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Calibration and evaluation of the Canadian Forest Fire Weather Index (FWI) System for improved wildland fire danger rating in the UK

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Abstract

Wildfires in the United Kingdom (UK) can pose a threat to people, infrastructure and the natural environment (e.g. to the carbon in peat soils), and their simultaneous occurrence within and across UK regions can periodically place considerable stress upon the resources of Fire and Rescue Services. "Fire danger" rating systems (FDRS) attempt to anticipate periods of heightened fire risk, primarily for early-warning purposes. The UK FDRS, termed the Met Office Fire Severity Index (MOFSI) is based on the Fire Weather Index (FWI) component of the Canadian Forest FWI System. MOFSI currently provides operational mapping of landscape fire danger across England and Wales using a simple thresholding of the final FWI component of the Canadian System. Here we explore a climatology of the full set of FWI System components across the entire UK (i.e. extending to Scotland and Northern Ireland), calculated from daily 2 km gridded numerical weather prediction data, supplemented by meteorological station observations. We used this to develop a percentile-based calibration of the FWI System optimised for UK conditions. We find the calibration to be well justified, since for example the values of the "raw" uncalibrated FWI components corresponding to a very "extreme" (99th percentile) fire danger situation can vary by up to an order of magnitude across UK regions. Therefore, simple thresholding of the uncalibrated component values (as is currently applied) may be prone to large errors of omission and commission with respect to identifying periods of significantly elevated fire danger compared to "routine" variability. We evaluate our calibrated approach to UK fire danger rating against records of wildfire occurrence, and find that the Fine Fuel Moisture Code (FFMC), Initial Spread Index (ISI) and final FWI component of the FWI system generally have the greatest predictive skill for landscape fires in Great Britain, with performance varying seasonally and by land cover type. At the height of the most recent severe wildfire period in the UK (2 May 2011), 50 % of all wildfires occurred in areas where the FWI component exceeded the 99th percentile, and for each of the ten most serious wildfire events that occurred in the 2010–2012 period, at least one FWI component per event was found to surpass the 95th percentile. Overall, we demonstrate the significant advantages of using a calibrated, percentile-based approach for classifying UK fire danger, and believe our findings provide useful insights for any future redevelopment of the current operational UK FDRS.

1 Introduction

Wildfires in the UK may not be as frequent or intense as those found in other regions of the world e.g. North America or Australia, but uncontrolled landscape-scale fires do occur throughout much of the country, particularly in the spring but also during the summer months (Davies and Legg, 2008; Albertson et al., 2009). Anthropogenic (and to a lesser extent, naturally occurring) fires have played a critical role in shaping UK ecosystems – notably in upland heath areas, but also in peatlands and grasslands (Davies et al., 2008). While individual UK wildfires rarely present a very serious risk to human life, they can pose a significant risk to livelihoods, infrastructure and important components of the UK natural environment, particularly in upland moorland areas where carbon stores in peat soils can be put at risk (Davies and Legg, 2008; Davies et al., 2008). In 2010–2012, the Department for Communities and Local Government (2013) reported that a total of 2899 wildfires were recorded by Fire and Rescue Services (FRS) across Great Britain (the UK without Northern Ireland). These fires are almost exclusively anthropogenic, typically resulting from accidental ignitions, and occasionally from arson or escaped “prescribed” burns conducted for the purposes of land management, for example the maintenance and improvement of moorland grouse habitat (Davies et al., 2006; Albertson et al., 2009). The impact of UK wildfires can be greatly exacerbated when periods of low fuel moisture (such as may occur in early spring, or during droughts) coincide with wind speeds conducive to fire spread. During these periods, a large number of sustained ignitions may result in many landscape scale fires burning near simultaneously across the UK, as happened most recently for example in 2003, 2006 and 2011. Such episodes can place extreme stress on resources within the UK FRS, both in terms of personnel and also fire fighting response assets (Davies and Legg, 2008). Accordingly, use of a fire danger rating system (FDRS) to help forecast when and where these wildfire episodes are more likely is of growing interest to those who manage or have to respond to landscape-scale fire events. An FDRS system of sufficient reliability, available in a timely operational manner to UK FRS, could enhance short term wildfire response planning and resource allocation (Eastaugh et al., 2012).

The Met Office currently operates an FDRS for England and Wales – the Met Office Fire Severity Index (MOFSI; Met Office, 2015) – that is based upon the well-established Canadian Forest Fire Weather Index (FWI) System (Van Wagner, 1987). In the MOFSI system, numerical weather prediction (NWP) data produced by the Met Office's operational forecast model is used to produce fire danger forecasts up to 5 days ahead (Met Office, 2015). The MOFSI system is capable of highlighting periods of "exceptional fire danger" across regions of England and Wales (Met Office, 2005), but to date relatively little calibration of the underlying FWI System model and its sub-components has been conducted, so the overall outputs are only relatively crudely tuned to UK environments via a series of broad thresholding operations. As such, we suspect that there remains significant potential for improving the tailored use of the Canadian FWI System in the UK, as has been conducted in a number of other fire-affected environments around the world (e.g. de Groot et al., 2007; Taylor and Alexander, 2006).

An FDRS system built upon UK-specific empirical relationships between meteorological conditions, individual fuel type conditions and fire behaviour would probably permit the most accurate assessment of UK fire danger, as has been developed extensively in Canada (Van Wagner, 1987). Initial attempts to develop such relationships in UK fuels have been made by Legg et al. (2007) and Davies et al. (2006, 2009), however further experimental burning is required to ensure that relationships are suitably robust for inclusion in an operational UK FDRS. Here we explore the simpler and potentially more easily attainable goal of "calibrating" the Canadian FWI system for use in UK conditions, with the aim of enhancing the ability and accuracy of UK fire danger mapping based on Met Office NWP forecasts. We focus on an approach using locally and seasonally calculated percentiles of the individual components of the FWI System to highlight periods of extreme fire danger conditions, a method routinely used in the USA (Andrews et al., 2003) and applied by Dowdy et al. (2009, 2010) in Australia, and Camia and Amatulli (2010) at a European level. The approach has the advantage of accounting for both the historic variability and range of the FWI System components at each location in the targeted area, and thus allows assessment of any current forecast of a particular "fire danger index" with respect to past values representative for that location and time of year. We evaluate our approach using historic fire records from the UK Fire and Rescue Service Incident Recording System (IRS) database, available across Great Britain (Department for Communities and Local Government, 2012, 2013).

2 Background

2.1 Fire Danger Rating Systems

The term "fire danger" generally "refers to an assessment of both fixed and variable factors of the fire environment (i.e. fuels, weather and topography) that determine the ease of ignition, rate of spread, difficulty of control, and impact of wildland fires" (Merrill and Alexander, 1987 in Taylor and Alexander, 2006, p. 122). An FDRS is generally designed to systematically evaluate and integrate these factors into qualitative and/or numerical indices of fire potential, primarily in order to guide fire management activities (Stocks et al., 1989; Lee et al., 2002). The most comprehensive FDRS, such as the Canadian Forest Fire Danger Rating System (CCFDRS; Stocks et al., 1989), incorporate multiple factors and datasets into their calculations, though many less sophisticated FDRS are based almost entirely upon meteorological data which are easy to acquire and which generally allow for a reasonable estimation of the

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moisture content of dead fuels – typically the most flammable component of the fire environment (Chuvieco et al., 2009). The MOFSI employed across England and Wales is an example of a meteorologically-based FDRS, since it is based entirely upon the meteorological module of the CCFDRS, the Canadian Forest Fire Weather Index (FWI) System (Van Wagner, 1987).

2.2 The Canadian Forest Fire Weather Index System

The FWI System of Van Wagner (1987) is one of the most widely used FDRS worldwide (Taylor and Alexander, 2006; Lawson and Armitage, 2008). The FWI System was originally developed for use in jack/lodgepole pine forest environments – a dominant Canadian forest type particularly prone to fire – using calculations based solely upon meteorological inputs (air temperature, wind speed, relative humidity and 24 h cumulative rainfall, assessed at noon local time) (Van Wagner, 1987). The FWI System consists of six components. The first three are "moisture codes" – the Fine Fuel Moisture Code (FFMC), the Duff Moisture Code (DMC) and the Drought Code (DC), each relating to the moisture content of the three major ground fuels commonly found in a mature pine forest environment; the fine surface litter, loosely compacted organic material ("Duff"), and deeper organic layers/large surface fuels, respectively (Van Wagner, 1987). These moisture codes, developed to relate to the water content of dead vegetation and the "duff" and organic soils that are derived from it, are then used within the FWI System to determine three further "fire behaviour index" components, each providing information related to the potential behaviour of a fire should an ignition occur. The Initial Spread Index (ISI) represents the potential rate of fire spread, the Buildup Index (BUI) indicates the total amount of available combustible fuel, and the final "FWI" component combines the ISI and BUI to provide a measure of the potential frontal intensity of a fire. While originally developed for use in Canadian pine forests, the relative simplicity of the FWI approach has resulted in its extensive use in other environments, both within Canada and elsewhere, often by establishing new relationships between one or more of the six FWI System components and the actual fire behaviour seen in local fuels (e.g. Fogarty et al., 1998; de Groot et al., 2005, 2007; Taylor and Alexander, 2006; Bedia et al., 2012, 2014; Karali et al., 2014; Venäläinen et al., 2014). In tests, the FWI System has generally been found to perform very well compared to other FDRS when utilised in other environments (e.g. Dowdy et al., 2010; Viegas et al., 1999).

2.3 FDRS in the UK: the Met Office Fire Severity Index

The UK MOFSI system (Met Office, 2015) makes use of the final FWI component of the FWI System, which is calculated using UK numerical weather prediction (NWP) forecasts and classified into one of five fire danger categories (representing “low” to “exceptional” fire danger). The MOFSI was originally designed as a decision support tool for land management organisations (e.g. Natural England, Natural Resources Wales) who, under the UK Government’s Countryside and Rights of Way (CRoW) (2000) Act, are responsible for restricting access to public land in England and Wales when fire danger reaches “exceptional” levels. The Met Office considered several alternative FDRS as the basis for the MOFSI, with the FWI System selected as it was considered to highlight periods of high fire danger under a range of different weather conditions, could identify periods of both short-term increased fire risk and periods when fire-risk increased gradually over time, and appeared to respond well to changing fire risk levels in different UK vegetation types (Kitchen et al., 2006; Met Office, 2005). In addition to its use under the CRoW (2000) Act in England and Wales, UK-wide fire danger forecasts are also integrated into the Natural Hazards Partnership hazard assessment reports, issued daily to the UK government and nationwide emergency services to support planning and decision making processes (http://www.metoffice.gov.uk/nhp/daily-hazard-assessment).

