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epa Research

Quantification of the Area of Land Burned and Habitats Affected by Wildfires in Ireland, 2015–2021, and the Resulting Emissions

Authors: Fiona Cawkwell, Emma Chalençon, Ned Dwyer, Clara Felberbauer, Stig Hellebust, Beatriz Martin, Thedmer Postma, Guy Serbin and Dean Venables

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Rialtas na hÉireann
Government of Ireland

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3. Office of Evidence and Assessment
4. Office of Radiation Protection and Environmental Monitoring
5. Office of Communications and Corporate Services

The EPA is assisted by advisory committees who meet regularly to discuss issues of concern and provide advice to the Board.

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Lead organisation: University College Cork

Identifying pressures

Information on wildfires in Ireland is currently collated from fire services, media, social media reports and satellite-based programmes that record elevated heat signals of fires active under clear skies at the time of the satellite overpass. However, these sources are incomplete and inconsistent, with the omission of many small fires, bias towards population centres and limited data on the spatial extent of the fire and the type of land cover burned. In recent years, efforts have been made at the European scale to map burned areas greater than 30 ha by manual digitisation of satellite imagery. However, this still overlooks smaller fires and is subjective in its approach. Due to this lack of knowledge about wildfire events, it is not known to what extent changing climate and land management conditions are having an impact on the number of fires and their magnitude. Likewise, the estimated atmospheric emissions and loss of biodiversity arising from wildfires are poorly understood. This research aims to develop an automated methodology that allows the aftermath of a wildfire to be mapped and emissions estimated more accurately using factors determined specifically for Irish vegetation species.

Informing policy

Different measures have been implemented to reduce the incidence and impact of wildfires, for example periods when burning of growing vegetation is prohibited, forest fire danger ratings and notices, and fire breaks. However, with no reliable information on the timing and extent of a burn, or whether fires are repeatedly occurring in the same locations, the effectiveness of these measures cannot be evaluated. Likewise, to understand how climate changes may impact on the timing and extent of wildfire events, more information on where and when fires have occurred in the past is needed. Similarly to all EU countries, Ireland reports annual emissions of anthropogenic pollutants and greenhouse gases, but, at present, it is likely that those arising from wildfires are underestimated, given the paucity of information on events smaller than 30 ha. More detailed information on where and when a fire occurs, the nature of the vegetation that is burned, previous fires in a region, and the relationships between fires, weather and land management will enable the introduction of more targeted measures and policies to reduce the impact of wildfire events.

Developing solutions

To ensure the most comprehensive mapping of wildfire events, a fully automated method relying on identification of burn scars on medium-resolution optical satellite images was developed. Landsat and Sentinel-2 satellites carry sensors that record surface reflectance at a scale of 10–30 m, with new images acquired every few days under cloud-free conditions. These images permit the change in reflectance from live green vegetation to dead burned remains to be identified, and, through a filtering process, false alarms arising from agricultural activities or misclassification due to cloud shadows can be eliminated. Emission factors for three species of vegetation commonly associated with Irish wildfire events (gorse, heather and purple moor grass) were established using a dedicated combustion facility. The satellite-based methodology can be applied to historical images as well as those acquired by current and future sensors, and the atmospheric emissions more accurately calculated with a better knowledge of the vegetation that burned. Consequently, the contribution of wildfire emissions to the national total can be better estimated, and the efficacy of measures taken to reduce the incidence of fire events evaluated.

EPA RESEARCH PROGRAMME 2014–2020

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by

University College Cork

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The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

Wildfires in an Irish context are uncontrolled fires in vegetation in the countryside or a wilderness area. Information on these fires can be collated from fire services, media and social media reports, and satellite-based thermal hotspots. The information from these sources is incomplete and inconsistent, with the omission of many small fires, bias towards population centres and limited data on the spatial extent and type of land cover burned. Consequently, the atmospheric emissions and loss of biodiversity arising from wildfires are poorly understood. Burn scars on satellite images have a different spectral signature to live vegetation, and thus can provide a more complete and objective approach to recording the aftermath of a fire. The habitats or vegetation species burned can be identified and the emissions estimated using standard values for biomass and emission factors; however, these may be unsuitable for distinctive Irish habitats and species.

The Fires, Land and Atmospheric Remote Sensing of Emissions (FLARES) project investigated the role of satellite remote sensing in mapping burned areas and estimating greenhouse gas and air pollutant emissions, with field and laboratory activities supporting the refinement of emission factors and an understanding of pollutants released.

