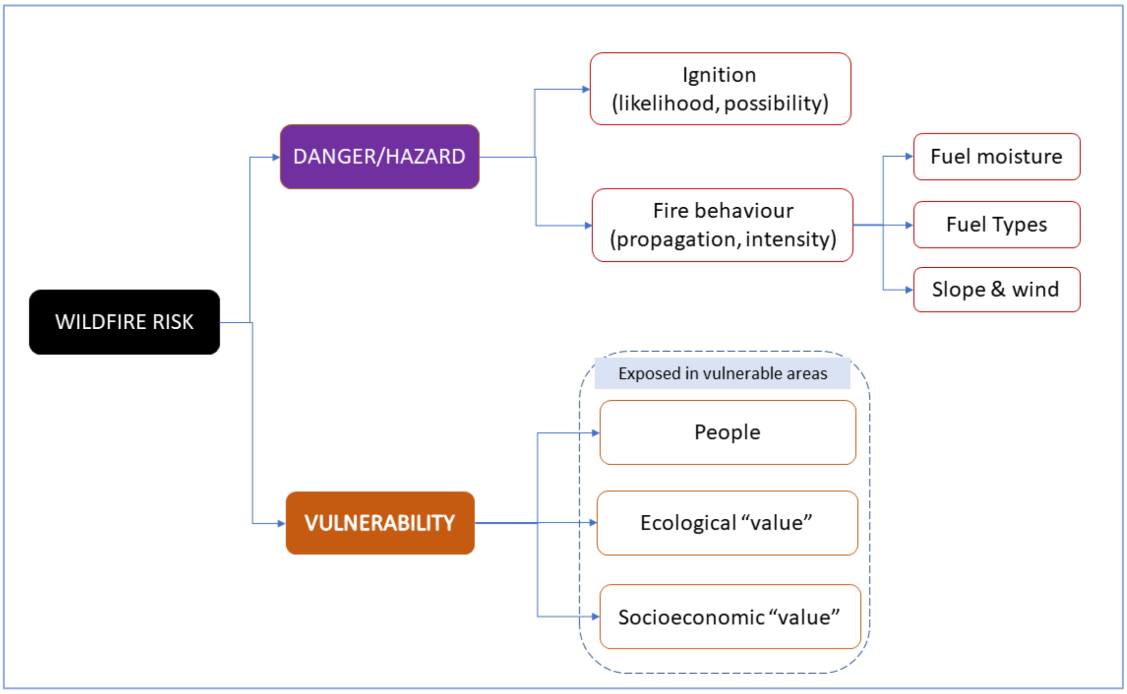

Figure 1. Main components of the pan-European wildfire risk assessment (WRA) (modified by San-Miguel-Ayanz et al., 2019 and Oom et al., 2022).

Ignitions

Wildfires need an ignition source. Lightning is a weather event that can cause wildfires to ignite, particularly in the case of 'dry lightning' (not accompanied by significant rainfall). This is a significant source of ignitions in some parts of the world, for example Australia and Canada, but is very rare in Europe where the vast majority of ignitions are due to human factors including accidental or deliberate ignition, land use, land management and any efforts to suppress the fire (Perry et al., 2022).

Historical records on the location, damage and number of fires could be used to assess the contribution of fire ignition to fire danger. These can come from sources such as National Fire Services, although these data are generally lacking or are not always appropriate for identifying wildfires (Davies and Legg, 2016, Gagkas et al., 2022). Alternative datasets include burnt areas delineated from the analysis of satellite imagery, such as burned area from EFFIS based on the semi-automatic classification of NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery using ancillary spatial datasets (Oom et al., 2022). Every day, two full image mosaics of the European territory are processed in EFFIS to derive burnt area maps. Burnt scars of approximately 30 hectares (ha) in size are mapped, although the product may also include the perimeters of burned areas of smaller dimension, especially post-2020 when MODIS imagery has been largely replaced by Sentinel-2 imagery that enables detection of smaller burn scars (<10 ha). EFFIS state that their system only detects a small fraction of the total number of fires, but that the total burned area is only underestimated by 20–25%, given that a small number of large fires is responsible for most of the burnt area.

Fire behaviour

Fire behaviour is conceptually influenced by the fuel moisture content of both dead and live fuels, the different fuel types, slopes, and wind patterns that will determine the propagation (rate of spread and spread direction) of a wildfire (Oom et al., 2022). Weather conditions have a direct impact on the likelihood and severity of fires occurring. Variations in weather such as temperature, relative humidity and precipitation affect the amount of moisture held in both live and dead vegetation ('fuel') – which is crucial for flammability (Perry et al., 2002). Strong winds help fires to spread more quickly and there is usually insufficient green vegetation in spring to prevent the spread of a fire. In summer, however, fires are generally driven by high temperatures and prolonged dry conditions which reduce the amount of moisture in the living vegetation (Perry et al., 2022). Both seasons exhibit spells of dry, warm/hot, windy weather which therefore favours the start and spread of wildfires, but conditions can fluctuate greatly on a daily basis. As well as short-term conditions, soil moisture is affected by antecedent rainfall amounts over previous weeks and months.

Fuel moisture content

Fuel moisture content (FMC) is a fundamental element for availability of fuel for combustion, and as dry fuels burn easily is a fundamental element to provide favourable conditions for wildfire propagation (Van Wagner, 1987). FMC, defined as the proportion of water contained in the vegetation in relation to dry mass, fluctuates in time and space and is highly dependent on weather conditions. It can be divided into FMC of dead fuels or live fuels (Chuvieco et al., 2010). In addition to the moisture content of dead fuels, the live fuel moisture content is essential in determining fire spread and intensity. Existing approaches for the estimation of moisture content of live fuels rely on empirical methods or simulations, such as those based on radiative transfer models (RTM) (Chuvieco et al., 2010). However, estimation of live fuel moisture content is difficult and has proven successful mainly for grasslands and shrubs. An alternative approach is to use databases of measured plant water content to calibrate and validate remote sensing algorithms used to predict live FMC (Yebra et al., 2019).

Fine fuel components may show a fast response to changing weather, so that a windy, dry day might easily trigger a noticeable drop in their moisture content (Oom et al., 2022). On the other hand, thicker parts of the vegetation define quite a different fuel component: if thicker fuel requires more time (even several days or weeks) to dry under weather conditions facilitating the process, it conversely may preserve this dryness for a longer period, with a higher latency to fast changing weather. Even (not major) precipitation events may be unable to significantly increase a low fuel moisture content in thicker fuels, while a minor rainfall could easily saturate the moisture of finer fuels (Oom et al., 2022). Therefore, the behaviour of a wildfire is not only linked with the very recent weather conditions, but also with the cumulative effect of the past weather. This implies that numerical estimates of fire danger by weather for a certain time should include modules able to preserve the information of the weather history before that time.

Canadian Fire Weather Index System (CFWIS)

The Canadian Fire Weather Index System (CFWIS) is one of the most widely used tools for the general assessment of wildfire danger in the world (Van Wagner, 1987). The CFWIS was developed empirically on evidence of many thousands of fuel moisture readings, live fire tests and case studies of well documented fires (Taylor et al., 2022). The CFWIS uses a main reference fuel type of forest floor material on flat terrain under mature jack pine (*Pinus banksiana*) or lodgepole pine (*Pinus contorta*). The main fuels in these systems are the undecomposed surface litter and organic matter in the top layers of the soil (i.e., dead organic matter). CFWIS is based on three numerical components for assessing the moisture content of dead fuels of specific sizes and three components of fire behaviour that relate to the probability of fire ignition, spread or fire intensity (Figure 2 and Table 1). The fuel moisture components are based on four weather observations: air temperature, rainfall in the previous 24 hours, relative humidity, and wind speed for a reference fuel type (Figure 2).

Table 1. Description of codes of the Canadian Fire Weather Index System

Type	Code/Index	Description
Fuel moisture	Fine Fuel Moisture Code (FFMC)	Moisture content of cured leaves, needles and small dead twigs on the forest floor
	Duff Moisture Code (DMC)	Moisture content of loosely-compacted, partially decomposed needle litter
	Drought Code (DC)	Moisture content of deep layers of compact humus and organic matter
Fire behaviour	Initial Spread Index (ISI)	Combines FFMC and wind speed to provide representation of potential rate of spread without fuel quantity estimate
	Build-up Index (BUI)	Weighted combination of DMC and DC designed to represent total fuel available for combustion
	Fire Weather Index (FWI)	Weighted combination of ISI and BUI designed to provide representation of potential fireline intensity

The Fine Fuel Moisture Code (FFMC) represents the moisture content of dead fine litter and grasses 1 to 2 cm deep and gives an indication of ignition potential. The Duff Moisture Code (DMC) represents the moisture content of the duff layer, consisting of loosely compacted organic material, and indicates the potential for combustion in this layer, contributing to fire intensity. The Drought Code (DC) represents the moisture content of compacted organic material 10 to 20 cm deep and does not really contribute to the FWI calculation of fire intensity, but instead indicates the potential for deep-seated smouldering fire (Van Wagner, 1987). Each moisture code has a time lag and a rainfall threshold, which means that if rainfall is lower than this threshold value, the code value does not decrease (Taylor et al., 2022). The Initial Spread Index (ISI) combines FFMC with wind speed and indicates fire spread potential without considering fuel quantity. The Built-up Index (BUI) combines the DMC and DC and indicates combustion potential of the available fuel. Finally, the Fire Weather Index (FWI) combines ISI and BUI to create an indirect representation of the potential fire intensity, usually expressed as kW/m. In the Canadian situation and, where validated in generally similar habitat types, the values of the three fire behaviour indices increase as the various elements of fire danger increase (Taylor et al., 2022).