2.4 Limitations of the MOFSI for forecasting fire danger in the UK

Since its instigation in 2002, the MOFSI has proven suitable for its primary purpose of triggering the closure of public land under the CRoW (2000) Act during periods of “exceptional” fire danger. However, it is considered that there exists significant scope for improving the details of this system, and for developing its use as a wider decision support tool for land managers, government agencies and emergency services (Legg et al., 2007; Davies and Legg, 2008). We suggest that the current system has several key limitations:

1. The current MOFSI “exceptional” category used to trigger land closures under the CRoW (2000) Act was defined relatively subjectively based upon FWI conditions observed in the years 1976, 1995 and 2003 when UK wildfires were particularly widespread (Met Office, 2005). The lower categories were then defined based upon a geometric progression from this threshold. None of these thresholds have any immediately understandable meaning in relation to fire danger – e.g. they are not calibrated to any specific changes in potential ecological damage or suppression difficulty. As suggested by Fogarty (1998), there is much potential for improved fire danger rating if the FWI system (and associated fire danger categories) was adopted to make use of relationships between the individual FWI components and corresponding fuel moisture/fire behaviour in UK fuels. Such relationships are well understood for boreal forests (Alexander and de Groot, 1988; Taylor and Alexander, 2006), and have been derived for tropical grasslands (de Groot et al., 2005, 2007) and Mediterranean fuels (Viegas et al., 1999, 2001). However, these relationships have proved challenging to establish in common UK fuels such as heather and gorse (Davies et al., 2006, 2009; Anderson and Anderson, 2009), and additional experimental burning campaigns likely necessary for further such developments here are difficult to conduct.
2. The FWI threshold values used to define the fire danger categories of the MOFSI are held constant across the UK, which fails to take into account the significant

climatic variations seen across the country, both in terms of latitude and in terms of elevation. Whilst the relative importance of live and dead fuel moisture content (FMC) is not yet fully understood in UK fire prone environments e.g. heather (*Calluna vulgaris*) moorlands (Davies et al., 2009), it is clear that the FMC of both live and dead fuels is strongly influenced by meteorology (Chuvieco et al., 2009), and low FMC of either type of fuel is likely to play an important role in a location's flammability. The physical processes governing the wetting and drying of dead fuels is unlikely to vary with location in the country (Taylor and Alexander, 2006), and as a result raw FWI component values should relate well to the FMC of dead fuels of a particular class (e.g. the fine surface fuels) wherever they are located. However, the relationships between meteorological-based fire danger indices and the FMC of live plants is much more variable, due for example to species-specific water balance mechanisms (Chuvieco et al., 2009). In fact, in past work in the UK, only weak relationships have been found between raw values of the FWI system components and live (and indeed even dead) FMC (Legg et al., 2007; Legg and Davies, 2009). However, Dowdy et al. (2010) did find that extreme (e.g. 98th percentile) values of the FWI system components correspond consistently to periods of extensive fire activity in Australia, and a similar percentile based approach is used in the USA to highlight elevated fire danger and to determine FRS staffing levels (Andrews et al., 2003). Hence a percentile-based approach is due for evaluation in the UK, in order to ascertain whether it can provide an improvement in FDRS skill level beyond the use of a single threshold across the entire UK.

3. The existing fire danger rating in MOFSI is only derived using the final FWI component of the FWI System, even though from a fire management perspective the FWI is often considered to be less useful than some of the other FWI System components (Van Wagner, 1987). While some research in Mediterranean Europe suggests that the Drought Code (DC) component may give an indication of live fuel moisture content (Viegas et al., 2001), Van Wagner (1988) proposes that

fire danger in non-forest environments may be better reflected by the Fine Fuel Moisture Code (FFMC) and Initial Spread Index (ISI) components of the FWI System alone. The FWI is derived from a combination of all the other components, including the DC and Duff Moisture Code (DMC) that appear rather specific to the type of densely forested environments under which deep organic soils can form. Accordingly, across the UK these components are likely to be of varying relevance – while potentially of minimal use in e.g. grassland environments, they may highlight the extremely dry periods in which peatland areas begin to dry out (Krivtsov et al., 2008), and thus indicate when ecologically damaging peat fires may occur.

To tackle limitations (1) to (3) we developed and evaluated a new, percentile-based FDRS for potential use in the UK. The new approach is still based upon the FWI System, but now makes use of individual forecasts of each of the FWI System components which are interpreted in the context of their historical range at a local level (2 km grid cells) as percentiles. The approach here does not attempt to take explicit account of the complex relationships between specific fuel type, live fuel moisture, and fire behaviour, and therefore is intended for highlighting extreme fire danger purely from a meteorological perspective rather than giving e.g. an indication of potential ecological damage or levels of suppression difficulty. Developing these elements in future would augment the system further, however, we do believe that this percentile-based approach improves upon the existing system by removing the subjectivity of threshold selection found in the MOFSI and making thresholds clearly understandable, whilst also accounting for the regional climate variations seen across the country.

3 Datasets

The new UK FDRS developed herein is based upon, and tested with, two principal datasets. (1) a spatially and temporally detailed long-term UK record of the FWI components – a so-called “FWI climatology” (Sect. 3.1) – which we used to define the extremes (and thus percentiles) of each component for each 2 km × 2 km grid cell and season across the country. This dataset formed the foundation of the percentile-based FDRS. (2) A record of fire incidence across Great Britain extracted from the UK FRS Incident Recording System (IRS) database (Sect. 3.2) and enhanced by land cover data (Sect. 3.3) was then used to examine percentiles of the FWI components during past wildfire periods.

3.1 FWI climatology data

In order to base identification of the percentile values of the FWI System components on sound statistics, ideally a dataset capturing the long term intra-seasonal variability of each FWI component is required, particularly because UK weather conditions that appear to lead to exceptional wildfire danger, and thus "extreme" values of the FWI components, seem to be relatively infrequent. The revised UK FDRS system developed herein is to be based upon daily 2 km × 2 km resolution Met Office NWP forecasts, and so this long-term "FWI climatology" should ideally also be derived from a historical archive of these same data. Unfortunately, iterative changes and enhancements to the Met Office NWP system meant that a consistent archive at 2 km × 2 km spatial resolution across the entire UK is only obtainable since 2010, and thus we were limited to a four year (2010–2013) record (hereafter termed the "NWP-derived" FWI dataset). To develop a longer term climatology, we accessed a much more temporally extensive (several decades) of station-based meteorological observations taken at 38 sites across the UK, and used these to derive the same set of FWI System components (hereafter termed the "met station-derived FWI" dataset).

Since the ultimate aim of the UK FDRS is to derive useful fire danger forecasts from NWP forecasts, the met station-derived FWI dataset was primarily employed in assessing whether the limited four year length of the NWP-derived FWI dataset was of sufficient statistical robustness to use in deriving meaningful percentiles for each of the FWI System components. Further detail on the NWP- and met station-derived FWI datasets is provided in the following subsections.

3.1.1 NWP-derived FWI data

For the period 1 January 2010–16 December 2013, we calculated a daily "NWP-derived" FWI dataset from the 24 h (midday to midday) Met Office NWP model accumulated rainfall and matching daily noon air temperature, wind speed and relative humidity data for each 2 km × 2 km grid cell. Due to problems with the NWP archive, no data were available for the periods 1 January 2013–20 June 2013 and 5 August 2013–30 September 2013, inclusive, and the resulting dataset consisted of 1217 individual daily forecasts of each of the six FWI System components.

3.1.2 Met station-derived FWI data

The "met station-derived" FWI dataset was calculated from noon air temperature, relative humidity and wind speed values and 24 h cumulative rainfall totals extracted from hourly observation records for 38 UK meteorological stations. The stations used were operational during the 2010–2013 NWP data period, and all have much longer term data availability; the longest running station dataset covers a 44.0-year period from 1 January 1970 until 31 December 2013, with the median and shortest running station datasets extending back from December 2013 for 21.9 and 13.3 years, respectively. Sites are well distributed around the UK, ensuring capture of regional climate variations.

3.2 Historic fire data: the Great Britain Fire and Rescue Service Incident Recording System dataset

Since March 2009, detailed information on all fires reported to Great Britain's FRS has been stored within a national Incident Recording System (IRS) (Department for Communities and Local Government (DCLG), 2012, 2013). In excess of 210 000 outdoor "vegetation fire" records were logged within this database between March 2009 and May 2013, and all were made available for use in this study by Forestry

Commission England/DCLG. No similar dataset relating to vegetation fire occurrence in Northern Ireland was available, so Great Britain (England, Scotland and Wales) was the focus of the evaluation component of our work. The IRS provides information on a wide range of factors relating to each vegetation fire incident, and of particular relevance here were:

- Fire location (Coded as a six-figure British National Grid Reference).
- Time between reporting and extinction of the fire.
- Fire footprint size estimate (hectares).
- Number of fire fighting utilities in attendance.

For the purpose of this study, only the major “wildfires” were of primary interest. Consequently, IRS vegetation fire incidents were considered wildfires only when they met one or more of the following criteria used to define a true “wildfire” event (Scottish Government, 2013):

- Footprint of affected area $>$ 1 ha
- A minimum of 6 h to extinguish
- Attendance by $>$ 3 fire fighting appliances

A total of 2897 vegetation fire events occurring during the 2010–2013 NWP-derived FWI dataset period met one or more of these “wildfire” criteria, and were retained for further analysis. Data from 2013 were omitted due to the lack of NWP-derived FWI data for the first half of this year.

3.3 Landcover data

Whilst the IRS database offers very useful information on fire occurrence, it is important to note that it was designed as an operational tool, and trade-offs may have been made in terms of data quality for the sake of recording speed. As such, caution is required when using these data in scientific studies. Analysis of fire record data pre-instigation of the IRS system (MacKinnon, 2008; McMorrow et al., 2011) found that Fire and Rescue Services frequently recorded the parked locations of the FRS appliances as the incident location (potentially up to 3 km apart). The IRS system is believed to have improved location accuracy (McMorrow et al., 2011), however there is likely to be uncertainty associated with the correct identification of landcover type in the database. Therefore, instead of using the land cover classifications recorded in the IRS dataset, we determined the land cover type for each fire incident using a combination of three spatial land cover datasets. The UK Land Cover Map 2007 (LCM2007; Morton et al., 2011) was used to classify most (83 %) incidents, however for the 12 % of incidents occurring in areas mapped in the more spatially detailed Forestry Commission England National Forest Inventory (NFI; Forestry Commission England, 2012) this was used instead. For some incidents where the two datasets overlapped spatially, there was disagreement between the NFI and LCM2007 classification (e.g. an area classified as woodland by the NFI but as arable by the LCM2007). In these cases (5 %), the highly detailed Ordnance Survey MasterMap® Topography Layer dataset (Ordnance Survey, 2014), digitised from aerial photography, was used to determine the classification. The resulting land cover classifications were then aggregated into one of seven broad categories; broadleaved woodland, coniferous woodland, arable, grassland, heath/bog/marsh, urban and other.

4 Methodology

4.1 Development and initial testing of a percentile-based FDRS

For each 2 km × 2 km grid square in the NWP-derived FWI dataset, we determined the seasonal values of the 10th to 90th percentile of each FWI component (in 10 % percentile intervals), creating nine percentile “reference” datasets. Five additional reference datasets were also calculated for the 1st, 5th, 95th, 97th and 99th percentiles, to capture the extremes of each FWI component's range at each grid cell location in greater detail. These reference datasets form the foundation of the percentile-based FDRS; any NWP-derived forecast of a FWI component for a particular grid cell and season could now be converted to a percentile value by linearly interpolating between the reference dataset values. As an indicator of fire danger frequency, FWI component conditions would be expected to have exceeded the 99th percentile for only 3–4 days in any given season during the 3–4 year period of the NWP data. Since weather conditions corresponding to episodes of elevated fire danger typically persist for several days at a time (Met Office, 2005), the 99th percentile is broadly comparable to a "one in several year extreme" that the original MOFSI "exceptional" fire danger category was intended to represent (Met Office, 2005; Davies and Legg, 2008), though now with the equivalent FWI values being tailored to each UK grid cell rather than having a single value for the entire country.