Key Findings

- Optical satellite imagery of medium spatial resolution can be used to successfully map burn scars larger than 0.4 ha, but Sentinel-1 C-band microwave imagery (central frequency 5.405 GHz, wavelength 5.55 cm) cannot be used to reliably identify burned areas.
- The FLARES project results indicate that burned areas were significantly larger than indicated by all prior estimates, ranging from 5200 ha in 2019 to 31,500 ha in 2015.
- Burn scars are evident on satellite images for weeks to months, with vegetation regenerating more quickly after fires that occur in spring.
- Sentinel-2’s higher spatial and temporal resolutions enable better detection and delineation of burn scars, with fewer false positives, than Landsat-8, but the multi-date and thresholding approach taken for the Sentinel-2 data makes it a more conservative product.
- False positives are generated from agricultural activities, peat bogs, cloud and shadow, but many could be eliminated using the EPA/Ordnance Survey Ireland (now known as Tailte Éireann) Irish National Land Cover Map.
- Up to half of the area burned each year lies within designated protected areas, about one-quarter is heavily improved grassland, according to the National Parks and Wildlife Service Habitat Asset Register definition, and trees account for less than 4% of burned vegetation.
- A total of 180 km^2 of gorse was mapped from satellite imagery. Although Irish wildfires are often referred to as “gorse fires”, many affect a range of habitats.
- Emission factors for gorse, heather and purple moor grass measured in a dedicated combustion facility were within the range reported for comparable vegetation, suggesting that reliable estimates of emissions from Irish wildfires can be obtained if the amount of vegetation burned is known.
- Particulate matter emitted from burning vegetation includes that emitted directly from the fire and up to a further 10% arising from post-fire atmospheric processing.
- The national air quality monitoring network is inadequate for the detection of emissions from all wildfires.
- Fire events have a noticeable influence on pollutant concentrations recorded by Copernicus Atmosphere Monitoring Service (CAMS) products, but these primarily relate to large fires with the delineation and quantification of emissions attributable to other fire events being unrealistic.

Key Recommendations

- Automated approaches for burn scar mapping from medium-resolution optical satellite imagery should be adopted to improve knowledge of emissions from wildfires and habitats burned.

- The FLARES methodology should be applied to historical Landsat data to extend the time series and enable the refinement of reported emissions attributable to wildfires, the investigation of spatio-temporal trends in wildfire events and the exploration of potential links to climate change, air pollution, land management policy and human activity.
- Up-to-date information on Irish land cover should be considered essential for understanding the impacts of fires.
- Biomass values and emission factors should be measured for more Irish vegetation species and habitats, to enable more refined calculations of the quantity of biomass lost and the amount of particulate and gaseous emissions resulting from wildfire events.
- The remit of the national air quality monitoring network should be extended to support wildfire emission estimates in the National Inventory Report, the validation of remotely sensed products and air quality models.
- Through further engagement with the CAMS team, FLARES project results should be used to inform improvements in CAMS products, to enable the identification of small-scale fires and the development of more refined emission factor values and datasets more suitable for the Irish context.

1 Introduction

1.1 Wildfires in Ireland

1.1.1 Irish wildfires: an incomplete understanding

Fire disturbance has been identified as an essential climate variable (Mason *et al*., 2010), and data on burned areas have been highlighted as important by the Intergovernmental Panel on Climate Change (IPCC) and the United Nations Framework Convention on Climate Change (UNFCCC), as fire disturbance events are both indicators of climate change, e.g. of vegetation becoming drier and more combustible, and contributors to climate change, e.g. through the release of greenhouse gases (GHGs) from vegetation burning (Hawbaker *et al*., 2017). Wildfires have also been identified as having a direct impact on human and animal health through the release of fine particulates.

Wildfires are defined in an Irish context as uncontrolled fires in combustible vegetation that occur in the countryside or a wilderness area, and occasionally in the wildland–urban interface or zone of transition between unoccupied land and land that has been subject to human development. Wildfires differ from controlled fires in their extensive size, the speed at which they can spread, their potential to change direction unexpectedly, their ability to jump gaps such as roads, rivers and firebreaks, and their propensity to disrupt and threaten human safety, conservation and economic land management objectives (Nugent, no date, p. 5). Although wildfires in Ireland do not typically affect large areas, information on their impacts in terms of atmospheric emissions and loss of biodiversity is essential. Irish wildfires are commonly associated with periods of dry weather and may be started accidentally or as a result of controlled burn events that become uncontrolled. To limit the number of such uncontrolled burn events, setting fire to vegetation is prohibited between 1 March and 31 August. Fighting these fires requires significant levels of resources from many agencies and has a high economic cost. Wildfires also have air quality and health impacts, in particular when they occur close to urban areas.

Even though the physical location of a fire largely influences the response to and impact and implications of the event, very few spatial or temporal analyses have been undertaken in Ireland for prediction purposes. Equipment and tactics to fight fires have been improved, and an increasingly coordinated approach is being taken by responding agencies, but no harmonised approach is taken to the way data are collated in relation to events (e.g. area burned, land cover affected). European Union (EU) satellite data are sometimes used for comparison with local records for larger fires, but no further analysis is performed. With respect to characterising the land cover affected, burn events are often referred to in Ireland as “gorse fires”, but evidence from fire service personnel suggests that this is a generic term mainly used for public engagement, and that heather is in fact the most common scrub vegetation burned (pers. comm.). Compared with many European countries, information and statistics regarding wildfire events in Ireland are scarce, with limitations including incompleteness, inconsistency in reporting of the extent and nature of the burned area, and a lack of timeliness in reporting.