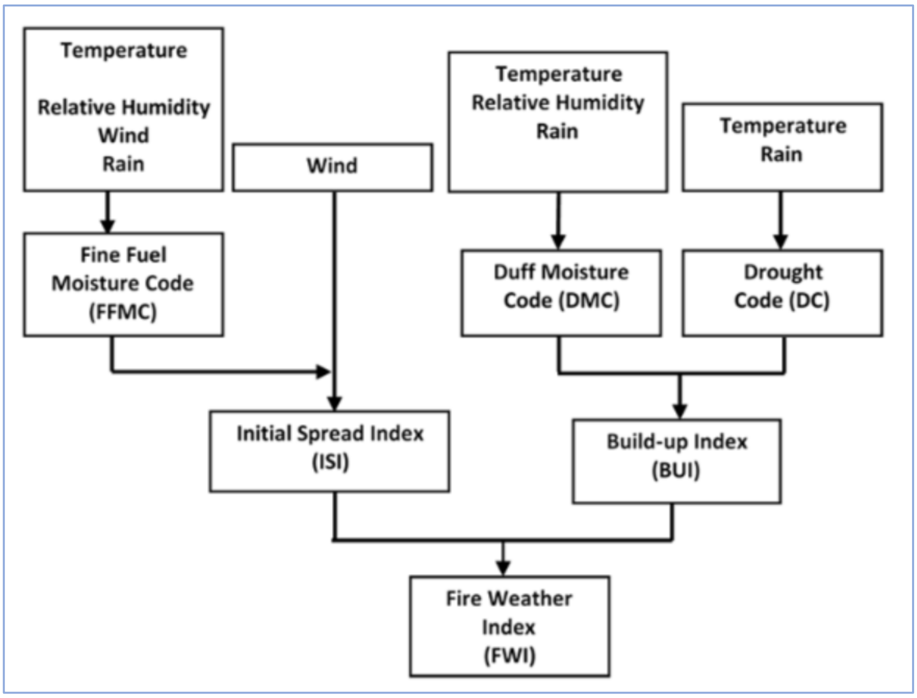

Figure 2. Components of the Canadian Fire Weather Index system (CFWIS) (from Taylor et al., 2022)

Fuel types

The type of fuel available to burn, which may include trees, shrubs, grasslands, etc., will directly influence the wildfire propagation and is key to fire propagation risk assessment as it considers the changes and dynamics of vegetation due to fire (Chuvieco et al., 2010). Each type of vegetation fuel, with its physical and chemical specific attributes and its phenology, affects wildfire behaviour (rate of spread, fire intensity, and propagation) and the impacts of wildfires (Oom et al., 2022). Moreover, wildfire behaviour is highly dependent on the horizontal and vertical structure of the fuels and their spatial connectivity, which may determine the horizontal and vertical progression of the fire front. Fully characterising vegetation and its susceptibility to disturbances (including wildfires) would require its composition, structure, and management to be known, along with its suitability, resistance and resilience to the changing bioclimatic conditions of the local habitat. Fuel types are usually characterised from land cover data, such as maps generated using remote sensing analysis.

Landscape controls

Landscape characteristics such as slope or local aspect, can be quite relevant for fire behaviour and wildfire propagation. For example, steep slopes (15°-20°) may affect wind direction and speed facilitating fire spread, and southern facing slopes in the northern hemisphere are likely to be hotter and drier as they receive more sunlight, and hence can effectively dry fuels that may become prone to fire ignition and propagation (Oom et al., 2022). Also, elevation could affect fire behaviour where higher elevations may be associated with low humidity or conversely with increased precipitation and increased wind speed, depending on the prevailing winds. In areas subject to frequent fire occurrence, even the local soil and vegetation composition may differ depending on the orography (de Rigo et al., 2017). Associated with terrain characteristics, local wind conditions (direction, speed) could also affect wildfire propagation and intensity. As mentioned above, wind can be considered for wildfire danger assessment through the ISI from CFWIS, but further research is needed to assess the potential of using both orographic information, and direct use of wind in refining wildfire danger and risk assessments (Oom et al., 2022).

Assessment of Fire Danger in Scotland

Overview

The assessment of current fire danger regime in Scotland follows the components of the WRA shown in Figure 1 and is based on findings from recent literature and information derived from the combined analysis of wildfire occurrence determined from burnt areas mapped from the analysis of satellite imagery and fuel type composition determined from land cover mapping.

Ignitions

Natural wildfires, e.g., due to lightning strikes, are rare in the UK and most wildfires are the result of human action, through either arson or accident (Glaves et al., 2020). Analysis of SFRS IRS fire incidents (Gagkas et al., 2022) found that arson is more frequent in the lowlands and in urban and rural-urban fringe areas, while the proportion of accidental fires is higher in the uplands and probably in more rural areas in general. These fire incidents tend to be associated with public access and recreation, with the majority of accidental wildfires resulting from 'camp' and other fires, especially in the uplands, though land management burns getting out of control are believed to be a significant cause in the uplands, although robust evidence is lacking. Small deliberate fires in or close to urban centres seemed to be driven mainly by anti-social behaviour or relatively trivial cases of negligence with fire, while the causes of fires in the more accessible rural areas could be a mixture of burns getting out of control or careless handling of equipment or other heat sources along with ignitions from anti-social behaviour.

This analysis also provided some clear indications regarding fuel types and ignition motives. For example, it was found that seminatural vegetation (grass, heath, scrub) were more likely to be responsible for ignition and fire spread in fires caused by accident, especially in larger wildfires where almost all IRS records had grass, heath, and scrub as the vegetation types responsible for ignition and fire spread. On the other hand, trees and to a lesser degree straw/stubble were more likely to be the most frequent vegetation type responsible for ignition and fire spread in, mainly smaller and less trivial, fires caused by deliberate ignitions.

Fire occurrence

Fire occurrence in Scotland was determined using burnt area polygons (*n*=514) for the 2013-2022 period provided in ESRI shapefile (vector) format by EFFIS. Burnt areas until 2019 were primarily generated from analysis of MODIS satellite imagery (detection mainly for burnt areas >30 ha), while Sentinel-2 imagery (20m pixel) was used for detecting and delineating burnt areas from 2020 onwards. Burnt area polygons contained information about the location of the fire, the respective administrative unit (i.e., Local Authority), initial and final fire dates and the size of the burnt area (in ha) (Figure 3).

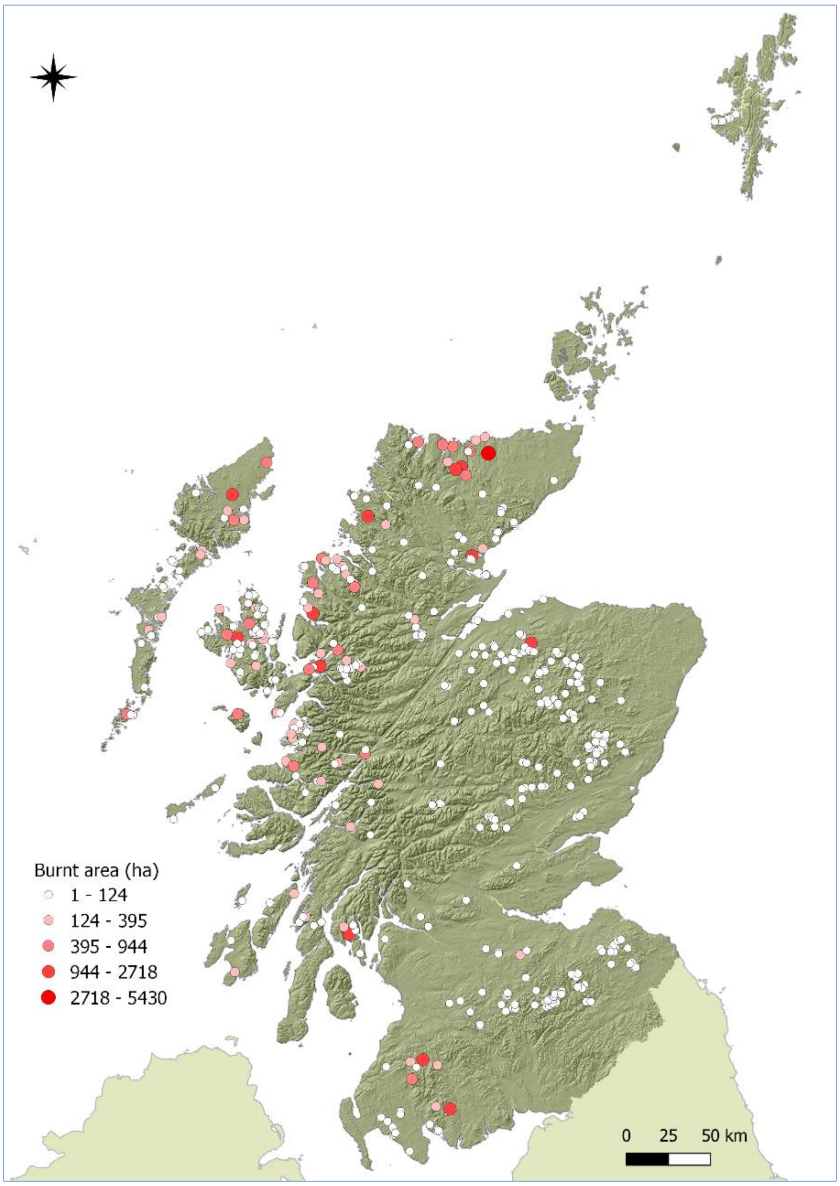

Figure 3. Location and burnt area (in ha) of EFFIS fire polygons for the 2013-2022 period.