4.2 Evaluating the suitability of the NWP-derived FWI dataset as the basis for an FDRS

To assess whether the newly constructed NWP-derived FWI dataset (and thus the percentile reference datasets derived from it) are a suitable basis for a new FDRS, we needed to address whether these ~ 4 years of FWI System data are representative of the longer term met station-derived FWI climatology. This was done by a statistical comparison of the NWP-derived FWI dataset and the much longer-term met station-derived FWI dataset.

In fact, agreement between the NWP- and met station-derived FWI data at matched locations was found to be relatively poor on a day-to-day basis (not shown here). As has been discussed elsewhere (Legg et al., 2007; Dowdy et al., 2010), this is likely a result of differences in the spatial scales of the two datasets (individual meteorological station locations vs 2 km × 2 km grid cells), which can be particularly important for rainfall due to the occurrence of sub-grid scale convective events and the impact of complex terrain (e.g. Hoadley et al., 2004; Finkele et al., 2006; Field et al., 2014). However, on close inspection, a comparison of the 99th percentiles of the met station-derived and NWP-derived FWI datasets suggests that their upper extremes are similar. To demonstrate this, 99th percentiles were calculated seasonally for each meteorological station in the met station-derived FWI dataset for the January 2010–December 2013 period (termed the "post-2010" met station-derived FWI dataset 99th percentiles), matching the temporal extent of the NWP-derived FWI dataset. For each FWI component, these percentile values were then compared to those from the 99th percentile reference dataset (extracted from the 2 km grid cells containing the meteorological stations) using OLS linear regression.

Furthermore, to investigate whether the variation in FWI components between 2010 and 2013 is reasonably representative of a longer term FWI climatology, the 99th percentiles were calculated seasonally for each meteorological station in the met station-derived FWI dataset for the period prior to January 2010 (termed the "pre-2010" met station-derived FWI dataset 99th percentiles). OLS linear regression models were then calculated for the pre-2010 and post-2010 met station-derived 99th percentile data for each FWI component to compare the two periods.

4.3 Exploring the percentile based FDRS using historic fire records

After developing our percentile-based FDRS using the NWP-derived dataset (Sect. 3.1), we examined the behaviour of the FWI System components in relation to the historic fire records from the IRS database (Sect. 3.3). These data were explored in detail for a number of particularly "extreme" wildfire incidents (Sect. 4.3.1), and then more broadly in relation to all IRS fire events using the rank percentile curve approach of Eastaugh et al. (2012) to identify the FWI System components that best highlight fire danger in the UK (Sect 4.3.2). Additionally, the distributions of raw FFMC data during wildfires was also investigated, as previous studies (e.g. de Groot et al., 2005, 2007; Davies and Legg, 2008) have identified FFMC thresholds below which wildfire activity is extremely rare.

4.3.1 Analysis of FWI System components during several "extreme" historic wildfire events

We investigated the temporal evolution and peak values of the FWI components during the ten largest incidents in the IRS dataset. These events were selected based upon the criteria that they had the largest number of fire fighting appliances in attendance, one of several key indicators identified by the Scottish Government (2013). Additionally, to illustrate the potential impact of our new spatial varying percentile-based FDRS, and to highlight the differences between it and the MOFSI system, we then classified the midnight 12 h NWP-derived forecast of the FWI component for 2 May 2011 using both the MOFSI and percentile-based FDRS approaches. This date was selected as it coincides with one of the most extreme UK wildfire periods experienced during 2010–2013, when 61 wildfires were identified as simultaneously burning across Great Britain from the IRS dataset. For both approaches, the proportion of UK grid cells where these fires were burning and the total UK area assigned to each MOFSI category/above a specific percentile were calculated.

4.3.2 Comparing performance of the FWI System components across all IRS wildfire events

Since each of the FWI components can be considered a fire danger index in its own right (Camia and Amatulli, 2009), and in certain environments some components are believed to be better predictors of extreme fire danger than others (Van Wagner, 1988), it is useful to compare the performance of each component relative to one another. As noted by Verbesselt et al. (2006a), evaluating the performance of fire danger rating systems is challenging since the concept of fire "danger" is rather ill-defined. Nevertheless, whilst fires can occur under many different "fire weather" situations, it should be the case that ignitions are more likely to be sustained and wildfires more difficult to control during conditions of "elevated" fire danger. Accordingly, a number of studies have attempted to evaluate the skill of various fire danger indices via comparisons to records of historical fire occurrence and fire behaviour (e.g. Viegas et al., 1999; Andrews et al., 2003; Verbesselt et al., 2006b; Dowdy et al., 2010; Arpaci et al., 2013; Eastaugh and Hasenauer, 2014). A percentile based evaluation method is appealing for such a comparison, since these data were readily available to us and are uninfluenced by the differences in frequency distributions and scales of the raw components. Comparing differences in percentiles on fire/non-fire days between indices, as used by previously by Andrews et al. (2003), can form a simple yet effective evaluation method, but the choice of percentiles for evaluation can influence which index is considered to have greatest skill (Eastaugh et al., 2012). Therefore, we elected to use the "ranked percentile curve" approach devised in the review of fire danger index comparators conducted by Eastaugh et al. (2012). This method has subsequently also been applied by Arpaci et al. (2013) and Eastaugh and Hasenauer (2014).

A brief description of the "rank percentile curve" approach of Eastaugh et al. (2012) is provided here. For daily time resolution fire danger indices, all index values are first converted to percentiles, and the percentiles on days on which fires occurred ("fire days") are extracted and plotted by ascending rank to create a "ranked percentile curve". A nonparametric regression model is then fit to this curve using the Theil–Sen method (Theil, 1950a, b, c; Sen, 1968), selected because it is more resistant to outliers than are other regression techniques (due to the fact that the slope and intercept are determined using a median based approach; Helsel and Hirsch, 2002; Granato, 2006). This resistance to outliers is well suited to the evaluation of fire danger indices, since the causes of wildfires extend well beyond the meteorological factors that are the only factor accounted for by the indices (e.g. variations in human activities – caused for example by weekend *vs.* weekday activities – might tend to lead to many more ignitions on particular days or times of year for example). For illustrative purposes, Fig. 1 shows Theil–Sen models for three hypothetical fire danger indices: a "perfect" index (i.e. the highest index percentile possible occurs on each fire day) where slope = 0 and intercept = 100; a fire danger index with no predictive skill (i.e. the distribution of percentiles on fire days is the same as on non-fire days) where slope = the maximum observed percentile value divided by the total number of fire days and intercept = 0; and an index with some predictive skill, where slope and intercept values fall between the "perfect" and "no skill" indices. Accordingly, intercept and slope values from the Theil–Sen model fits to the fire danger index data can be used to assess index skill, and allow comparison between different indices.

The relationships between fire behaviour, fuel moisture and meteorology change across different environments and by time of year (e.g. Davies and Legg, 2008, 2011; Pardilla and Vega-Garcia, 2011), thus, the performance of the FWI components in forecasting UK fire danger is likely to vary seasonally and between land cover types. Accordingly, in our study we performed two seasonal rank percentile curve analyses of the FWI components during wildfire incidents – the first at a national level for spring, summer and autumn, and the second disaggregated by land cover type for spring and summer – too few fire events occurred in autumn to perform an adequate analysis at land cover level, and the winter NWP-derived FWI data were considered to be unsatisfactory for further analysis (see Sect. 5.2 for more details). A study by Legg et al. (2007) investigated the predictive power of the raw FWI components in Scotland by examining data on fire days and non-fire days in grass, heath, bush/gorse and forest woodland environments. They concluded that the FFMC, ISI and FWI have broadly equivalent discriminatory power for fire occurrence, while the DC is of little value. Our study builds upon this approach as we make use of data for the whole of Great Britain, and we believe that a climatologically based percentile approach may be more powerful than using raw FWI component data.

Most UK wildfires recorded in the IRS dataset do not extend beyond one day in duration. For each of these 1 day events the daily value of each FWI component coinciding with the event was extracted from the corresponding NWP-derived dataset grid cell. For multi-day events – which account for 22, 29 and 51 % of total spring, summer and autumn events, respectively – the maximum daily value from each event period was extracted. The value of each component associated with each event was then converted to a seasonal percentile value via a linear interpolation of the percentile reference datasets. Rank percentile curves and Theil–Sen models were then constructed for each FWI component, both at a national level and split by broad UK land cover type. For both the national and land cover disaggregated level analyses only wildfires identified as occurring in “arable”, “broadleaved”, “coniferous”, “grassland”, or “heath/bog/marsh” environments were considered since these accounted for the majority (81 %) of recorded British wildfires (see Table 1), and fires in classes such as “urban” will actually be occurring in an unknown land use sub-class (e.g. grassland, parkland etc).

5 Results and discussion

5.1 Characteristics of historic UK fires: analysis of the IRS database

The spatial and seasonal distribution of wildfire activity in Great Britain (2010–2012) and the spatial distribution of the aggregated UK land cover types is shown in Fig. 2. A breakdown of wildfire activity by both land cover class and season is also provided in Table 1. From Fig. 2b it is apparent that wildfires occur in all areas of the UK, although the number of wildfires per 2 km × 2 km Met Office grid cell was highest in South Wales, South East England and the southern Pennines region of northern England. From Fig. 2c wildfire occurrence can also be seen to be highly seasonal, with the majority (60 %) of events occurring in spring (March, April and May) or summer (25 %; June, July and August). Considerably fewer wildfires occurred in autumn (12 %; September, October and November) and winter (3 %; December, January and February). Wildfires in “grassland” account for the largest proportion of all land cover types (Table 1), both on an annual basis (33 %) and during spring (40 %). “Heather/bog/marsh” wildfires are also considerable (18 %) in spring, and are probably a consequence of the prescribed heather burning occurring during this season (Albertson et al., 2009). The majority of summer wildfires occur in “arable” (29 %) or “grassland” (27 %) land cover types, with “arable” wildfires also dominating fire activity in autumn (48 %).

5.2 Evaluation of the suitability of the NWP-derived FWI dataset as the basis for an FDRS

Figure 3 presents the seasonal relationships between the 99th percentile values of the FWI components derived from (a) meteorological station data and NWP data from grid cells geographically intersected by these stations (for the 2010–2013 period), and (b) meteorological station data for pre- and post-2010 periods for the same stations, with OLS linear regression fits and coefficients of determination (r^2). The geographical locations of the meteorological stations used for this analysis are shown in Fig. 2b.