1.1.2 Collating a wildfire database from media and social media reports

Jeffers (2021) exploited newspaper archives to construct a history of wildfires in County Donegal, and he explained how “rich qualitative and quantitative data” can be retrieved from such sources. To better understand the temporal and spatial distribution of Irish wildfires, a geodatabase with information collated from a variety of media and social media sources was compiled for 2015–2021. Spatial biases were identified towards those fire brigades that are more active on social media (Dublin, Cork and Bantry) and the larger population centres, which have a greater media catchment area, as evident in the map shown in Figure 1.1. The most recent archives (2018 onwards), especially in the case of social media, were easier to access and more comprehensive, giving a temporal bias towards later years.

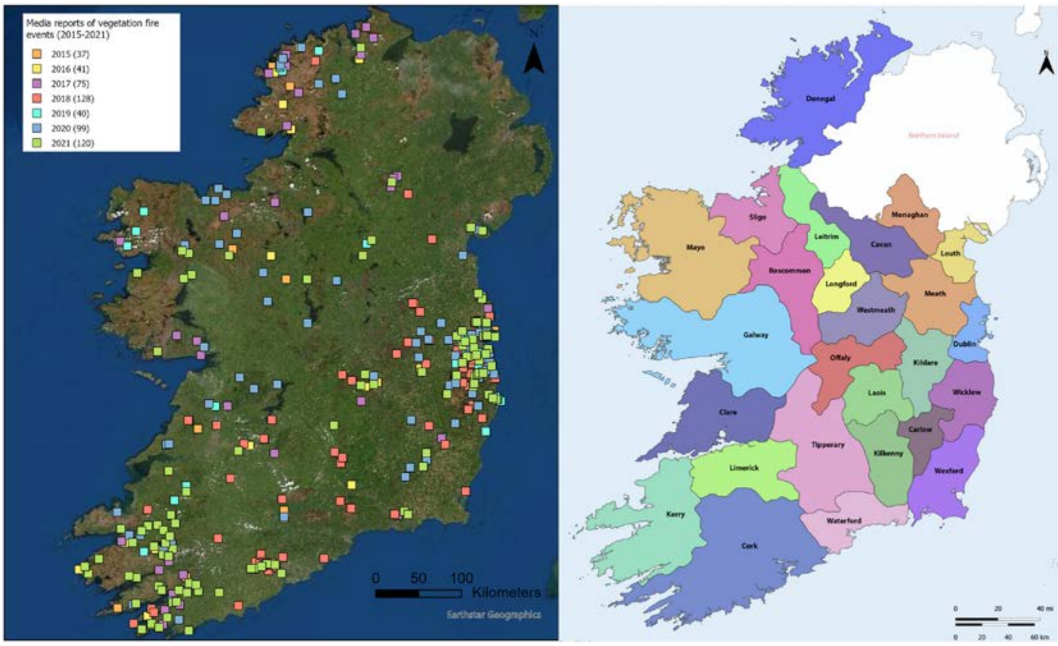

Figure 1.1. Map showing the location of fires based on media and social media reports, 2015–2021, highlighting the bias towards population centres and more recent years (left), and map showing the counties of Ireland (right).

Media and social media reports were found to often report only the general location of the fire event, e.g. “large gorse fire in Wicklow hills”, and the size of the burned area was very rarely reported. In conclusion, these reports highlighted incompleteness and inconsistency in recording the occurrence and location of fire events – in terms of both extent and nature – so direct communications were made with fire services across the country to request information on wildfire interventions or call-outs.

1.1.3 Collating a wildfire database from fire brigade intervention reports

Fire brigade intervention databases are managed by regional control centres (RCCs) but, as of 2021, there is no harmonisation between the provinces with respect to how the data are stored, or the level of precision and information attached to fire reports. A fire’s coordinates are often defined as centroids of the townland from where the 999 call was made, and the labels ascribed to each event are not necessarily reliable, as “gorse fire” is often used as a generic term for all wildfires (pers. comm.). Figure 1.2 illustrates differences in the numbers of annual vegetation fires between county fire brigades. When considering the distribution of fire reports through the year from each county fire brigade (Figure 1.3), it is apparent that fires are more common in the spring in the west of the country and are spread throughout the year in more easterly counties.

From communications with representatives of the county fire services, it was apparent that, although they have been more frequently notified about controlled agricultural burning events in recent years, a large number of such fires are unreported and unattended. They also commented on the absence of a national reporting system (although, as of 2021, one is in development) and highlighted the discrepancies between counties in the way fires are labelled and therefore counted, and the limitations of RCC databases, which depend on reports from 999 calls and are thus biased towards larger population centres or locations of concerned citizens.

1.2 Satellite Remote Sensing for More Complete Estimates of Areas Burned

Since the 1990s, there has been a growth in the use of Earth observation (EO) satellite images for burned area detection and mapping (dos Santos *et al*., 2021). Moreover, global operational fire alert systems have been established to aid the management of ongoing fire events.