Based on the burn area polygons, a total area of 59,881 ha was burnt in Scotland in the 2013-2022 period. Most of the fire incidents occurred in the Highland area (*n*=230 fires), followed by the Scottish Borders (*n*=50 fires), while a total of 20-30 fires were detected in each of the Aberdeenshire, Angus, Dumfries and Galloway, Eilean Siar, Moray and Perthshire and Kinross Local Authorities (LAs). Around 39,350 ha were burnt in the Highland area (~66% of the total burnt area), followed by 4,771 ha, 3,429 ha and 3,291 ha in the Eilean Siar, Moray and Dumfries and Galloway LAs, respectively. Burnt area was less than 2,000 ha in the remaining LAs.

There was a great increase in the number of burnt areas delineated by EFFIS for the 2021 and 2022 years (Figure 4a), but this was not accompanied by a respective increase in total burnt area, with most burnt area recorded in 2019, followed by 2018 and 2022 (Figure 4b). Moreover, median burnt area decreased from 72-890 ha in the 2013-2019 period to 11-15 ha in 2020-2022. This provides an indication that the increase in detected burnt areas may not necessarily be due to an increase in fire activity for 2021-2022, but it could be attributed to the change of the imagery source (from MODIS to Sentinel-2) that enabled the detection of smaller burns that could be controlled, prescribed burns rather than wildfires.

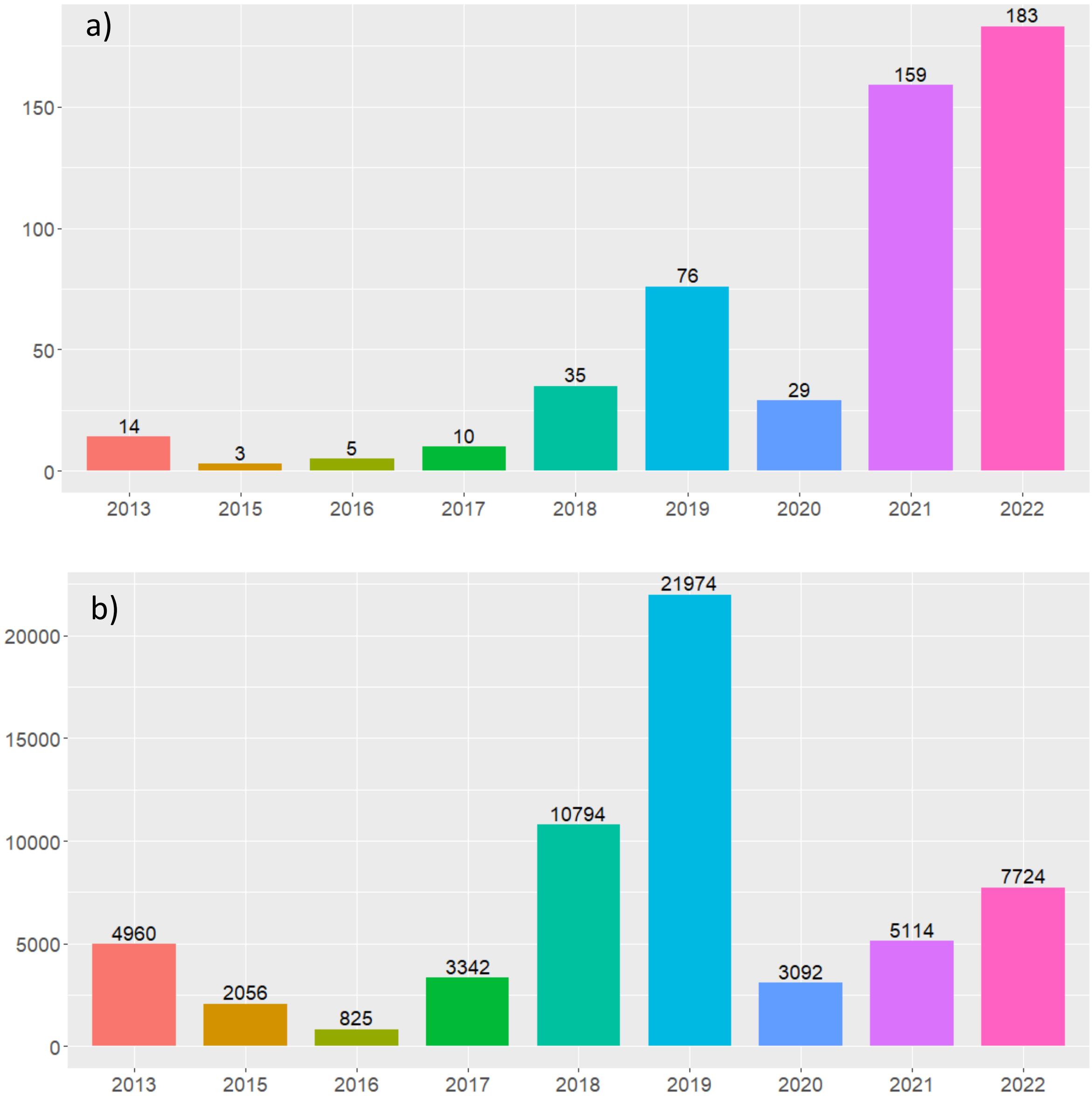

Figure 4. Yearly a) counts of fire incidents and b) burnt area (in ha) for the 2013 – 2022 period.

This hypothesis is further supported when overlaying the 2013-2022 EFFIS burnt area polygons with a map produced by Matthews et al. (2020) that gives the likely presence or absence of muirburn within each 1km pixel nationally. This analysis found that median burnt area for the 2013-2019 period (*n*=144 fires) was 120 ha and 36 ha for the fires located within the muirburn absence and presence pixels, respectively, but for 2020-2022 (*n*=370 fires) median burnt area was just 15 ha for fires within the muirburn presence pixels compared to 60 ha for those fires within the muirburn absence pixels. Hence, when assessing patterns of wildfire occurrence using the EFFIS burnt area polygons, we also need to consider that it is likely that a number of the smaller and more recent burns could be prescribed burns and not wildfires.

Fuel type composition

We used the UKCEH Land Cover Map (LCM) for 2019 to determine fuel type composition within the EFFIS burnt area polygons for the 2013-2022 period because a) our recent assessment of the performance of LCM 2019 for land cover/ habitat mapping (Gagkas et al., 2023) concluded that it is an appropriate data layer for use for the purpose of the D5-2 project; and b) both LCM datasets and the more recent (post-2020) EFFIS burnt areas are based on the analysis of Sentinel-2 imagery, which should ensure a good degree of consistency and compatibility between the LCM BH and EFFIS maps. Land cover in LCM 2019 is given as 21 UKCEH Land Cover Classes based upon UK BAP Broad Habitats[3] (Table 2) at a 20m grid cell resolution and have been created using new automatic techniques that combine Bootstrap Training with a Random Forest (RF) classifier to classify Sentinel-2 Seasonal Composite Images generated using the Google Earth Engine, representing median reflectance per season (Morton et al., 2020). For determining fuel type composition, Broad Habitats (BHs) were translated to respective Fuel Types (Table 2) that matched the classification scheme used by the EFFIS (EFFIS, 2017), excluding built-up areas and areas of freshwater. LCM-based fuel types were then extracted, and fuel type area and coverages were calculated for each burnt area polygon to determine the dominant fuel type of each fire incident, i.e., the fuel type covering the greater area within each burnt area polygon.

Table 2. LCM Broad Habitats (BH) translated to Fuel Types.