As observed in Fig. 3a, a strong association between post-2010 met station-derived and NWP-derived FWI percentiles exists for all FWI System components during UK spring and summer (r^2 min: 0.55, median: 0.82, max: 0.93). With the exception of ISI ($r^2 = 0.33$), strong relationships are also found during autumn (median $r^2 = 0.70$). Relatively low bias is observed in the spring, summer and autumn seasons, with slope values for all FWI components lying between 0.73 and 1.30. As the extreme percentiles of the NWP-derived and the met station-derived FWI data are generally in good agreement, the NWP-derived FWI data was considered a suitable basis for a FDRS in spring, summer and autumn. Poorer association is observed between winter percentiles (r^2 min: 0.19, median: 0.35, max: 0.78), and considerable positive biases are evident in the DC intercept value (166.26) and DMC, BUI and FWI slope values (2.67, 2.93 and 2.58, respectively). However, as the summer/spring period is generally of most concern for wildfires in the UK (see Fig. 2 and Table 1) this is not considered to be a significant issue.

Figure 3b shows that while many of the relationships between the pre- vs. post-2010 met station-derived FWI dataset 99th percentiles are relatively strong ($r^2 > 0.5$); they are generally weaker than those between the NWP-derived and post-2010 met station-derived 99th percentiles (Fig. 3a). The poorest agreements and greatest biases are observed in the DMC and the BUI in winter and autumn; and in the DC in winter and spring. Whilst the spring is a particularly important period for UK wildfires

(Fig. 2c), the poor DC agreement ($r^2 = 0.4$) is strongly influenced by data from a single meteorological station located in Marham, Norfolk. Outside of this station, the spring and summer 99th percentiles from the 2010–2013 period agree reasonably well with the 99th percentiles observed in the longer term for the other FWI components (median r^2 for all FWI components in spring and summer = 0.64).

Our findings above suggest that the NWP-derived FWI dataset captures reasonably well the long term variability of the FWI components seen in the UK during spring and summer (and for most FWI components, during autumn as well), and thus forms a suitable foundation for a percentile-based FDRS. Given the weak relationships observed both between met station-derived and NWP-derived data and pre- and post-2010 data in the winter months, we believe that this approach is not suitable for assessing winter fire danger in its current form, and so the remaining work carried out in this paper focus on the months of spring, summer and autumn. In any case, as Fig. 2c shows, winter wildfires are much rarer in the UK than fires at other times of year. It is also worth noting that an operational system developed using our approach would likely become more robust over time as the years included in the FWI climatology expanded, which could improve some of the weaker relationships highlighted above.

5.3 Spatial variation in percentiles and its implications for an FDRS

For all FWI components and seasons, a large degree of spatial variability exists in the percentile reference datasets. Figure 4 illustrates the spatial variation of the 99th percentile of the FWI for each season across the UK. In summer, the 99th percentile varies by over an order of magnitude; from 1.6 in North West Scotland to 56 in South East England, clearly demonstrating the benefits of using a "percentile based" FWI threshold that is allowed to vary spatially across the country, rather than the current MOFSI system where the fire danger class for the entire UK is set using a spatially "fixed threshold". As mentioned previously, the 99th percentile is roughly analogous to the "one in several year extreme" fire weather conditions the MOFSI system was intended to highlight. However, whilst “exceptional” summer fire danger as defined by the MOFSI is signified by an FWI value exceeding 52.4, the 99th percentile of the FWI only actually reaches this value in a small region of South East England. Thus this small area is likely to be the only one in which the “exceptional” category of the MOFSI system correctly reflects a “one in several year extreme” of fire weather.

As can also be seen from Fig. 4, much lower FWI thresholds are required to represent “one in several year” (99th percentile) extreme conditions in parts of northern/western England, Wales, Scotland and Northern Ireland. Thus adopting locally calculated percentiles as thresholds for fire danger bandings avoids the geographical bias inherent in the existing MOFSI system, and would much more realistically reflect “one in several year extreme” fire weather conditions for the entire UK.

5.4 Analysis of FWI System components during several “extreme” historic wildfire events

Figure 5 shows the temporal evolution of the forecast FWI components for the widely reported spring 2011 Swinley forest fire that burned 300 ha of woodland in Berkshire, South East England. While not the largest British wildfire event on record in terms of burnt area, the Swinley forest fire is of particular note due to the fact that an enormous number (202) of fire fighting appliances were in attendance (Department for Communities and Local Government, 2013), the location was the rural-urban interface of a densely populated area, and crown fire activity occurred (which is itself a rare event in the UK; Kitchen, 2012). While the incident as reported by the IRS spans the period of 27 April–9 May, the fire only became highly significant in terms of fire suppression efforts between 2 and 6 May (Kitchen, 2012). At this time, multiple independent fire fronts developed; crowning occurred in a 5 m high pine thicket; and the fire spread across 7 ha of forest in around 20 min, jumping fire breaks up to 10 m wide. As Fig. 5 shows, each of the FWI System component percentiles clearly increase significantly in advance of this date, and with the exception of the DC, each component peaks in magnitude above the 95th–99th percentile during the event. Given that a forecast would be available from the Met Office NWP system at least three days prior to the actual date on which peak fire activity occurred, this appears to confirm that the FWI forecasts converted into percentile thresholds do contain significant information that could be useful as a short term operational planning and decision making tool for UK FRS. Similar behaviour of the FWI components is observed at the other major UK wildfire events examined – Table 2 summarises the maximum percentile exceeded by each component during each event. In all ten of these fire events, at least one of the FWI components exceeds its 95th percentile value.

5.5 Comparison of the percentile-based FDRS to the current MOFSI system during a historic period of widespread "exceptional" UK wildfire activity

UK Fire danger on 2 May 2011 as classified using (a) the MOFSI and (b) the percentile-based approaches is mapped in Fig. 6, with active fires marked as hollow circles. The proportion of the UK grid cells where wildfires were burning and the total UK area assigned to each MOFSI category and above a specific percentile are summarised in Table 3. Other than the "exceptional" MOFSI category and the 99th percentile, the MOFSI categories are not directly relatable to specific percentiles, as they are based upon a geometric progression down from the exceptional threshold rather than being based upon specific "1 in *X* year" events. This makes an intercomparison relatively subjective, but as anticipated, large spatially dependent differences are seen between fire danger mapped using the MOFSI and percentile-based classification systems (Fig. 6). In this example, the highest fire danger is forecast in southern areas of the UK using the MOFSI approach (Fig. 6a), despite wildfire activity actually occurring nationwide. The percentile based approach appears to much better indicate the extreme nature of the fire weather conditions that existed across much of the country at this time (Fig. 6b).

Using the percentile-based FDRS proposed here, the modal FWI category is the > 99th percentile category, both when considering only grid cells where wildfire events occurred (50 % of grid cells) and all UK grid cells (37 % of grid cells) (Table 3), as would be expected from a correctly operating forecasting system at a time when pan-UK fire danger is extremely high. In contrast, under the MOFSI system very few (2 %) wildfires actually occurred in areas designated as being in the "exceptional" fire danger class and the vast majority (98 %) occurred in other areas.

5.6 Comparing performance of the FWI System components across all IRS wildfire events

5.6.1 Evaluation of the FWI System components at national level

Seasonal rank percentile curves and Theil–Sen models for each FWI component at national (all land cover types) level, constructed using the maximum value of each FWI component during each wildfire event, are presented in Fig. 7. From Fig. 7a and c, it can be seen that FFMC and ISI are the best performing indices with respect to wildfire occurrence in spring and autumn, respectively. The FFMC, ISI and FWI components exhibit generally similar forecasting skill during these seasons, considerably outperforming the DMC, BUI and DC. The FWI shows the greatest skill in summer (Fig. 7b), with an intercept similar to that observed in spring. While FFMC and ISI skill is relatively worse in summer than in spring, DMC, DC, and BUI all perform somewhat better.

Our results highlight the fact that during spring, the moisture content of slow drying fuels (reflected in the DMC, DC and BUI) is generally high, preventing combustion even if an ignition were present. However, fires are frequent in spring due to the so called "spring dip" – where the moisture content of live vegetation is generally lower than in summer due to limited leaf canopy development (Davies and Legg, 2008; Alexander and Cruz, 2012) – and thus fires are more likely to take hold if an ignition is sustained. As a result, spring wildfires are dependent on whether fine fuels are dry enough to allow self-sustaining ignitions, and spread is enhanced by elevated wind speed – factors reflected in the FFMC and ISI. In contrast, UK summer wildfires tend to occur during either prolonged dry periods or drought (Met Office, 2005), when the fuel moisture of slow drying dead fuels of larger diameter, and even live fuels, can become lowered. In these cases the slower reacting FWI components (i.e. DMC, DC and BUI) have a chance to peak, and thus their performance improves slightly in the summer months. Furthermore, despite the decrease in performance of the FFMC/ISI relative to the spring, the improvements seen in the DMC, BUI and DC in the summer ultimately lead to the final component of the system, the FWI, exhibiting the best performance during the summer period.

Figure 7 shows that during all seasons, the DC performs poorly for predicting wildfire occurrence, particularly in spring, when it has almost zero skill. This is likely due to its time-lag of 52 days (time to lose $\sim 2/3$ of free moisture above equilibrium) (Van Wagner, 1987), which significantly limits its sensitivity to the type of short term (maximum ~ 5 day) weather system changes common in the UK. As an indicator of long term drought conditions (Camia and Amatulli, 2010), the DC is probably best used to indicate when a particularly severe fire season is imminent, rather than to forecast the timing or location of individual wildfire events. If the DC is elevated while other conditions are favourable for fire establishment (e.g. high wind speeds, high ignition potential of fine fuels), fires intensity and suppression difficulty is likely to be high.

5.6.2 Evaluation of the FWI System components by landcover type

Seasonal rank percentile curves and Theil–Sen models for each FWI component at land cover type level, constructed using the maximum value of each FWI component during each wildfire event, are presented in Figs. 8 and 9, respectively, and highlight that performance of the FWI components varies considerably by vegetation type and season.

During spring (Fig. 8), the best performing index in broadleaved, grassland and heath/bog/marsh environments is the FFMC, while the FWI outperforms the other indices in coniferous and arable land cover types – though there is little difference in skill between FFMC, FWI and ISI in the arable case. FFMC, ISI and FWI perform substantially better than the other components overall in grassland and arable areas, most likely a result of quick drying fine fuels dominating these land cover types during this season. A similar effect is observed in heath/bog/marsh environments; while deeper slow drying peat layers may burn during very dry conditions, most spring fires occur in the potentially dry canopies of heather stands (Davies and Legg, 2011). In coniferous – and to a lesser extent, broadleaved – environments, performance of the DMC and BUI components increases. DMC and BUI perform similarly to the ISI in coniferous environments, and outperform FFMC. With the exception of the FFMC, all FWI components perform best in coniferous environments, and the FWI component (the final “summary” index of the FWI System) demonstrates the greatest overall skill. The improved skill shown here relative to other environments, particularly in coniferous woodlands, likely reflects the increased availability of slow drying fuels (duff, dead and live woody material) in these environments.