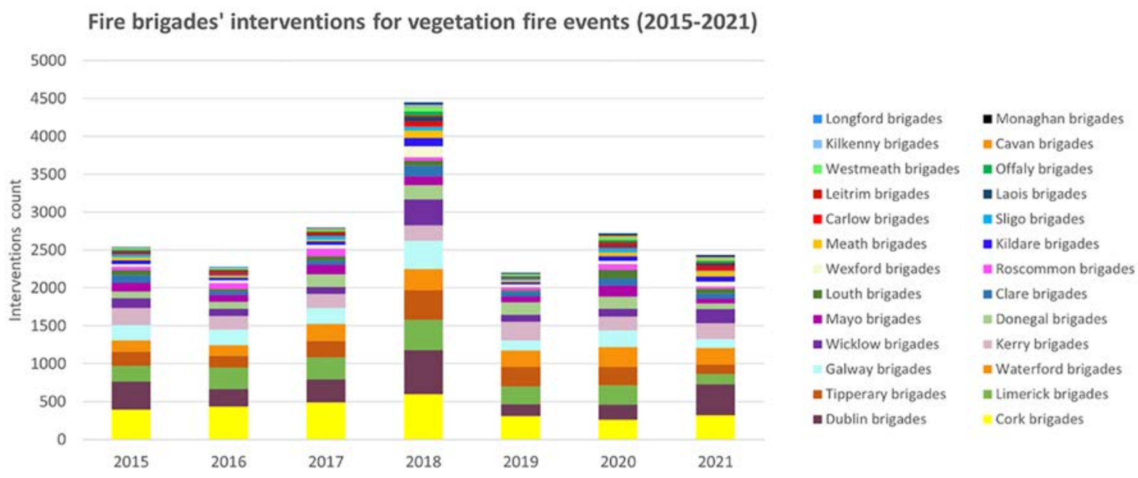

Figure 1.2. Number of fire events labelled as “vegetation” fire events by year and county fire brigades.

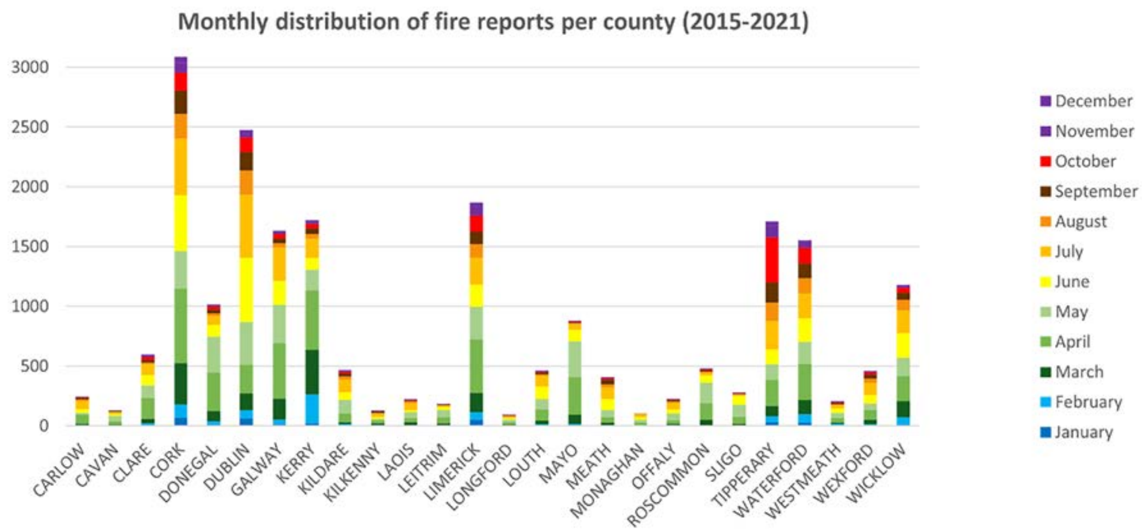

Figure 1.3. Monthly distribution of wildfires recorded by fire brigades from each of the counties.

1.2.1 Active fire products

The European Forest Fire Information System (EFFIS) supports national services responsible for managing fire hazards in the EU and neighbouring countries and provides European Commission services and the European Parliament with updated and reliable information on wildfires in Europe. The Fire Information for Resource Management System (FIRMS) – which is part of the Land, Atmosphere Near Real-time Capability for Earth Observation Systems (LANCE) of the United States National Aeronautics and Space Administration (NASA) – distributes active fire data within 3 hours of satellite observation. Both of these systems derive fire event information from four satellite instruments: the moderate-resolution imaging spectroradiometer (MODIS) on NASA’s Terra and Aqua platforms, and the Visible Infrared Imaging Radiometer Suite (VIIRS) on the National Oceanic and Atmospheric Administration’s (NOAA’s) Suomi National Polar-orbiting Partnership (Suomi NPP) and NOAA-20 platforms. An automated image-processing algorithm identifies areas on the ground that are anomalously hot, with a higher temperature than their surroundings, and flags them as active fires. The spatial resolution of the active fire detection pixel for MODIS is 1 km, meaning that the fire must be fairly large for it to be detected within a 1 km^2 area, while VIIRS has a 375 m spatial resolution. Consequently, many small fires are not detected, especially when extensive cloud or smoke cover persists, as the four satellite instruments are dependent on relatively clear sky conditions, and the spatial extent of burning cannot be reliably established by the MODIS or VIIRS products because of their low spatial resolution (Boschetti *et al*., 2015). Errors can also be introduced by hot features that are not fire events, such as gas flares. At mid-latitude locations, the four abovementioned platforms pass overhead several times in a 24 hour period, giving information with high temporal frequency. The MODIS product has been available on the two platforms mentioned above since 2002, but the VIIRS product has been available on two platforms only since the end of 2019, resulting in an increase in the number of events identified since that date, given the increase in the number of overpasses. The location of active fires is updated six times daily within the EFFIS database, while the FIRMS fire map is updated every 5 minutes.