LCM BH	Fuel type	LCM BH	Fuel type
• Arable and Horticulture	• Arable	• Broadleaved Woodland • Coniferous Woodland	• Broadleaves • Conifers
• Bog • Fen, Marsh, and Swamp	• Bog • Fen	• Inland rock • Supralittoral rock • Littoral rock	• Rock
• Acid Grassland • Calcareous Grassland • Neutral Grassland	• Acid grass • Grass	• Heather • Heather grassland	• Heather
• Improved Grassland	• Improved grass		

This analysis clearly showed that the dominant fuel type of most fires was heather (Figure 5a) and that most of the total area burnt over the 2013-2020 period was heather moorland (Figure 5b), followed by bog vegetation and acid grasslands. There is a well-recognised issue of interclass confusion when mapping these upland, seminatural habitats of low vegetation that usually occur on peaty soils using analysis of satellite imagery due to their similar spectral signatures (Morton et al., 2020). Hence, this distinction between heather and bogs may be misleading as it is effectively based on the depth of the organic layer of the soil and because a major fuel type above ground on peat bogs is also shrubs (mainly heather). But overall, it can be assumed that around 96% of all fires and

[3] UK BAP Priority Habitats | JNCC - Adviser to Government on Nature Conservation

92% of all burnt area affected areas of mosaics of heather and bog vegetation and acid grassland vegetation.

There were also nine (9) fires recorded where conifers were the dominant fuel type that burned a total area of 2,617 ha of conifer forests. Comparison with the Caledonian Pinewood Inventory[4] showed that these burnt area polygons did not fall within areas of native pines, and visual inspection of Google satellite imagery confirmed that these fires affected mostly conifer plantations. Small areas of broadleaved and improved grasslands were also affected by fire occurrence (353 ha and 700 ha, respectively).

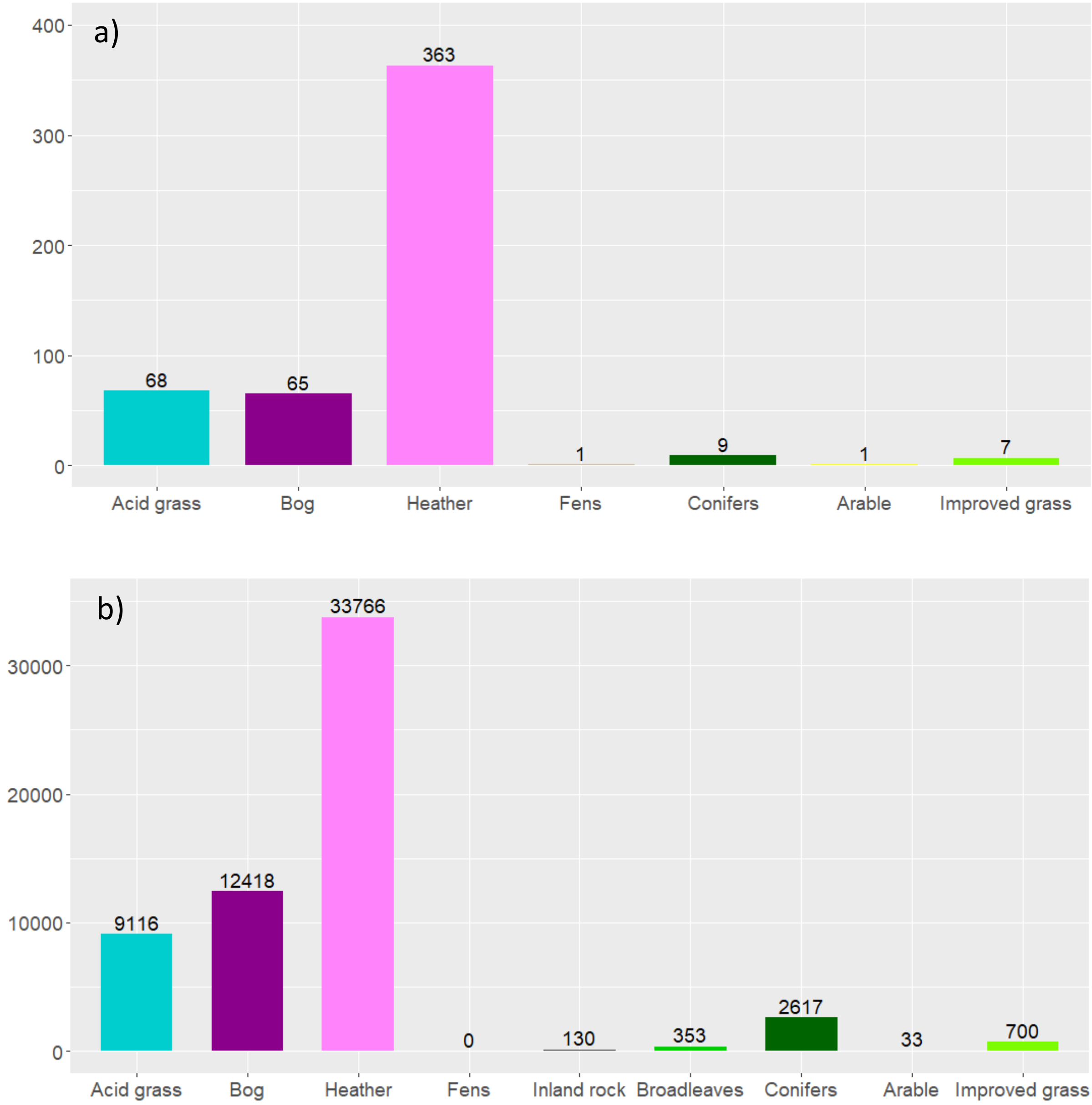

Figure 5. Total a) count of fire incidents per dominant fuel type and b) total burnt area (in ha) per fuel type for the 2013 – 2022 period.

[4] https://open-data-scottishforestry.hub.arcgis.com/

Regarding the seasonality of fire occurrence (Figure 6), 404 of the 514 fire incidents occurred in March and April with 44 and 22 fires occurring in February and May, respectively, and only 10 fires were detected in the summer (June, July and August). Around half of the total area affected by fires in the 2013-2022 period was burnt in April (30,524 ha), with 13,108 ha and 12,427 ha burnt in March and May, respectively. Median area burnt was 25 ha, 14 ha and 38 ha for February, March, and April, respectively, but greater at 149ha for fires that occurred in May. Hence, the analysis of the EFFIS burnt area polygons shows the dominance of the spring fire season in Scotland, in relation to both fire incident numbers and total area burnt.

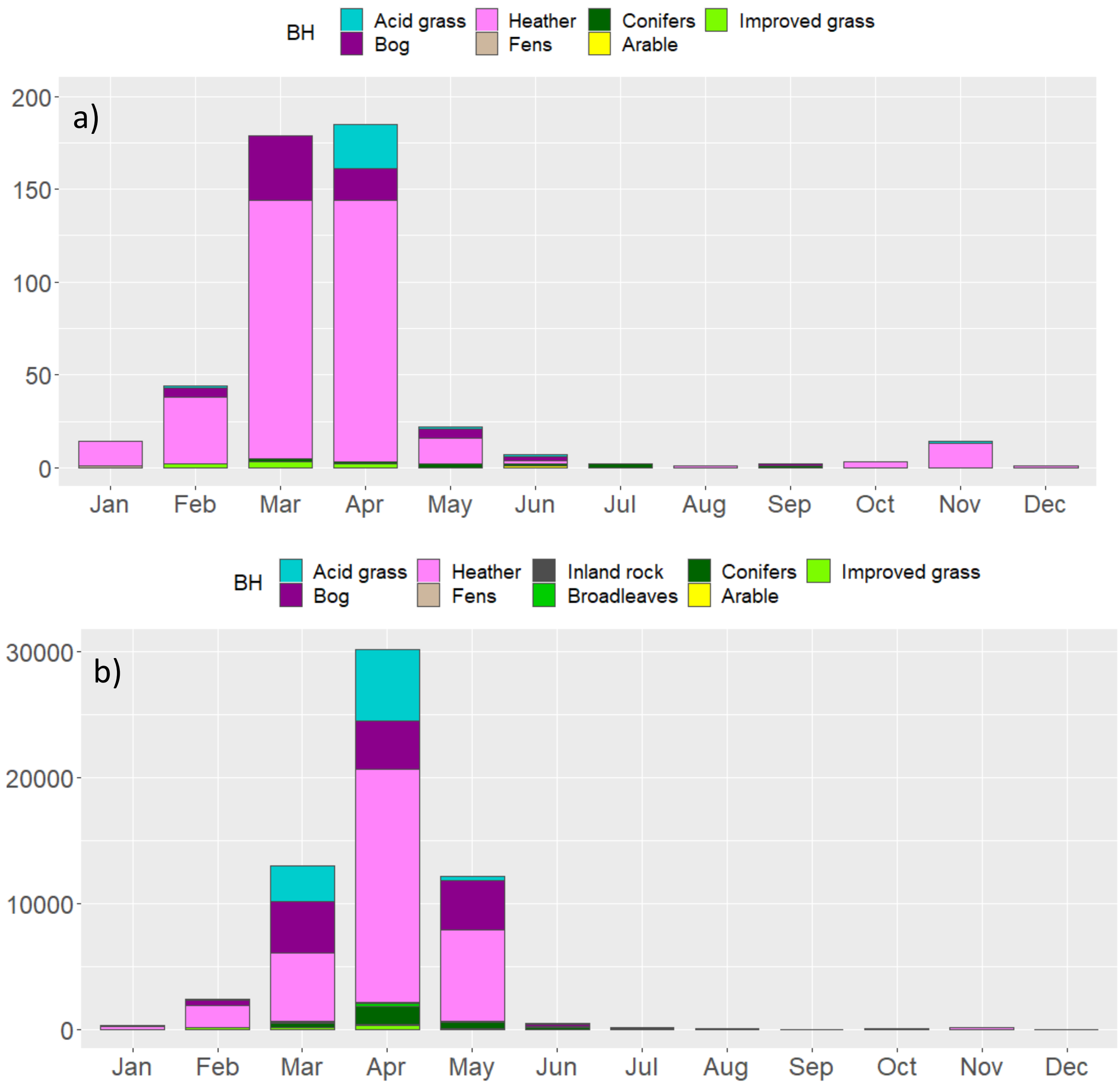

Figure 6. Monthly a) count of fire incidents per dominant fuel type and b) total burnt area (in ha) per fuel type for the 2013 – 2022 period.