During summer (Fig. 9) the FWI component exhibits the greatest predictive skill, in this case across all land cover types. The skill of the indices related to slow-drying fuels (DMC, DC, BUI) increases or shows little change relative to the skill in spring for each corresponding land cover type, with the improvements in coniferous, grassland and heath/marsh/bog land covers the most significant. This is consistent with how fire behaviour changes from spring to summer in the UK (as highlighted in Sect. 5.6.1). These components likely reflect the increasing importance of slower drying live and dead woody fuels to the overall fuel load in these environments (Arpaci et al., 2013). In heath/bog/marsh areas this may reflect the drying processes that litter, moss and peat layers can undergo in summer, as has been suggested by Davies et al. (2006) and Krivtsov et al. (2008). Conversely, with the exception of coniferous and heath/marsh/bog environments, summer FFMC and ISI performance decreases relative to spring. The skill of the FWI component improves in summer in all non-arable environments. Performance of the indices in summer is of particular note in coniferous environments; where with the exception of the DC all indices show a very high degree of skill, both relative to other environments during summer, and when compared to coniferous environments during spring. The indices generally display the poorest performance in arable land in both spring and summer; perhaps a result of farming practices and societal factors (e.g. ignitions in baled crops) being of significant importance for fires in these environments. The overall poor DC performance found across all seasons in Sect. 5.6.1 is also observed when indices are evaluated by vegetation type.

It is interesting to note that for each of the individual "extreme" wildfire events discussed in Sect. 5.4 and summarised in Table 2, while at least one of the FWI components exceeds its 95th percentile value during each of the ten fire events examined, it is not always the component identified in this ranked percentile curve analysis as having greatest forecasting skill for that particular season and land cover type. For example, during both the Upton (Dorset) and Swinefleet (East Yorkshire) major summer wildfires, the ISI exceeds the highest percentile, despite the FWI performing better in general in heath/bog/marsh environments such as these in the summer months (Fig. 9). Similarly during the Lightwater (Surrey) spring wildfire, the highest percentile exceeded is in the FFMC, despite the FWI, DMC, ISI and BUI all performing better overall in coniferous forests in spring (Fig. 8). This highlights the importance of considering the behaviour of all FWI components when attempting to interpret forecasts of fire danger, rather than just relying upon the component that appears to performs best overall for a given season and land cover.

5.6.3 Raw FWI component values during historic wildfires: the FFMC as an on/off switch for fire danger?

While advocating the adoption of our percentile-based approach to fire danger forecasting in the UK, we also examined the "raw" component (i.e. non-percentile) values of the NWP-derived FWI component forecasts in grid cells where wildfire events occurred. As has been shown in other studies (e.g. de Groot et al., 2005, 2007; Davies and Legg, 2008) non-spatially sensitive thresholding behaviour was observed in FFMC. Distributions of the maximum FFMC values during wildfire events in 2010–2012 are shown in Fig. 10, where 90 % of all fires are seen to have occurred above a FFMC value of 72 in spring, 74 in summer, and 69 in autumn. Below these values, ignitions appear to be rarely sustained. This suggests that there may be some merit to restricting the forecast fire danger level based upon the raw FFMC value, regardless of the forecast value of any other FWI component percentile. No similar behaviour is observed in any of the other indices, however, justifying the choice of a percentile-based approach to give more detailed information on fire danger once the FFMC surpasses these "sustained ignition" thresholds.

6 Summary and conclusions

When fuel moisture is low and wind speeds are conducive to fire spread, multiple large fires can occur simultaneously across large parts of the UK, as last happened in April/May 2011. A UK Fire Danger Rating System (FDRS) could be used to forecast such problematic periods, so as to better forewarn FRS, emergency planners/responders and land managers (Eastaugh et al., 2012). The current UK FDRS – termed the Met Office Fire Severity Index (MOFSI) – is operated by the UK Met Office (Met Office, 2015) and is based on simple thresholding of the Fire Weather Index (FWI) component of the Canadian Forest FWI System, as calculated from daily numerical weather prediction (NWP) forecasts made up to 5 days ahead. Here we have investigated how this approach might be extended, both by examining the behaviour of the sub-components of the FWI System in UK environments, as suggested by Van Wagner (1988), and by identifying the values of the FWI components that represent "extremes" around the country by undertaking a percentile-based calibration that varies with location and season.

We find that our percentile-based "calibration" of the FWI components is strongly justified, since the "raw" values of the FWI components that appear to represent "extreme" conditions are highly location dependant. For example, the 99th percentile of the FWI component varies by more than an order of magnitude in summer across the

UK, ranging from 1.6 in North West Scotland to 56 in South East England. Indeed, for all FWI components, a strong north-west to south-east gradient is identified in these "extreme" (99th) percentiles. We also note an extreme spatial bias in the current MOFSI system; for example, in summer a region is only considered to be at "exceptional" fire severity when the FWI exceeds a value of 52.4 – a situation that based on the historical datasets examined herein seems unlikely ever to be reached in many areas of the northwest UK.

Using several "exceptional" wildfire events as examples, we demonstrate that our locally-calibrated percentile based FDRS system can correctly identify peak periods of fire danger; and at least one FWI component exceeded the 95th percentile for each of the 10 "exceptional" wildfires selected here, with many exceeding the 99th. Of course, as with all other wildfire events, such exceptional fires also require an ignition source in addition to landscape scale fuel and meteorological conditions that are conducive to fire spread. Ignitions in the UK overwhelmingly come from anthropogenic activity (Davies et al., 2006), and to some extent the relationships we find between fire occurrence and elevated values of the FWI components might be influenced by e.g. more increased human recreational activity in the countryside during periods of fire-conducive weather, and/or more spring "prescribed" burns being carried out in the uplands at this time. Nevertheless, physical factors relating to the fuels and "fire weather" are still crucial components of fire behaviour, and if the right conditions are not present an ignition will be unlikely to be sustained sufficiently to lead to a rapidly spreading wildfire such as those we identify here. Our analysis also highlights the benefit of having multiple components of the FWI System available for decision making, rather than just the final FWI component as is currently the case, and for each fire event studied we find values of one or more FWI components generally climatologically uncharacteristic for the locality.

We further evaluated the utility of our spatially varying percentile-based fire danger categories by using a historic FWI "forecast" for 2 May 2011; a time of exceptional wildfire activity nationwide (Kitchen, 2012). We find that our approach appears to highlight extreme fire danger with far more skill than the existing MOFSI system, with 50 % of wildfires occurring in areas classified as exceeding the 99th percentile of the FWI component, whereas only 2 % were in areas classified as "exceptional" fire danger under the existing MOFSI system.

In order to further investigate which FWI components best highlight periods of extreme fire behaviour in different areas and seasons across the UK, we carried out a seasonal performance evaluation of the NWP-derived FWI data using all wildfire records recorded in the FRS Incident Recording System (IRS) dataset between January 2010 and December 2012 using Eastaugh et al.'s (2012) percentile ranking with a Theil–Sen (Theil, 1950a, b, c; Sen, 1968) fitting approach. Spring is the time of the majority (60 %) of UK wildfires, and during this season the FFMC metric performs the best, which is the FWI component most closely related to the moisture conditions of quick drying fine fuels. When examined by land cover type, we identify that in spring the FFMC is the most skilful component in broadleaf, grassland and heath/bog/marsh land cover types, whilst the FWI component is the most skilful in arable and coniferous environments. Overall, the FFMC, FWI and ISI components stand out as the best predictors of spring fire activity in the UK, in agreement with the findings of Legg et al. (2007) for Scotland. The FWI component generally performed best in all environments during summer (see Sect. 5.6.2 for further details). It was noted that in both spring and summer, indices appeared to generally perform best in coniferous environments – likely due to the initial development of the FWI System in Canadian boreal forests – and poorly in arable ones, possibly due to human activity driving fuel availability and fire behaviour in these areas. We also note that "raw" FFMC data may make a useful addition to a percentile based UK FDRS, as most fire activity occurs within a relatively narrow range of FFMC values (see Sect. 5.6.3).

Our study has provided new insight into the applicability of the Canadian Forest FWI System in the UK; the relationships between its various sub-components and fire behaviour across different seasons and land cover types; and the advantages of taking a percentile based approach to categorising fire danger in a future UK FDRS.

While there are clearly limits to what can ultimately be achieved by applying this sort of statistical driven approach to the empirically developed FWI System, and there may be further skill to be had by blending NWP data with actual rainfall observations (Field et al., 2014), we believe the approach used here to be a significant advance on the current MOFSI methodology and one that could hold considerable potential value for aiding UK wildfire responders and landscape managers.

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Table 1. Number of wildfire events reported in Great Britain between January 2010 and December 2012 from the filtered UK Fire and Rescue Service Incident Recording System (IRS) dataset developed herein, disaggregated by season and land cover type. See Sect. 3.3 for details on land cover classification.

Land Cover Type	Number of fires				
	Spring	Summer	Autumn	Winter	Total
Arable	151	206	173	39	569
Broadleaved	169	69	20	4	262
Coniferous	130	57	11	4	202
Grassland	692	191	65	20	968
Heath/Bog/Marsh	308	34	13	4	359
Other	20	7	6	1	34
Urban	264	149	72	18	503
Total	1734	713	360	90	2897
Total (Discounting Other/Urban)	1450	557	282	71	2360

Table 2. Maximum percentiles of NWP-derived Fire Weather Index components predicted for the ten most serious wildfire events reported in the FRS Incident Recording System between January 2010 and December 2012 in Great Britain. These events were selected on the basis that they had the greatest number of Fire and Rescue Service (FRS) appliances attending. Note that two records are provided for the Swinefleet, East Yorkshire event, as this incident occurred over the summer/autumn season boundary.

Site name	Land cover type	BNG Easting	BNG Northing	Season	Event start date	Event date	Maximum index percentile during event					
							FFMC	DMC	DC	ISI	BUI	FWI
Belmont, Lancashire	Heath/Bog/Marsh	367 051	416 574	Spring	29 Apr 2011	4 May 2011	99	99	94	99	98	99
Belmont, Lancashire	Heath/Bog/Marsh	367 051	416 577	Spring	3 May 2011	5 May 2011	98	99	95	99	98	99
Curdworth, West Midlands	Arable	418 052	291 811	Spring	23 May 2010	23 May 2010	99	95	46	94	93	96
Frensham, Surrey	Broadleaved	485 021	141 145	Summer	11 Jul 2010	12 Jul 2010	95	99	85	96	99	99
Hevingham, Norfolk	Coniferous	620 143	320 410	Summer	11 Jul 2010	13 Jul 2010	96	94	64	99	95	99
Kirkby, Lancashire	Grassland	343 846	399 875	Spring	30 Apr 2011	3 May 2011	99	98	49	99	96	99
Lightwater, Surrey	Coniferous	493 080	161 148	Spring	19 May 2010	23 May 2010	96	84	55	81	85	86
Swinefleet, East Yorkshire	Heath/Bog/Marsh	475 230	416 591	Summer	29 Aug 2010	9 Sep 2010	79	35	80	96	35	80
				Autumn	29 Aug 2010	9 Sep 2010	96	74	74	99	74	97
Swinley, Berkshire	Coniferous	485 480	165 492	Spring	27 Apr 2011	8 May 2011	97	99	60	99	99	99
Upton, Dorset	Heath/Bog/Marsh	398 960	93 771	Summer	9 Jun 2011	9 Jun 2011	69	68	51	95	68	87

Table 3. Distributions of "Fire Danger" classifications of the midnight 12 h NWP-derived Fire Weather Index (FWI) component forecast for 2 May 2011, calculated using the Met Office Fire Severity Index described in Kitchen et al. (2007), and the percentile-based FDRS developed herein. For each approach, two distributions are provided: the first for only the 2 km × 2 km resolution UK grid cells in which wildfires were burning, and the second for all grid cells within the UK.