A database of MODIS and VIIRS hotspots for 2015–2021 was retrieved from the EFFIS and FIRMS portals (Figure 1.4), with just one record per satellite instrument per 2 km radius in a 48 hour period retained to avoid over-reporting of a fire event. Constant false positives over cement factories, which present as large heat sources, were discarded.

All sources of fire information were consistent in terms of reporting the largest number of fires in April (Figure 1.5), with April to August inclusive accounting for the majority of wildfires in Ireland, when vegetation is more flammable and recreational activities are most conducive to accidental sparks.

1.2.2 Burned area products

The temporal frequency with which satellite images are captured is a key parameter in the identification of burn scars and the recovery of vegetation (Boschetti *et al*., 2015). Post-fire surfaces are likely to change rapidly, and multi-date images are often needed to reliably distinguish disturbances due to fire from land cover changes due to human activity, e.g. crop harvesting, or natural variation, e.g. vegetation phenology (Roy *et al*., 2005). The first burned area products were derived mainly from Landsat imagery on a local scale (Chuvieco *et al*., 2019), with the Advanced Very High Resolution Radiometer and Along Track Scanning Radiometer sensors later used to map burned areas at a 1 km spatial resolution and generate some of the first global products (Simon *et al*., 2004).

The EFFIS Rapid Damage Assessment product provides a daily update on the perimeters of burned areas in Europe for fires larger than 30 ha, and, since 2018, the addition of Sentinel-2 imagery has allowed the delineation of some smaller fires. Burned areas are identified from the change in land cover evident in visible and near- and mid-infrared images, and are initially defined on the basis of an automated procedure and then visually verified and corrected (EFFIS, 2021). Two EFFIS analysts spend approximately 80% of their time mapping European

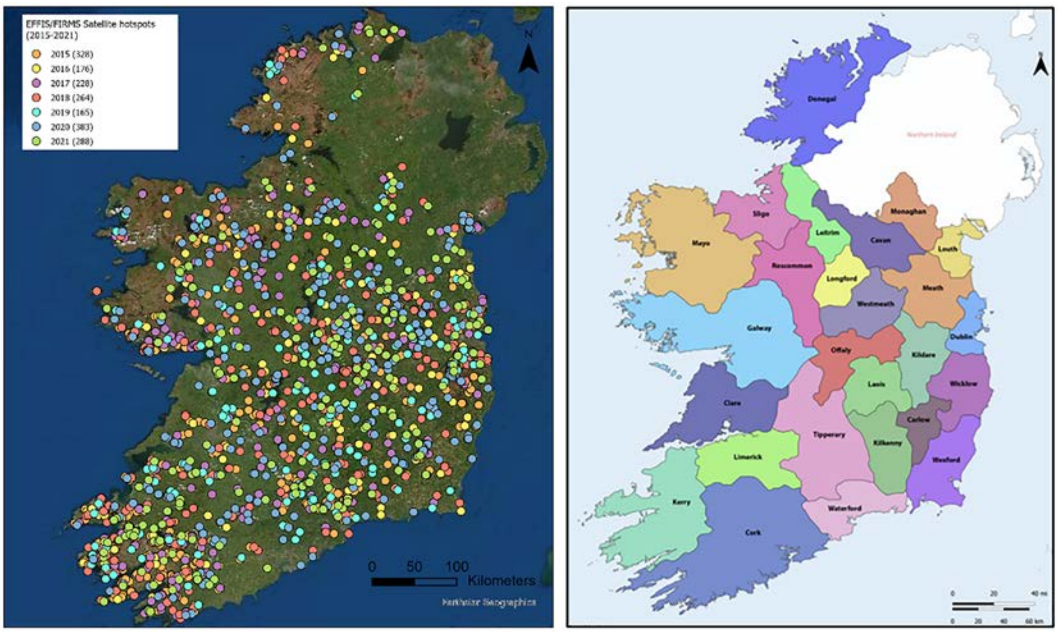

Figure 1.4. Map showing the locations of fires in Ireland from 2015 to 2021 identified from the EFFIS and FIRMS databases, with additional satellite sensors incorporated from 2020 (left), and map showing the counties of Ireland (right).