As expected, most burnt area comprised of heather moorland in these spring fires, followed by bog/peatland vegetation and acid grassland. However, almost all of the small (<20 ha) fires in the 2020-2022 period were on heather moorland, which provides an indication that these are more likely to be prescribed burns than uncontrolled wildfires. Five (5) of the nine (9) fires burning predominantly conifer trees occurred in spring and four (4) in the summer, but the late spring (May) and summer fires burnt a total area almost six times greater than the early spring ones (477 ha compared to 81 ha).

Fuel moisture content in heather moorland

Related in part to weather and also to season, habitat, plant and fuel type, and phenology, there is strong evidence that risk of ignition and spread is heightened when vegetation fuel moisture content in *Calluna* canopy and/or bryophyte/litter layer is relatively low or reduced in response to cold weather (Davies et al. 2010), In the UK physiological drought may be caused by cold, clear weather and frozen ground, and winter cuticle damage, which can reduce the fuel moisture content of live biomass and create the potential for ignition and extreme fire behaviour, particularly in the spring.

Tables 3 and 4 present measured field moisture contents (FMC) of different fuel fractions of heather moorland collected at the Glensaugh Farm, Laurencekirk, Aberdeenshire for the Scottish Fire Danger Rating System (SFRS) project (Taylor et al., 2022). As expected, the fine green shoots, being live had the greatest degree of control over moisture content. The FMC of the fine green shoots could reach 160% after rain events, which then reduced rapidly over a period of a few hours, but the values stabilised at ca. 95-100% (Taylor et al., 2022). Rarely values recorded during March and April 2019 were in the low 80%s. This would strongly suggest that the FMC of the green shoots reflects moisture held on the surface of the shoots after a rain event being quickly lost, until a relatively stable equilibrium is reached which is under control of the plant. The lowest FMC values recorded for green shoots was ca. 65% after prolonged very dry conditions in April 2021.

Table 3. Summary of field moisture contents (percentage of dry mass) of different fuel fractions of heather moorland at Glensaugh Farm over 3.5 hours on 27th March 2019. (Data collected from 11.20 – 14.50 GMT).

Fuel fraction	No. of samples	Mean	SE	Min.	Max
Green (<2mm)	20	97.2	1.6	83.4	109.1
Fine dead (<2mm)	20	29.7	1.0	20.8	38.9
Moss and litter	20	345.6	18.8	210.8	503.0

Table 4. Summary of field moisture contents (percentage of dry mass) of different fuel fractions of heather moorland at Glensaugh Farm over 6 days in April 2019. (Data collected on 5th, 8th, 16th, 22nd, 26th, and 29th April).

Fuel fraction	No. of samples	Mean	SE	Min.	Max
Green (<2mm)	105	108.3	1.7	82.7	163.0
Fine dead (<2mm)	105	42.3	3.3	12.1	200.4
Moss and litter	105	201.0	9.7	13.4	418.5

The fine, suspended dead fuel reacted similarly to the green shoots after rain events when FMC could reach 200%, which could then decline quickly over a few hours (Taylor et al., 2022). However, the stabilisation of values for the fine dead occurred much lower than for the green shoots. The mean values on the 8th, 22nd, 29th April were 23.7%, 15.3% and 26.1%, respectively, and were remarkably stable over the six-hour sampling period. The dead shoots have no active mechanism to influence the loss (or gain) of moisture, and the FMC of the shoots will link closely with the prevailing environmental conditions. For example, they can lose moisture rapidly over a matter of hours, but the dynamics of rewetting are largely unknown (Taylor et al., 2022).

The FMC of the litter and moss fraction had greater spatial variation and was less responsive than the fine fuel fractions, with the range of FMC values being very broad from ca. 500% to a minimum value of 13.4% during March and April 2019. The greater spatial variation in FMC will most likely be a reflection of the natural variation in moss cover on the heather moorland and hence this will influence the proportion of moss material in the samples collected for determining the FMC. The FMC of the moss and litter layer showed a slow reduction from 5th to 22nd April 2019, then increased from ca. 40% to 200% between the 2nd and 26th April. The latter increase was the result of a rain event. This huge range of FMC values of the moss and litter layer is a reflection of the ability of mosses to absorb many times their own mass in moisture, and their inability to control the loss of the captured moisture. Although the moss and litter represent living and dead components respectively, the mosses differ markedly from the heather green shoots, as they have evolved to survive cycles of drying and rewetting (Taylor et al., 2022). They lack the internal transport system of heather which transports water to the green shoots from the soil, and they lack any chemical or morphological mechanisms to restrict water loss from surfaces. In this way the moss fraction will share to a certain degree the drying properties of the litter. However, their ability to absorb water means that they will act as a reservoir of moisture which will increase the response time of the layer to drying conditions.

Fire weather indices for fuel types

Historical daily values of the FWI and its sub-indices have been calculated by the Copernicus Emergency Management Service using ERA5 reanalysis climatic data produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). Figure 7 gives an example of calculated fire danger indices (FFMC and FWI) for the day of August 10th, 2022, when parts of eastern Scotland were experiencing meteorological drought and issues of water scarcity. In a recent study, Taylor et al. (2022) extracted CFWIS index values from daily EFFIS multi-band layers (each band giving one of the six (6) CFWIS indices) based on location and fire date for the extent of EFFIS burnt area polygons for the 2013-2019 period for a number of northern European countries (including Scotland), to carry out a broad analysis of the relationships between actual fire occurrence in Scotland and the rest of northern Europe. For consistency between the different countries, they determined fuel type composition using the (relatively coarse) European Fuel Map at 250m gid resolution (EFFIS, 2017).

Here we refine this analysis by using LCM-based fuel types at 20m pixel along with median CFWIS index values calculated by Taylor et al. (2022) for each EFFIS burnt area polygon in Scotland for the 2013-2019 period (*n*=144 fires) to assess the range of CFWIS index values in which fires occurred in Scotland for different fuel types (Figures 8a and 8b). This time period excludes the post-2020 burnt area polygons when the EFFIS detection and mapping methodology changed, meaning that these fires were more likely to be wildfires and not prescribed burns. Most of the fire incidents were on heather (*n*=102) followed by bog (*n*=24), acid grassland (*n*=12) and conifer (*n*=4). Two fires, one with arable and one with improved grassland fuel types, were excluded from this analysis.

Regarding CFWIS fuel moisture codes (Figure 8a), fires on acid grassland, bog, heather, and conifers occurred in similar Fine Fuel Moisture Code (FFMC) values (80-85), although fires in heather moorland also occurred at much lower FFMC. However, Duff Moisture Code (DMC) and Drought

Code (DC) was much greater in the conifer fires than in acid grassland, bog and heather moorland; median DMC and DC was 26 and 202 for conifer forests, respectively, compared to 4-5 and 19-22 for fires on heather moorland and bogs, and 3 and 8 for fires on acid grassland, respectively. The DMC has a big influence on the FWI index value, and these fuels start to get involved in combustion at a DMC value of 20 (Taylor et al., 2022).