MOFSI system			Percentile-based approach		
MOFSI category	% of grid cells containing wildfires	% of all UK grid cells	Percentile category	% of grid cells containing wildfires	% of all UK grid cells
Exceptional	2	2	> 99	50	37
Very High	52	48	97–99	17	19
High	18	17	95–97	6	8
Moderate	20	16	90–95	15	18
Low	9	17	< 90	12	18

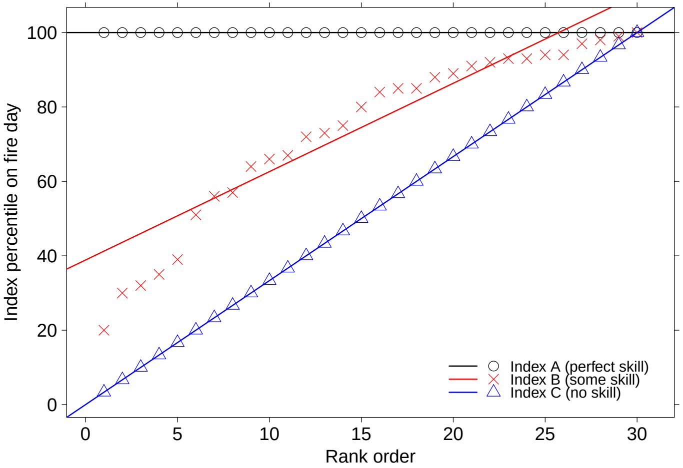

Figure 1. Demonstration of the use of data from three hypothetical fire danger indices (Index A, B and C) fitted with Theil–Sen models to compare the indices predictive skill on fire days. Index A demonstrates perfect skill (i.e. the highest index percentile value possible occurs on each fire day) and so slope = 0 and intercept = 100 for the Theil–Sen model fit to these data. The model fit to index B (which shows some predictive skill) has a smaller intercept and larger slope than the model fit to index A, but a larger intercept and smaller slope than the model fit to index C (an index with no predictive skill). Accordingly, by comparing the slope and intercept values of Theil–Sen models fit to percentile data from two or more fire danger indices, the relative predictive skill of the indices can be determined. See Eastaugh et al. (2012) for more details on this approach to skill assessment.

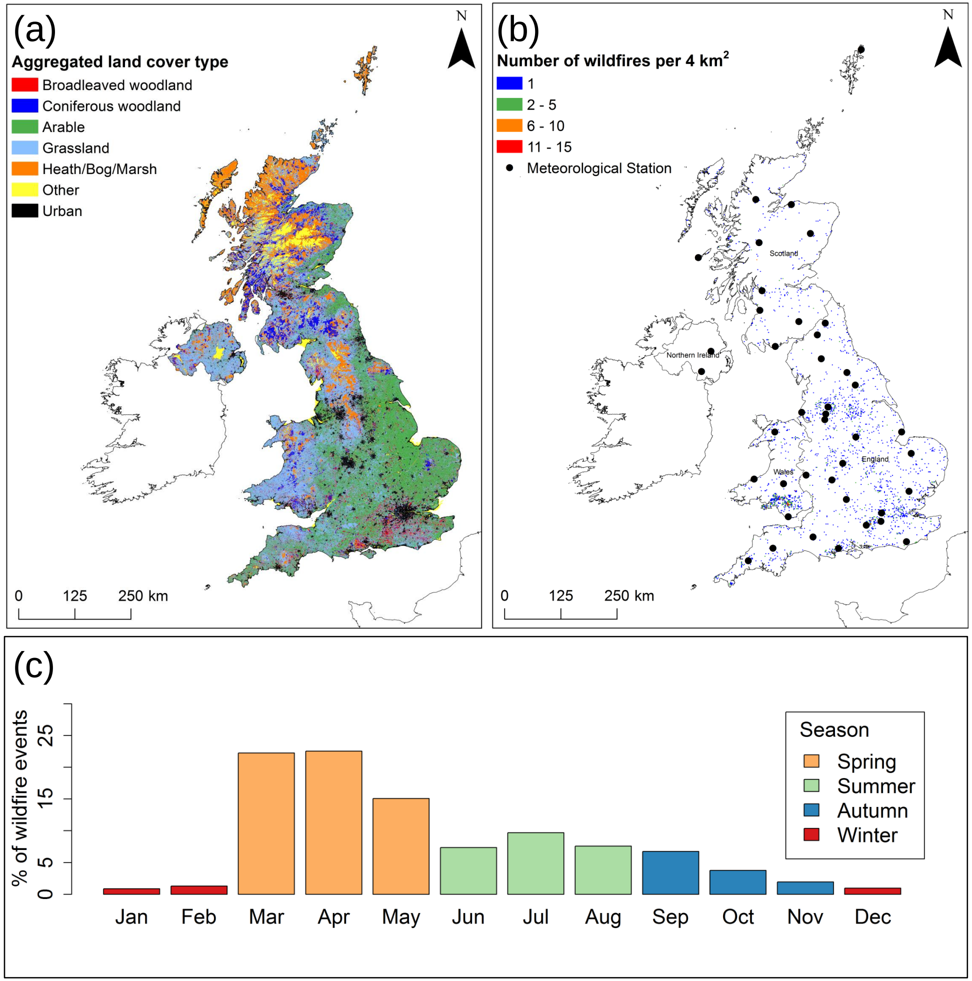
(a)
Aggregated land cover type
🟥 Broadleaved woodland
🟦 Coniferous woodland
🟩 Arable
Grassland
Heath/Bog/Marsh
Other
Urban
N
0 125 250 km
(b)
Number of wildfires per 4 km^2
🟦 1
🟩 2 - 5
6 - 10
🟥 11 - 15
● Meteorological Station
Scotland
Northern Ireland
England
Wales
N
0 125 250 km
(c)
% of wildfire events
0
5
15
25
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Season
Spring
Summer
Autumn
Winter

Figure 2. Land cover, meteorological station and fire occurrence data in the study area. **(a)** Aggregated UK land cover classes derived from the Land Cover Map 2007 (LCM 2007; Morton et al., 2011) **(b)** spatial and **(c)** temporal distributions of wildfire occurrence in Great Britain (England, Wales and Scotland) as recorded by the Fire and Rescue Service (FRS) Incident Recording System (IRS) between January 2010 and December 2012. The location of the 38 meteorological station sites used herein to create the long term "measured" Canadian Fire Weather Index (FWI) UK dataset are also shown (black circles) in **(b)**. As well as the availability of vegetation cover able to support the spread of fire, the anthropogenic influences on fire occurrence can also be clearly discerned from **(b)**, with loci of increased fire density in South Wales, South East England, and the southern Pennines region of northern England. 60 % of wildfires during this three year period occurred during Spring (March, April and May) and another 25 % occurred during Summer (June, July and August). Panel **(a)** is based upon LCM2007 © NERC (CEH) 2011. Contains Ordnance Survey data © Crown Copyright 2007. © third party licensors.

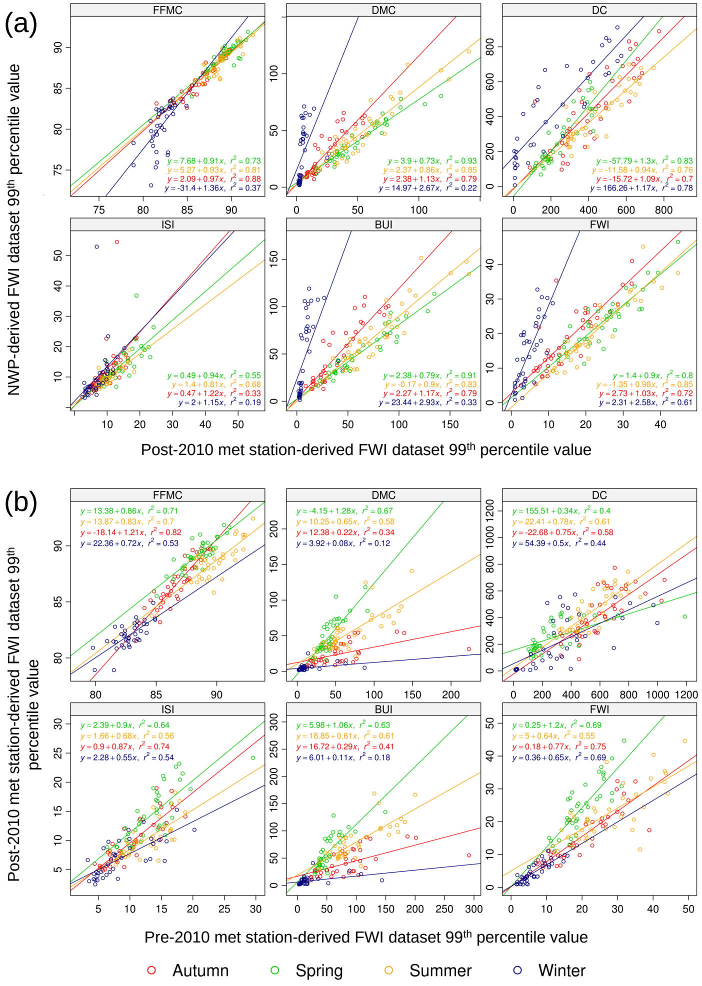
(a)
NWP-derived FWI dataset 99th percentile value
FFMC
y = 7.68 + 0.91x, r² = 0.73
y = 5.27 + 0.93x, r² = 0.81
y = 2.09 + 0.97x, r² = 0.88
y = -31.4 + 1.36x, r² = 0.37
DMC
y = 3.9 + 0.73x, r² = 0.93
y = 2.37 + 0.86x, r² = 0.85
y = 2.38 + 1.13x, r² = 0.79
y = 14.97 + 2.67x, r² = 0.22
DC
y = -57.79 + 1.3x, r² = 0.83
y = -11.58 + 0.94x, r² = 0.76
y = -15.72 + 1.09x, r² = 0.7
y = 166.26 + 1.17x, r² = 0.78
ISI
y = 0.49 + 0.94x, r² = 0.55
y = 1.4 + 0.81x, r² = 0.68
y = 0.47 + 1.22x, r² = 0.33
y = 2 + 1.15x, r² = 0.19
BUI
y = 2.38 + 0.79x, r² = 0.91
y = -0.17 + 0.9x, r² = 0.83
y = 2.27 + 1.17x, r² = 0.79
y = 23.44 + 2.93x, r² = 0.33
FWI
y = 1.4 + 0.9x, r² = 0.8
y = -1.35 + 0.98x, r² = 0.85
y = 2.73 + 1.03x, r² = 0.72
y = 2.31 + 2.58x, r² = 0.61
Post-2010 met station-derived FWI dataset 99th percentile value
(b)
Post-2010 met station-derived FWI dataset 99th percentile value
FFMC
y = 13.38 + 0.86x, r² = 0.71
y = 13.87 + 0.83x, r² = 0.7
y = -18.14 + 1.21x, r² = 0.82
y = 22.36 + 0.72x, r² = 0.53
DMC
y = -4.15 + 1.28x, r² = 0.67
y = 10.25 + 0.65x, r² = 0.58
y = 12.38 + 0.22x, r² = 0.34
y = 3.92 + 0.08x, r² = 0.12
DC
y = 155.51 + 0.34x, r² = 0.4
y = 22.41 + 0.78x, r² = 0.61
y = -22.68 + 0.75x, r² = 0.58
y = 54.39 + 0.5x, r² = 0.44
ISI
y = 2.39 + 0.9x, r² = 0.64
y = 1.66 + 0.68x, r² = 0.56
y = 0.9 + 0.87x, r² = 0.74
y = 2.28 + 0.55x, r² = 0.54
BUI
y = 5.98 + 1.06x, r² = 0.63
y = 18.85 + 0.61x, r² = 0.61
y = 16.72 + 0.29x, r² = 0.41
y = 6.01 + 0.11x, r² = 0.18
FWI
y = 0.25 + 1.2x, r² = 0.69
y = 5 + 0.64x, r² = 0.55
y = 0.18 + 0.77x, r² = 0.75
y = 0.36 + 0.65x, r² = 0.69
Pre-2010 met station-derived FWI dataset 99th percentile value
○ Autumn ○ Spring ○ Summer ○ Winter