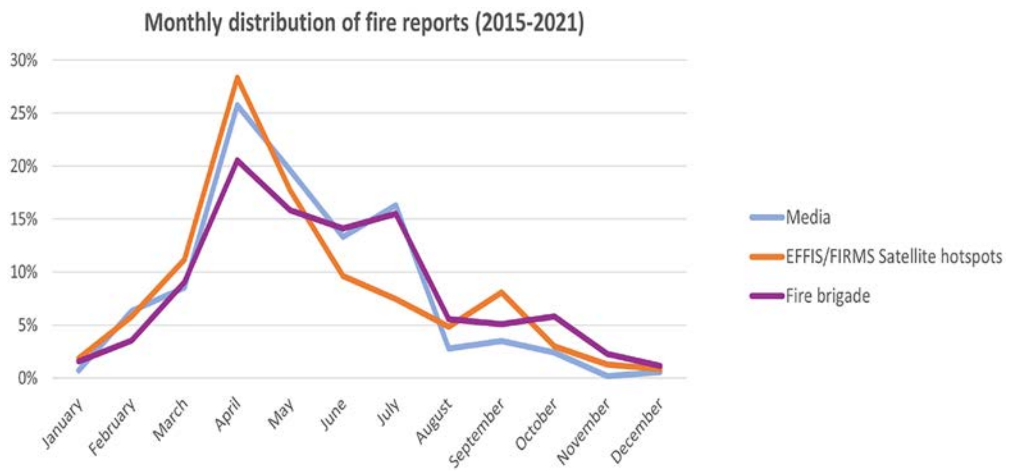

Figure 1.5. Monthly distribution of vegetation fires reported by different sources, showing a peak in April (of all media reports, 25% refer to a fire in April).

fires (pers. comm., Jesús San-Miguel-Ayanz, European Commission Joint Research Centre, 10 May 2022). The results of this manual method show commission errors close to zero, i.e. if a burned area was indicated then it was almost certainly accurate, but omission errors of up to 69%, owing to the reliance on coarse spatial resolution imagery, i.e. MODIS and VIIRS, to identify the initial event, thus omitting many smaller fires.

A burned area product, MODIS Fire_cci v5.1, based on MODIS imagery for the period 2001–2020 has been produced as part of the European Space Agency (ESA) Climate Change Initiative (CCI) programme. The burned areas were obtained by combining red and near-infrared spectral information from MODIS at 250 m resolution and thermal information at 1 km resolution from the MODIS active fire products. The validation of this product for Ireland shows, as with the EFFIS product, a very low rate of commission errors but also a very high rate of omission errors, reaching 93% on a national scale since 2018.

Three other burned area products are provided by the Copernicus Global Land Service. A 1 km product was derived from PROBA-V daily synthesis data, available to the user in near-real time every 10 days for the period 2014–2018. However, this product did not appear to detect any genuine burn scars for the period 2015–2018 in Ireland. Data from a higher (300 m) resolution PROBA-V daily surface reflectance product have also been available in near-real time every 10 days since 2014. Validation of the use of this product in Ireland showed a commission and omission error rate in excess of 90%, making it of limited value in an Irish context, and the product available since July 2020, which incorporates data from Sentinel-3 Sea and Land Surface Temperature Radiometer sensors, detected no burned area in Ireland up to the end of 2021.

1.2.3 The National Inventory Report: estimates of burnt area and related emissions

Each Member State must report an estimate of emissions and removals of GHGs to the UNFCCC in the form of an annual GHG inventory. National Inventory Report and Common Reporting Format data submissions include wildfire emissions (European Evaluation Helpdesk for Rural Development, 2020). In Ireland's 2022 National Inventory Report, burnt area within forests, derived from Forest Service statistics, was reported with "50% uncertainty", as determined by "expert judgement, guess" (Duffy *et al*., 2022, Table 6.10, p. 221). The area of forest burnt was then used to estimate the area of other land cover types burned, extrapolated from the NASA FIRMS database, and the relative proportion by land cover type defined by Coordination of Information on the Environment (CORINE) land cover maps. The unique land cover classes and fragmented landscapes of Ireland tend to be poorly mapped in CORINE maps (owing to CORINE's minimum mapping unit of 25 ha), and the level of uncertainty over the area burned for non-forest land cover types ranges from 86% to 100% (Table 6.36, p. 290, of the 2022 National Inventory

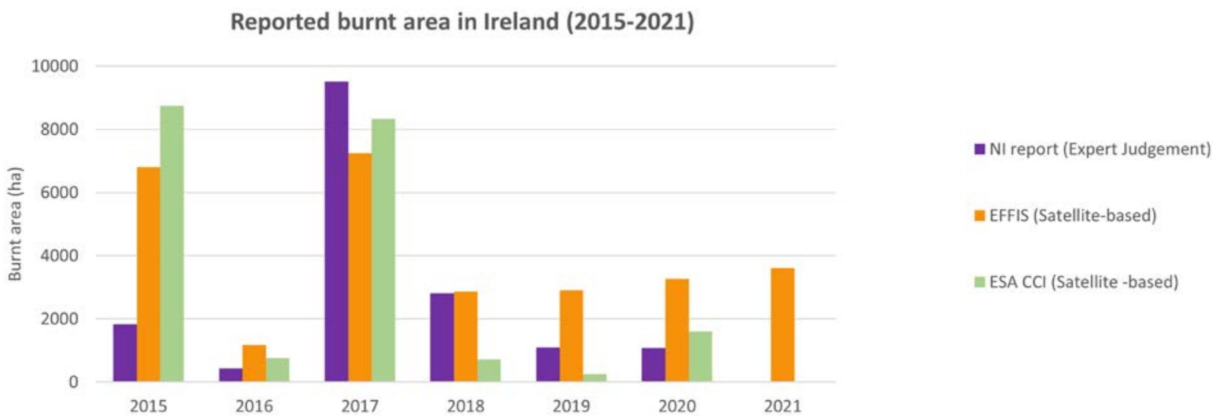

Figure 1.6. Burned area reported in Ireland by year, as derived from different sources, illustrating not only the large inter-annual variability but also differences in the size of the burned area reported between methods of identification. NI report, National Inventory Report.