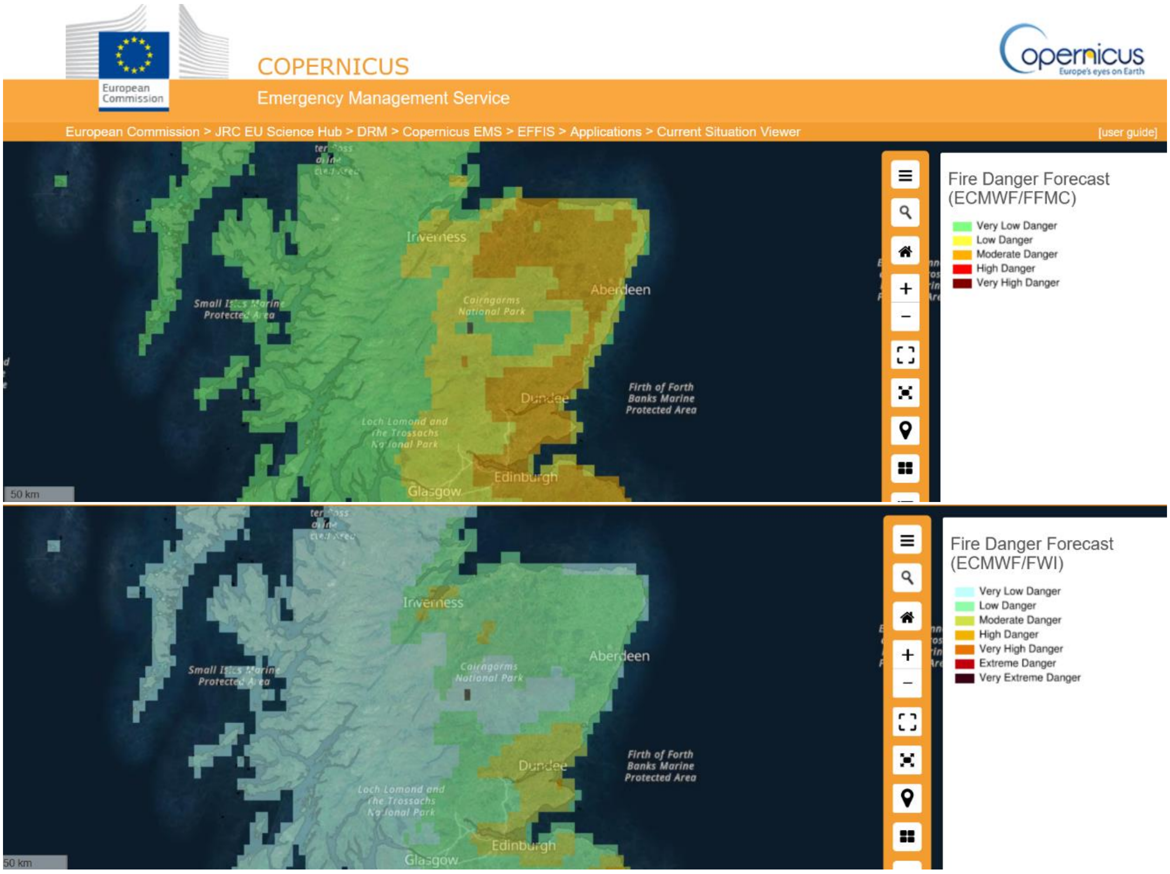

Figure 7. Calculated FFMC and FWI over Scotland for August 10th, 2022, generated by the Copernicus Emergency Management Service for EFFIS[5].

Regarding CFWIS fire behaviour codes (Figure 8b), median Initial Spread Index (ISI) values (combination of FFMC and wind speed) were similar for all fuel types and ranged from 3 in acid grassland and heather to 5 in conifer fires. However, median Built-up Index (BUI) and Fire Weather Index (FWI) values were much greater for conifer fires (37 and 11, respectively) compared to the other fuel types where median BUI ranged from 3 in acid grassland to 5 in heather, and median FWI ranged from just 1.5 in acid grassland to 4.5 in bogs. Based on the Met Office fire danger classes for the UK using FWI (Perry et al., 2022), three of the four forest fires occurred when fire danger was high (ca. >10) but most of the remaining fires (*n*=104) occurred when fire danger was deemed to be low (ca. <5).

[5] https://effis.jrc.ec.europa.eu/apps/effis_current_situation/

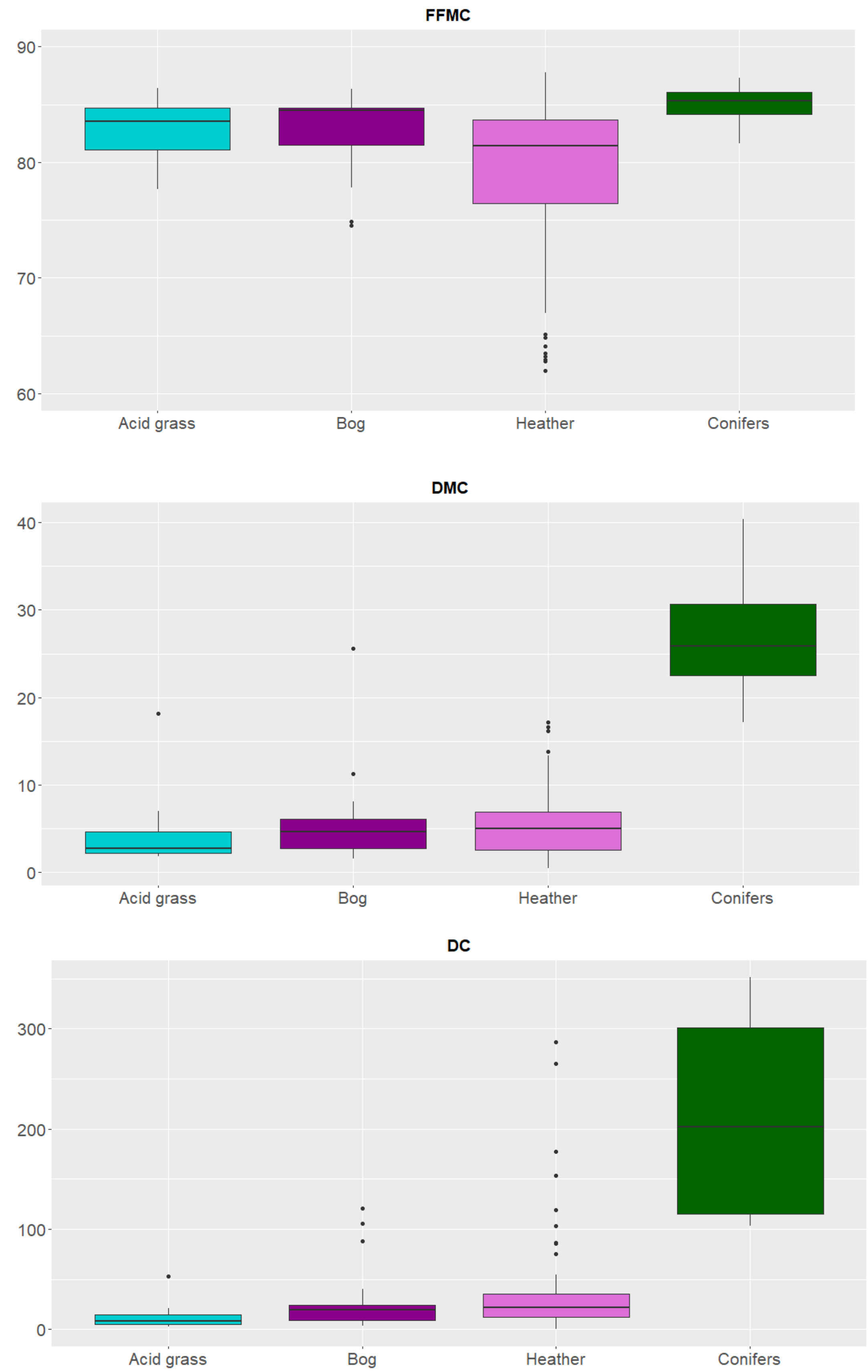

Figure 8a. Boxplots of CFWIS fuel moisture codes per dominant fuel types of fires that occurred in Scotland in the 2013-2019 period.