Figure 3. Comparison of the 99th percentile values of the six Canadian Fire Weather Index (FWI) components by season, derived **(a)** from meteorological station data and NWP data from grid cells geographically intersected by these stations, for the 2010–2013 period; and **(b)** from meteorological station data for pre- and post-2010 periods for the same stations, using OLS linear regression. Data in **(a)** indicates that extreme values of the FWI components calculated from the NWP-derived FWI data are similar to those calculated from meteorological station data during spring, summer and autumn. **(b)** shows that while there is some variation in the extreme FWI component values observed between 2010–2013 and the pre-2010 data (each met station used in this study has 13–44 years of data, including the years 2010–2013), the data from spring, summer and to a lesser extent autumn from 2010 to 2013 are broadly representative of longer term extremes. Accordingly, we conclude that a robust FWI climatology can be constructed from the NWP-derived FWI dataset for these seasons, despite its limited duration.

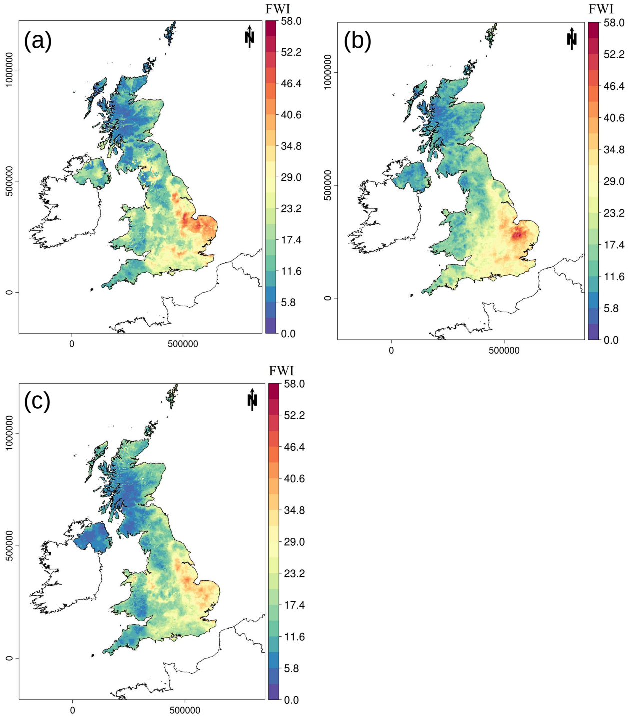

Figure 4. Spatial variation in the 99th percentile of the FWI component of the Canadian Fire Weather Index, as calculated from the 2010–2013 NWP-derived FWI dataset for **(a)** spring, **(b)** summer and **(c)** autumn. The warmer, drier climate of southeast England as compared to the wetter, cooler climate of the western and northern parts of the UK causes a distinct gradient in this percentile, which varies by an order of magnitude across the country. FWI components would be expected to exceed the 99th percentile for 3–4 days over four summers, making it broadly comparable to the "one in 4–5 year" extreme fire weather conditions that the "exceptional" category of the existing Met Office Fire Severity Index was intended to represent.

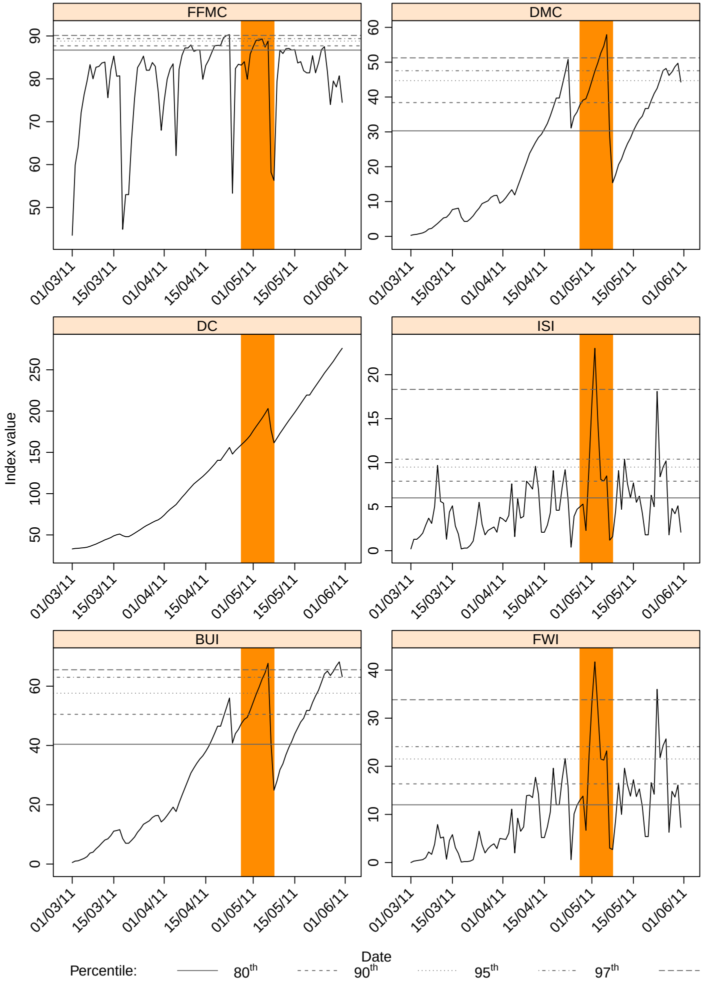

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Figure 5. Temporal evolution of the FWI components at the location of the Swinley Forest wildfire that occurred in Berkshire, England in April/May 2011. This fire was one of the most extreme fire events in the UK for many years, and burned for 13 days according to the Incident Recording System database (timing indicated by the orange bars). Peak fire activity (crowning of the fire in trees, and jumping of 10 m fire breaks) occurred on the 2 May, and extreme behaviour persisted until 6 May (Kitchen, 2012). Horizontal dashed lines indicate the 80th, 90th, 95th, 97th and 99th percentiles of each FWI component for this particular UK grid cell during the spring season, calculated according to the criteria described in Sect. 4.1. Components such as the ISI and FWI show extreme maxima during the period of the Swinley fire.

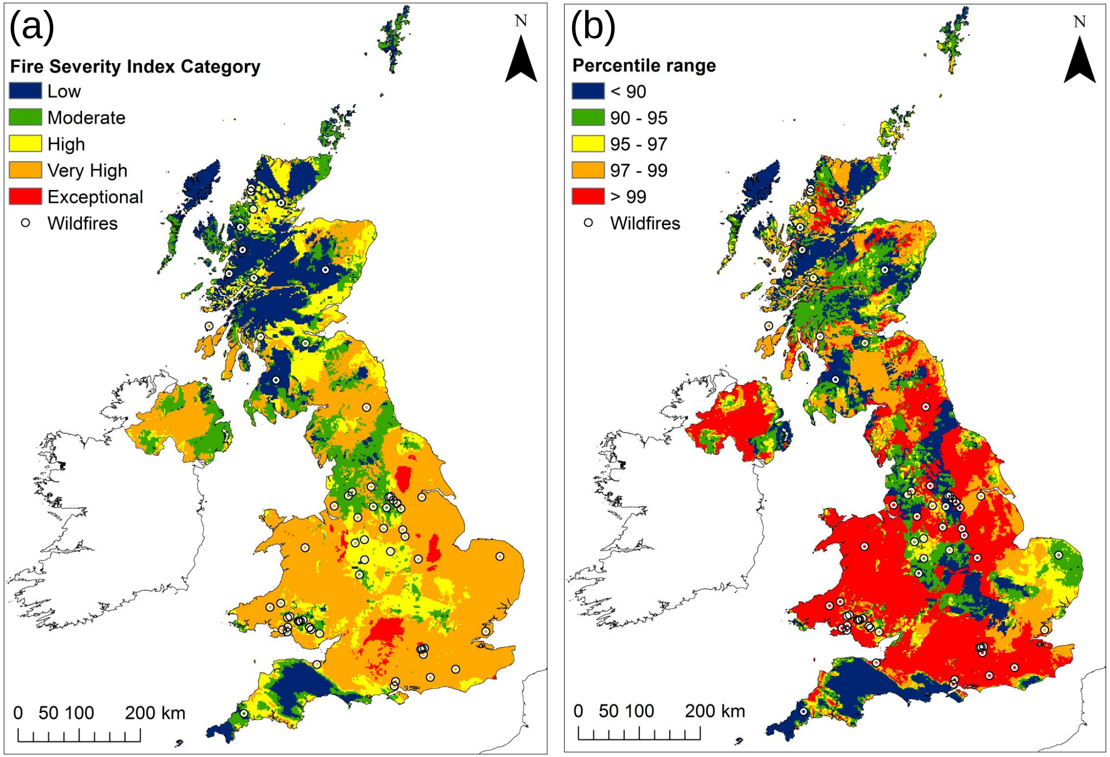

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Figure 6. “Fire danger” in the UK, mapped for 2 May 2011, and based upon the midnight 12 h-NWP-derived FWI component forecast as classified using **(a)** the existing Met Office Fire Severity Index (MOFSI) system described in Kitchen et al. (2007), and **(b)** the percentile-based FDRS described herein. This date coincides with the height of a period of extreme wildfire activity seen across Great Britain in Spring 2011, related to weather conditions extremely conducive to vegetation fire spread, with 61 wildfires reported in the Incident Recording System (IRS) of the Fire and Rescue Service as burning in mainland Britain on 2 May 2011. These incidents are shown as hollow circles on both maps. No fire data for Northern Ireland are recorded in the IRS. The 99th percentile shown in red in **(b)** is considered to indicate similarly extreme fire weather conditions as should be indicated by the “Exceptional” category of the MOFSI shown in red in **(a)**. However, in **(a)** the most extreme FWI conditions are confined to relatively small regions of England, whereas in **(b)** the most extreme conditions are much more widespread and are found across the entire UK, as is the fire activity. Consequently, as highlighted in Table 3, considerably more fires are located in NWP grid cells where the FWI exceeds the 99th percentile than are found in grid cells classified by the MOFSI approach as “Exceptional”.