Report). Figure 1.6 shows the total burned area from 2015 to 2021 according to the sources discussed in sections 1.2.2 and 1.2.3, with the wide range of values reported by the different systems each year highlighting the uncertainty in actual burned area.

The method for estimating emissions resulting from the fire events, as well as the standard values for mass of fuel available for combustion, combustion factors and emission factors (EFs), are derived from the 2006 IPCC Guidelines (IPCC, 2006, Volume 4, Chapter 2). However, these values are not typical of Irish wildfires and vegetation classes. It is specified, however, in the National Inventory Report that: “A national system needs to be developed to track the exact location of areas subject to fires” (Duffy *et al*., 2022, p. 340).

1.3 Objectives of the Fires, Land and Atmospheric Remote Sensing of Emissions (FLARES) Project

The current fragmented approach to calculating areas burned and resulting emissions highlights the need for a national system, not only to track the location of fires but also to identify the nature and extent of land cover types burned, and to generate refined estimates of the GHGs and air pollutants emitted as a result of these fires.

1.3.1 Development of an automated approach for national burn scar mapping

Wildfires in Ireland tend to be small and are often short-lived, and, because of cloud cover, their impacts may not be evident from space until several weeks after the fire. This necessitates a unique approach to mapping burn scars that exploits higher resolution sensors and focuses on changes in the ground spectral reflectance, rather than a thermal signal, to detect the aftermath of a fire. The databases compiled from data provided by fire brigades, media and social reports and international satellite programmes (Figure 1.7) are, however, an invaluable source of initial information and validation.

1.3.2 Quantification of the extent and type of land cover burned based on burn scar mapping

Having automatically identified burn scars from the satellite imagery, the area of each can be derived and the nature of the land cover defined based on the best available land cover information.

1.3.3 Quantification of greenhouse gas and air pollutant emissions released from the burn event

Having identified the type of land cover that burned, the GHG and air pollutant emissions released can be estimated based on standard values and, where available, on more species-specific information derived for application to common upland Irish plant species.

1.3.4. Assessment of the environmental and health impacts of the burn event

Having identified the locations of fire events and the land cover types burned, the impacts of fires can be better understood.

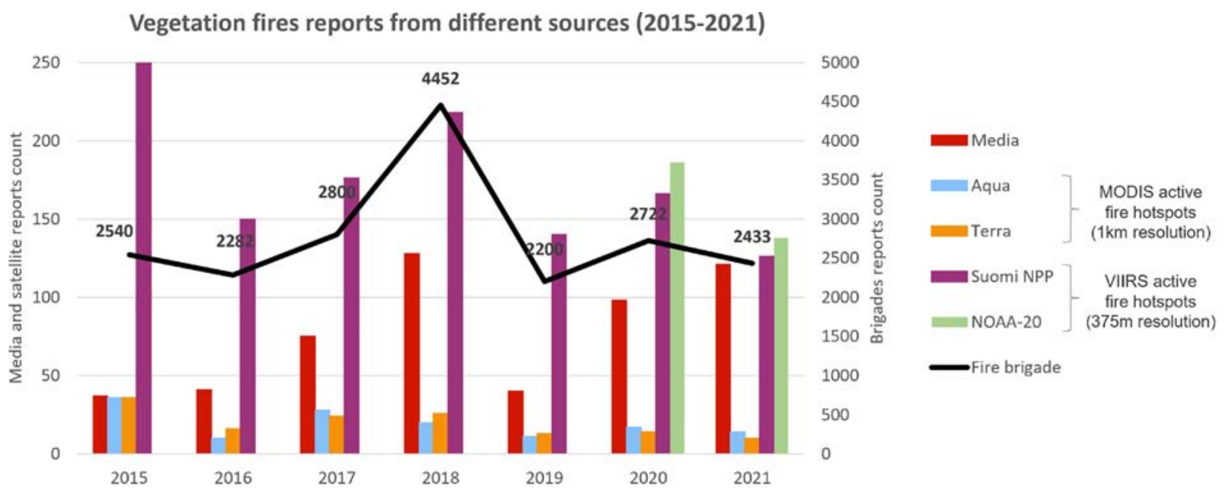

Figure 1.7. Numbers of Irish wildfires derived from media and social media reports, low-resolution satellite sensors (Aqua, Terra, Suomi NPP and NOAA-20) detecting active fires and fire brigade reports.