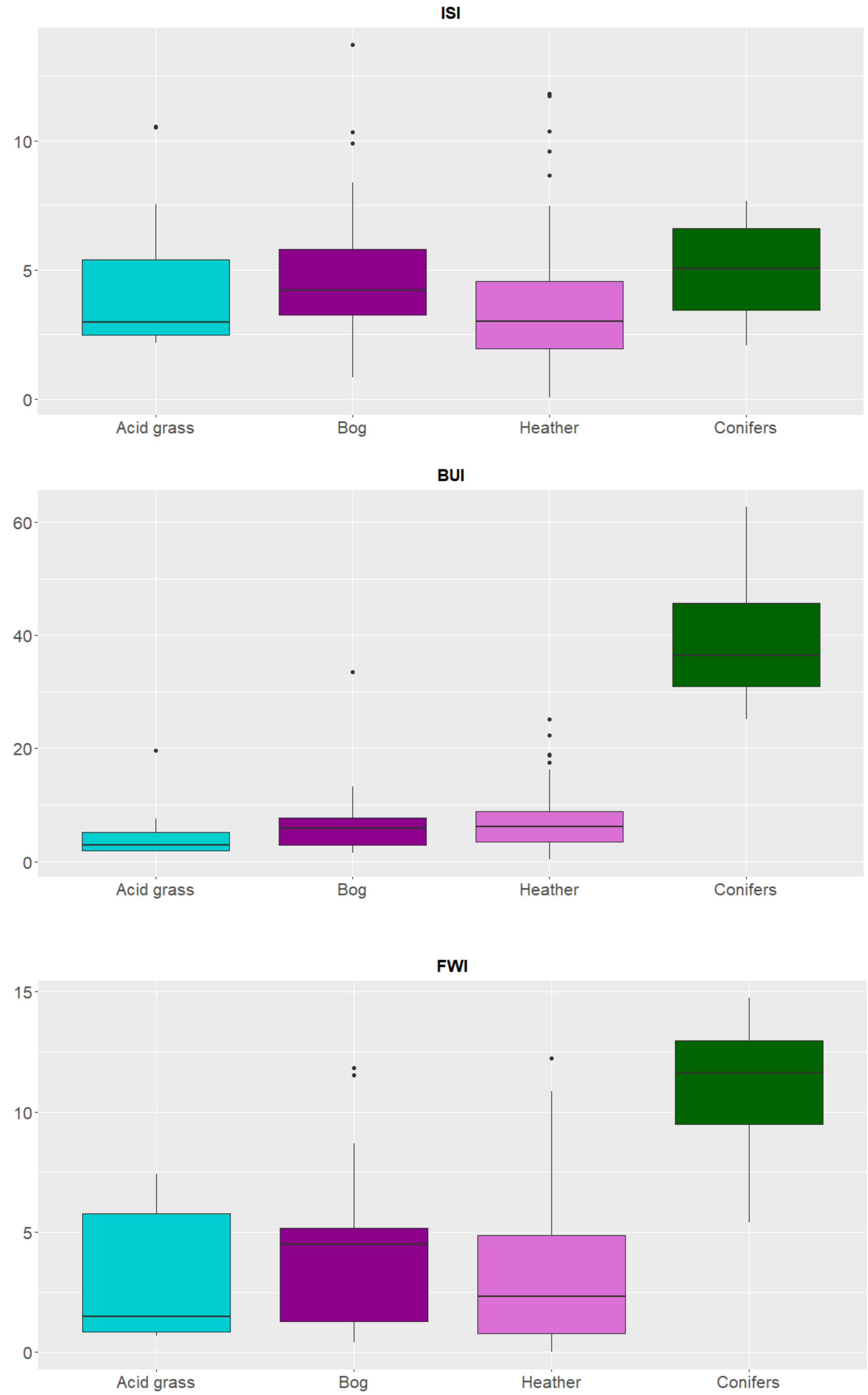

Figure 8b. Boxplots of CFWIS fire behaviour codes per dominant fuel types of fires that occurred in Scotland in the 2013-2019 period.

These results are consistent with previous work that has found that heathland and moorland fire occurrence is not well captured by the FWI value and CFWIS indices in Scotland (Davies and Legg, 2016; Taylor et al., 2022). The main reason for this is that the fuel models within the CWFIS do not match the fuel structure of heather moorland and hence cannot adequately capture the fire spread drivers in these systems, and fire behaviour in Scottish moorlands appears to be very different from the original forest fire scenarios in which the system was developed.

The poor performance of CFWIS for fire occurrence in heather moorlands can be attributed to the fact that live fuel moisture of heather can fluctuate greatly, particularly during spring, which may lead to extreme fire behaviour (Davies et al., 2010), while although peatland fire danger should be adequately reflected by the DC component, which indicates the potential for deep-seated smouldering fire (Van Wagner, 1987), DC has been shown to be the least predictive value for FWI calculations (Davies and Legg, 2016). However, a positive relationship has been found between FFMC, and also FFMC combined with ISI fire occurrence and burned areas in Scotland, UK and Northern Europe for winter-spring fires in heather moorland (Davies and Legg, 2016), which means that FFMC and ISI can be roughly linked to some existing EFFIS fire danger classes to provide a fairly accurate predictions of fire danger and fire occurrence in these habitats (Taylor et al., 2022).

On the other hand, despite the limited number of forest fires, CFWIS has been found to work relatively well for capturing the occurrence of late spring and summer forest fires in Scotland when DMC and DC are higher (Taylor et al, 2022), which is probably due to similarities in the forest floor material of conifer plantations and native pinewoods in Scotland with the main reference fuel type of jack or lodgepole pine forest floor material used by CFWIS.

Projected fire danger

Perry et al. (2022) assessed future climatic projections using an ensemble of regional climate models from the UK Climate Projections 2018 (UKCP18), combining climatic variables to derive fire weather indices for the UK. The results showed a large increase in hazardous fire weather conditions in the summer period. At 2°C global warming relative to 1850-1900, the frequency of days with ‘very high’ fire danger was projected to double compared to a recent historical period. This frequency increased by 5 times at 4°C of global warming. Smaller increases were projected for spring, with a 150% increase for England at 2°C of global warming and a doubling at 4°C. A particularly large projected increase for late summer and early autumn suggests a possible extension of the wildfire season, depending on fuel availability.

The number of days with ‘severe’ fire danger was projected to remain relatively low in northern England and Scotland, but still with marked projected increases for the future periods (Perry et al., 2022). However, many of the most significant historical wildfire events have taken place in these northern regions. It is likely that these areas are more vulnerable to wildfire due to their more rural nature and increased remoteness, which leads to greater fuel availability and increases the risk of fires being able to spread before they can be suppressed. The spatial distribution of different types of vegetation fuels also affects vulnerability to levels of the different fire weather indices (de Jong et al., 2016).

This direction of change is also supported by Rivington and Jabloun (2022), which provide details of an assessment of the spatial and temporal changes in Scotland’s observed climate since 1960 and future climate projections. The summary of their findings is provided in Appendix A. In brief, comparison of observed 1960-1989 baseline climate with UKCP18 climate projections (12 model individual simulations based on the high emissions scenario RCP8.5) for the 2020 - 2049 and 2050 - 2079 periods showed that Scotland's climate is expected to be wetter for the period 2020 to 2049, mainly in December, January and February, while August, September and October are expected to become drier, with eastern areas becoming wetter in late winter and spring and upland areas becoming drier in late spring, and mid-summer to autumn. These patterns continue in the 2050 - 2079 period with increases in the magnitude of change. There is also high agreement between all 12 projections on there being continued warming, with all exceeding 2°C by the 2070s, especially between May and November, with this warming being fairly spatially uniform over the whole of Scotland.

Rivington and Jabloun (2022) also looked at Climatic Water Balance (precipitation minus evapotranspiration) that indicates potential differences in water availability and found that future projections in warming indicate an increased rate of evapotranspiration over Scotland. A key finding was that some upland areas are projected to shift from water surplus to deficit, such as in May for the central Highlands and in August in the eastern and southern upland areas plus southern Argyll, Islay and Jura and parts of the Outer Hebrides (Figure A1, Appendix). Overall, the projected climatic changes tend to indicate a decrease of soil moisture and fuel moisture (both live and dead) in late spring to summer period in those areas where most of the larger wildfires tend to occur in Scotland, which could substantially increase the probability of ignition and risk of fire propagation and spread in a large area of Scotland.

Discussion & Conclusions

This study presented an integrated framework for fire danger assessment that is mainly composed by the likelihood/possibility of having a fire ignition, which depends on the presence of an ignition source, and the behaviour (propagation and intensity) of a fire once it is ignited, which depends on the interaction between weather conditions, fuel type characteristics and landscape controls that regulates the moisture of live and dead fuel material.

In Scotland, fire activity is mostly limited by fuel moisture conditioning and fuel availability, i.e., amount of dry vegetation susceptible to burn, hence it does not have to be warm for fires to occur, in fact the larger, upland wildfires often occur in dead and dry winter fuels. Most wildfires occur in grasslands and broadleaved woodlands (Gagkas et al., 2022), although, in terms of the size of area, heathlands, moorlands and grasslands present the largest burnt areas.

There are usually two fire seasons, the main one in spring and a secondary one in mid-late summer (Belcher et al., 2021). Regarding the most common spring fires on heather moorland and peatlands, projected increases in monthly precipitation for late winter and spring (Rivington and Jabloun, 2022) could result in lower fire danger in these habitats, but on the other hand reduced precipitation coupled with higher mean temperature and higher evapotranspiration could reduce fuel moisture and hence increase fire danger. Wind is also an important factor controlling fuel moisture dynamics in exposed upland habitats, but projections of wind speed changes are quite uncertain.

Drought frequency and the number of dry days is also projected to increase in the summer period (Rivington and Jabloun, 2022), which could lead to low fuel moisture and potentially to increased fire severity as moisture is a key control on severity. This climatic change could also extend the summer fire season and intensify fire danger. Findings from this study indicate that large, conifer forest fires can occur in Scotland when, climatic, fire danger is high. So far these have been rare, but a combination of more favourable conditions for fire ignition with increased fuel availability from woodland expansion could result in forest fires being an important threat in the near future. The significance of this threat would obviously depend on the spatial variability and patterns of climatic change; hence it is advisable that future fire danger is considered when planning new planting of trees.

Moreover, a great proportion of fires affect vegetated areas in close proximity to built-up areas, (Belcher et al., 2021), with most of these fires affecting broadleaves and grasslands and caused by a mixture of deliberate ignitions such as burns getting out of control or careless handling of equipment along with ignitions from anti-social behaviour/arson. Expansion of peri-urban woodlands and other green spaces coupled with a prolonged and more intense summer fire period could cause the emergence of fires typical of the wildland-urban interface (WUI), which could pose an important risk to Natural Capital assets and to human health and life as well.

Next Steps

- Develop an integrative spatial model that can generate simulations of fire danger assessments using projected climatic variables under different climatic scenarios.
- Liaise with the Horizon 2020 FirEUrisk[6] project for informing fire danger model structure and model inputs regarding updated European fuel classification systems, and for integrating approaches and methodologies of social, ecological, and economic vulnerabilities such those in D1.4 presented in: "Report on methodological framework for vulnerability assessment[7]".
- Liaise with the H2020 Firelogue[8] project that brings together European expertise on wildfire risk management in a common platform to enable knowledge exchange and best practices.
- Liaise with JHI-D4-4-B: Habitat management and restoration regarding the use of findings or maps related to prescribed burning in heather moorlands.
- Integrate fire danger model outputs in the ROAF to conduct spatial assessments of fire danger and risk impacts on Natural Capital assets, for current and planned land use change scenarios.