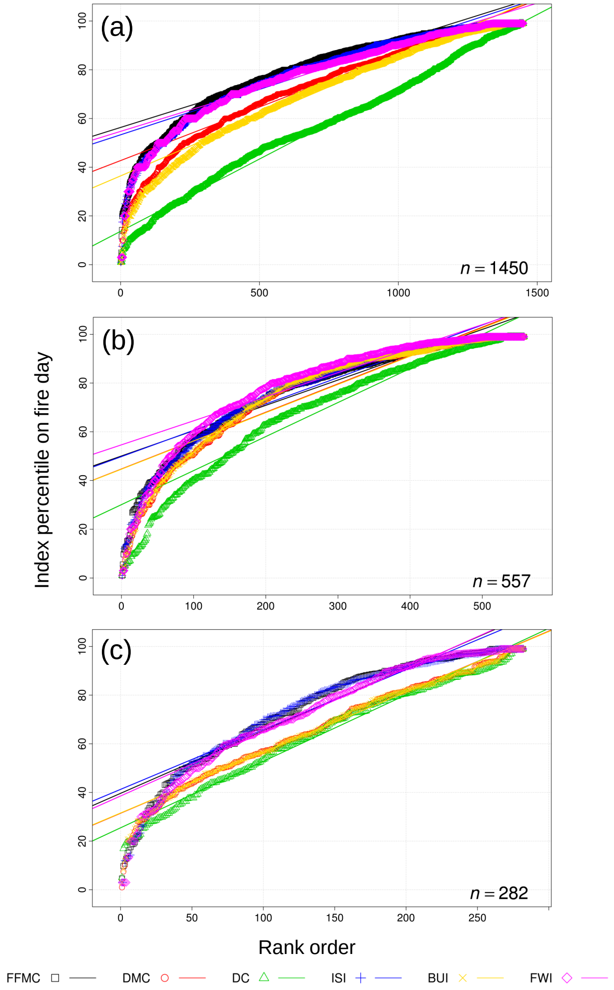
(a)
n = 1450
(b)
n = 557
(c)
n = 282
Index percentile on fire day
Rank order
0
20
40
60
80
100
0
500
1000
1500
0
100
200
300
400
500
0
50
100
150
200
250
FFMC □ ——
DMC ○ ——
DC △ ——
ISI + ——
BUI × ——
FWI ◇ ——

Figure 7. Rank percentile curves (after Eastaugh et al., 2012's approach) of NWP-derived Fire Weather Index components during all wildfire events recorded in the Incident Recording System (IRS) of the Fire and Rescue Service between January 2010 and December 2012 in Great Britain. See Fig. 1 for how to interpret these curves. For each wildfire event, the maximum daily FWI component percentile calculated over the duration of the event was extracted from the NWP grid cell in which the fire occurred. For each season and FWI component, the percentiles of each fire event were plotted in ascending rank order, and regression lines fit using the Theil–Sen method (Theil, 1950a, b, c; Sen, 1968) – a median based model that is minimally influenced by outliers (see Sect. 4.3.2). Seasonal plots are shown for **(a)** spring, **(b)** summer and **(c)** autumn. The greater the intercept value and smaller the slope value of a model fit, the more skilful the FWI component is, in terms of predicting severe wildfire behaviour. FWI components related to the moisture of quick drying fine fuels (FFMC and ISI) perform well in all seasons, while FWI components more closely related to the moisture content of slower drying fuels (DMC and BUI) demonstrate improved performance in summer. The final FWI component performs well in all seasons, and is the most skilful FWI system component in summer overall.

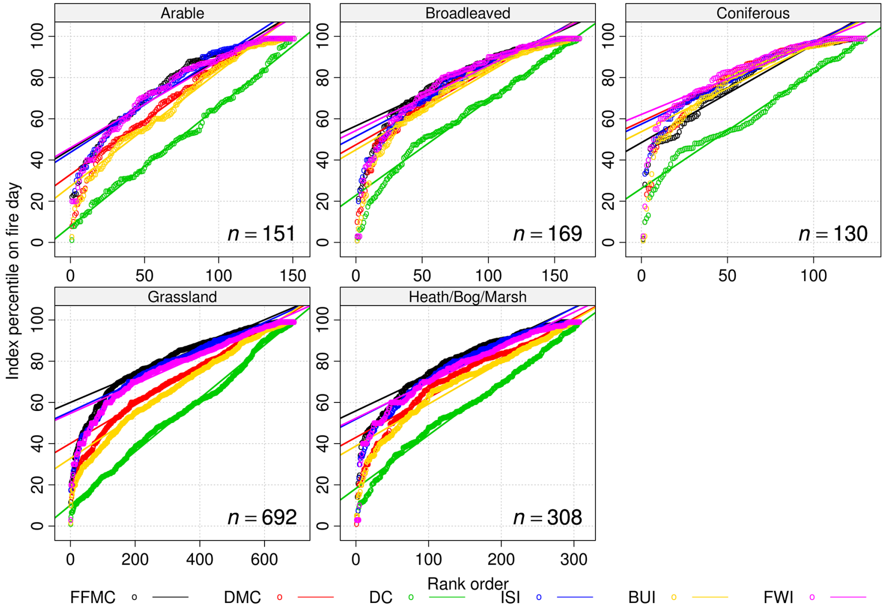

Figure 8. Rank percentile curves (after Eastaugh et al., 2012's approach) of NWP-derived Fire Weather Index components during all spring wildfire events recorded in the Incident Recording System (IRS) of the Fire and Rescue Service between January 2010 and December 2012 in Great Britain, split by dominant landcover type. See Fig. 1 for how to interpret these curves. For each wildfire event, the maximum daily FWI component percentile calculated over the duration of the event was extracted from the NWP grid cell in which the fire occurred. For each season and FWI component, the percentiles of each fire event were plotted in ascending rank order, and regression lines fit using the Theil–Sen method (Theil, 1950a, b, c; Sen, 1968) – a median based model that is minimally influenced by outliers (see Sect. 4.3.2). The greater the intercept value and smaller the slope value of a model fit, the more skilful FWI the component is, in terms of predicting severe wildfire behaviour. The FFMC component shows the greatest skill in broadleaf, grassland and heath/bog/marsh land cover types, while the FWI performs best in coniferous and arable environments.

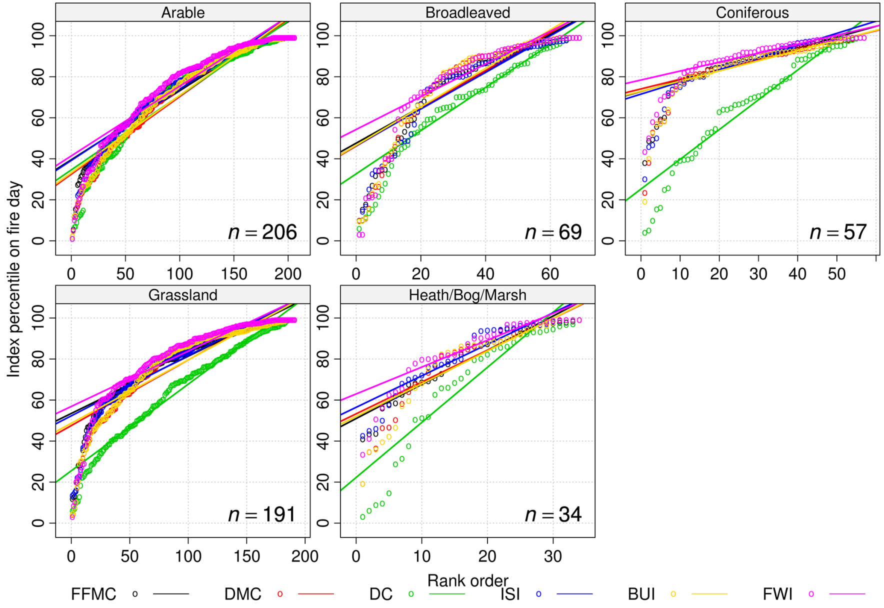

Figure 9. Rank percentile curves (after Eastaugh et al., 2012's approach) of NWP forecast-derived Fire Weather Index components during all summer wildfire events recorded in the Incident Recording System (IRS) of the Fire and Rescue Service between January 2010 and December 2012 in Great Britain, split by dominant landcover type. See Fig. 1 for how to interpret these curves. For each wildfire event, the maximum daily FWI component percentile calculated over the duration of the event was extracted from the NWP grid cell in which the fire occurred. For each season and FWI component, the percentiles of each fire event were plotted in ascending rank order, and regression lines fit using the Theil–Sen method (Theil, 1950a, b, c; Sen, 1968) – a median based model that is minimally influenced by outliers (see Sect. 4.3.2). The greater the intercept value and smaller the slope value of a model fit, the more skilful the FWI component is, in terms of predicting severe wildfire behaviour. Overall the FWI component has the greatest skill in all environments during the summer months.

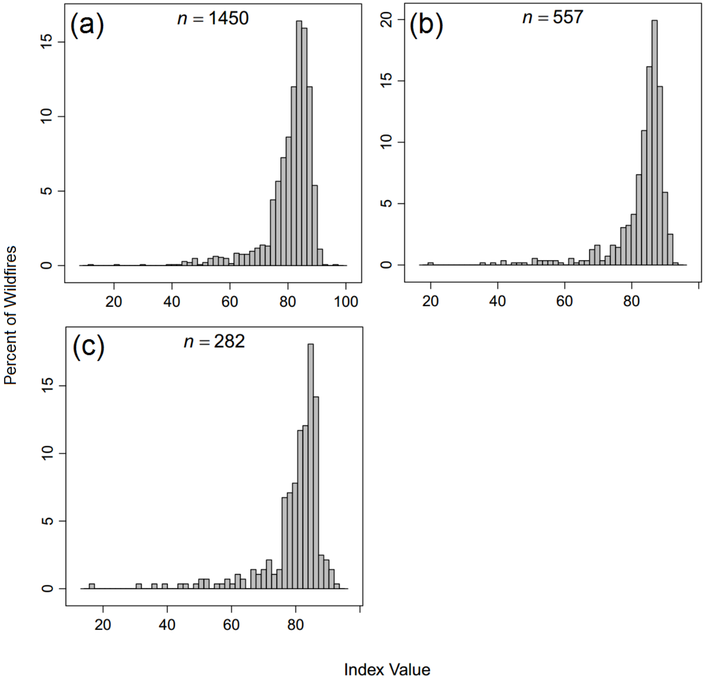

Figure 10. Distribution of raw FFMC values on wildfire days in **(a)** spring, **(b)** summer and **(c)** autumn in Great Britain, as recorded in the Fire and Rescue Service Incident Recording System database between January 2010 and December 2012. Thresholding behaviour is apparent in all seasons. 90 % of all fires during this period occurred above a FFMC value of 72 in spring, 74 in summer and 69 in autumn. We suggest that a revised fire danger rating system for the UK may be able to make use of these threshold values in addition to FWI component percentile information for assessing fire danger.