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[6] https://fireurisk.eu/
[7] The report will be made public at the end of March 2023.
[8] https://firelogue.eu/index.php

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Appendix A. Summary of the climate trends and future projections in Scotland.

Observed changes:

The observed trends in precipitation, maximum and minimum temperature are derived by comparing data from 1990 – 2019 with a 1960 – 1989 baseline period, which can be summarised as:

Precipitation:

- There has been an overall increase in precipitation, with the area of Scotland experiencing higher precipitation being larger than that of decreases.
- There is a wide variation in spatial and temporal change.
  - In the west precipitation increased in December to May, but either remained similar or decreased in July, August and October.
  - Eastern Scotland became drier in January, March, May, August, September and December, but wetter in February, June, July, October and November.
- The largest increases in precipitation occurred in February.
- There has been mixed response in terms of variability in temporal and spatial patterns of change in precipitation.
  - January, April, July and November (and to a lesser extent August) have seen a decrease in variability in the west.

Temperature:

- For all months there has been an overall increase in temperature, except for the maximum in June and to a lesser extent October and December for the minimum.
- February and March show the largest amount of warming, up to 2°C, whilst other months show an approximate average increase of 1°C.
- The rise in temperature is relatively uniform across the country, and does not reflect the topographical influence, though for some locations there has been little or no change from the 1960 – 1989 baseline period.
- There has been a mixed response on terms of variability of how much change there has been and where this has occurred.
  - January, February and August have seen an almost nationwide shift towards reduced standard deviation, whilst March, April (except the Lochaber and northern Argyll areas), September, October and November have seen a widespread increase.
- All months, with the exception of June and to a lesser extent April and August, show an general national trend of a positive increase (warming) in diurnal temperature range.

Projected future changes

Data from the UKCP18 climate projections (12 individual model simulations) for two time periods, 2020 – 2049 and 2050 – 2079, were compared with the observed 1960 – 1989 baseline to identify potential future changes. The 12 projections are based on the high emissions scenario (RCP8.5) but consist of a range of possible climate change from 1°C increase in temperature and an increase in precipitation total, to 3.7°C and a reduction in precipitation.

Precipitation:

- Projections for the period 2020 to 2049 indicate Scotland's climate to be wetter in December, January (both c.10%), February (45 – 55%) and April (25%) but less so in March (c. 5%).
    - These projected changes align with the observed changes already seen.
- For the 2020 to 2049 period, August, September and October are projected to become drier.
- These patterns continue in the 2050 – 2079 period with increases in the magnitude of change.
- There is a high level of agreement between projections that February and April precipitation will increase, whilst August, September and October will decrease.
- There is large spatial variation in changes to the monthly mean precipitation between projections: eastern areas may become wetter in some months (February, April, May, November and December); upland areas are likely to decrease in May, August, September and October, and November in the north.

Temperature:

- The observed warming trends in maximum and minimum temperature are projected to continue through the 2020 – 2049 and 2050 – 2079 periods.
    - There is high agreement between all 12 projections on there being continued warming, with all exceeding 2°C by the 2070s.
- There is a greater amount of warming between May and November (up to 4°C per month between 2020 – 2049), but also with substantial warming in the winter (variable by projection, approximately 2-3°C).
- The spatial distribution of change is relatively uniform across Scotland, e.g. does not reflect topographical differences.

Water availability indicated using the Climatic Water Balance:

Changes in the Climatic Water Balance (precipitation – evapotranspiration) indicate potential differences in water availability. Observed trends and future projections in warming indicate an increased rate of evapotranspiration.

Observed trends:

- There has been an observed change in Climatic Water Balance, which is variable both spatially and temporally.
    - West coast areas have becoming wetter (increased surplus water) between December to April.
    - March to May have experienced a decrease (reduced water) in the east as has the whole of Scotland in September.
    - June to August have experienced an increase in Climatic Water Balance (precipitation > evapotranspiration).

Projected changes:

- Projections show that there may be a shift in where and when parts of Scotland have a surplus or deficit of water.
- **A** key finding is that some upland areas of central Scotland are projected to shift from water surplus to deficit.
    - Most notably this is seen in May for the central Highlands and in August in the eastern and southern upland areas plus southern Argyll, Islay and Jura and parts of the Outer Hebrides.
    - By 2050 – 2079 for August there is a large increase in this upland area shifting from surplus water to a deficit.
        - Large parts of eastern Scotland in September are projected to see a shift to Climatic Water Balance deficit.
    - Such changes may have substantial impacts on the ecological and hydrological functions of peatlands, as well as other Natural Capital asset types.
- For both the 2020 – 2049 and 2050 – 2079 periods there is good agreement between the 12 projections that October through to March will remain in Climatic Water Balance surplus (precipitation is greater than evapotranspiration.
    - For both periods April shows large uncertainty in the direction of change.

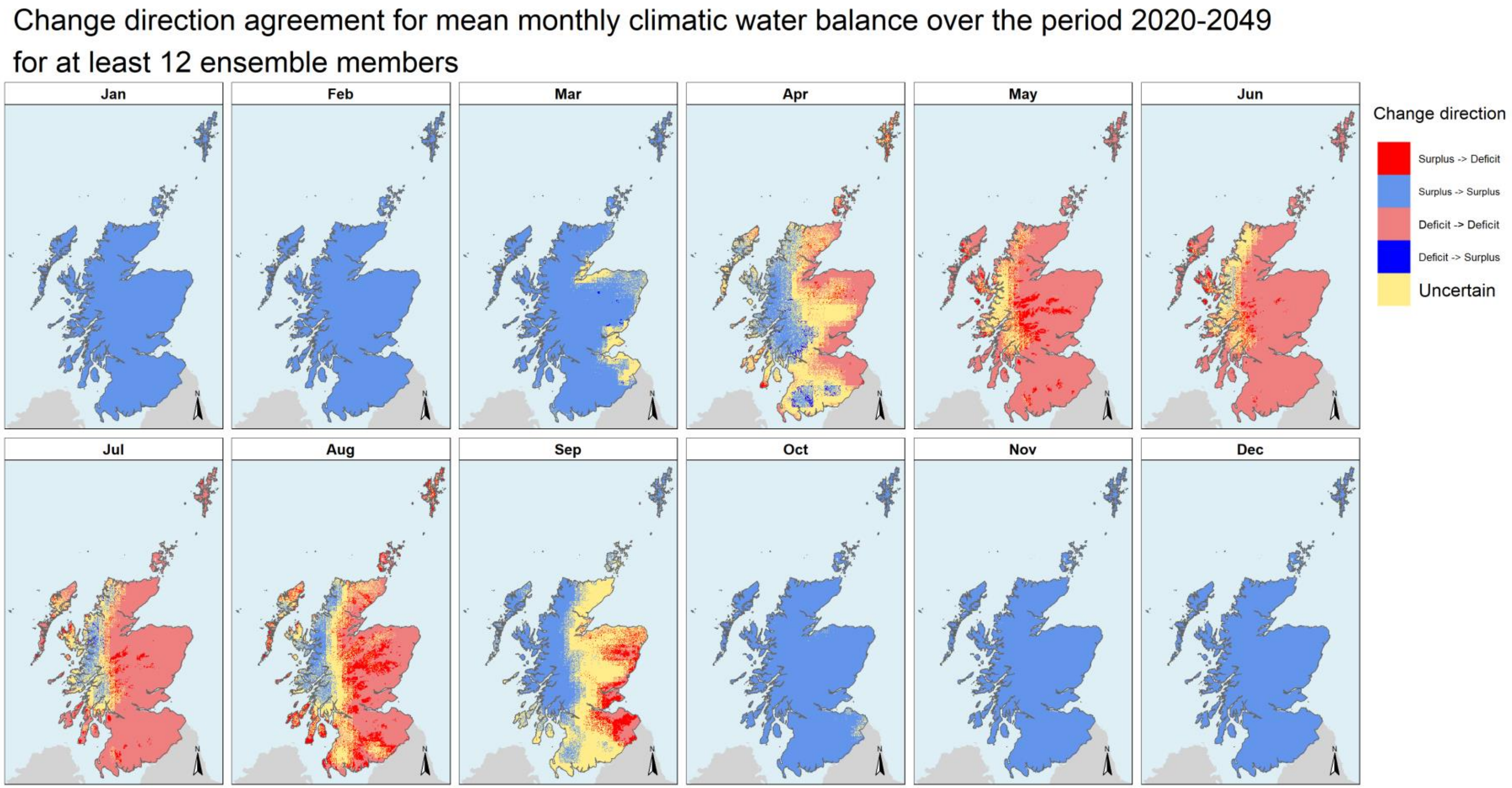

Figure A1. Agreement maps for the change direction (increase: blue, or decrease: red) of the Climatic Water Balance for the period 2020 – 2049 for all 12 climate projections (ensemble members). Yellow areas indicate no agreement between projections (Rivington and Jabloun, 2022)

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