2 Satellite Remote Sensing of Burn Scars

2.1 Review of Literature and Best Practice

2.1.1 Underlying physical principles of mapping burned areas from satellite Earth observation

Many different parameters influence the impact of fire on vegetation and consequently its manifestation in satellite images. The post-fire signal and its difference with respect to pre-fire reflectance, temperature or backscatter tend to vary from one location to another, but that change in signal forms the basis of most burn scar mapping (Chuvieco *et al.*, 2019). The type of fire, its behaviour and the interval between the extinction of a fire and the acquisition of an image have an impact on the signals that can be identified in satellite images. The principal spectral components of recent burn scars are charcoal and ash, but, depending on the fire regime and its intensity and length, leaves or vegetation can remain at the surface (Chuvieco *et al.*, 2019). Burn scars lose the ash and charcoal signal at different rates depending on the primary productivity at the site and the nature of vegetation recovery (Boschetti *et al.*, 2015). When the ash and charcoal signal disappears, the biomass lost and potentially different vegetation assemblages are the only parameters that allow burned areas to be distinguished from other areas (Chuvieco *et al.*, 2006).

The near-infrared (NIR) (0.7–1.2 μm) and shortwave-infrared (SWIR) (1.2–2.5 μm) spectral regions are the most sensitive to fire effects after a burn event is over (Pleniou and Koutsias, 2013), when leaf pigmentation changes and water contents are considerably reduced. These phenomena result in a strong decrease in the NIR reflectance (Silva *et al.*, 2004) and an increase in the SWIR reflectance (Chuvieco *et al.*, 2006). The microwave domain has been used mainly over tropical areas or at high latitudes to overcome high levels of cloud cover or low sun angles that prevent the use of optical satellite images (Goodenough *et al.*, 2011). Different techniques have been tested using synthetic aperture radar (SAR) data to estimate fire impacts, with the best results achieved using longer wavelengths, e.g. L-band (1–2 GHz, wavelength 15–30 cm) (Chuvieco *et al.*, 2019). However, their accuracy is reduced in areas of steep topography or high soil moisture levels (Tanase *et al.*, 2010), and distinguishing between a fire event and other land cover changes such as tree felling is challenging.

2.1.2 Selected sensors used for fire disturbance

Most global products rely on EO sensors with high temporal resolution, passing over every location on the globe at least once per day, and low spatial resolution (250–1000 m). The MODIS sensors on the Terra and Aqua platforms, launched in 1999 and 2002, respectively, were the first environmental satellite sensors with bands selected specifically for their fire-monitoring potential (Boschetti *et al.*, 2015). In 2011, VIIRS, another sensor type with dedicated active fire detection capabilities, was launched on board the Suomi NPP satellite (Schroeder *et al.*, 2014) and, subsequently, on the NOAA-20 platform launched in 2017. VIIRS sensors have a spatial resolution of 375 m, making them more sensitive to smaller fires than MODIS sensors (Briones-Herrera *et al.*, 2020). After the MODIS sensors have reached the end of their operational lives, the VIIRS sensors will be the primary global sources of fire detection for the EFFIS and FIRMS systems discussed in section 1.2.1. Regional or national products have been developed using higher spatial resolution sensors (Chuvieco *et al.*, 2019), such as the Enhanced Thematic Mapper Plus on Landsat-7 and Operational Land Imager (OLI) on Landsat-8 and -9, and the multispectral instrument (MSI) on Sentinel-2. These two missions provide free, easily accessible images in 7–12 spectral channels, with a spatial resolution of 10–30 m and a temporal resolution of 5–16 days.

Landsat imagery at 30 m resolution has been widely used for burn area and severity mapping, taking advantage of its medium resolution and the continuity of measurements from 1972. Landsat images have been processed via a range of techniques to derive accurate results about burned areas (dos Santos *et al.*, 2023), including image classification (Ngadze *et al.*, 2020) and principal component analysis (Elhag *et al.*, 2020), with the differenced Normalised Burn Ratio (dNBR) being one of the most widely accepted indices used for burn area delineation (Fang and Yang, 2014). However, the low temporal resolution of Landsat imagery (up to 16 days), its medium spatial resolution and the use of optical and thermal wavelengths limit its burnt area delineation capabilities, even in areas where large fires can occur and cloud-free conditions are common (Boschetti *et al*., 2015; Hawbaker *et al*., 2017).

Sentinel-2A was launched in June 2015 and was joined by an identical MSI sensor on Sentinel-2B in March 2017. Sentinel-2 MSI-A and -B are unique in that they record reflectance at a number of red-edge wavelengths, and several studies have explored this capability to define the best indices and methods for burned area mapping. Multiple studies focus on Mediterranean ecosystems, where megafires of over 7000 ha can occur, including in Spain (Fernandez-Manso *et al*., 2016; Colson *et al*., 2018; Garcia-Llamas *et al*., 2019), Portugal (Brown *et al*., 2018; Pádua *et al*., 2020) and Italy (De Simone *et al*., 2020). Many studies demonstrate the suitability of Sentinel-2 MSI images to map these burned areas (Brown *et al*., 2018) and discriminate between different levels of burn severity (Fernandez-Manso *et al*., 2016). The adequacy of the red-edge bands has been highlighted (Fernandez-Manso *et al*., 2016; Colson *et al*., 2018), as have the benefits of the high spatial resolution of the MSI imagery (Roteta *et al*., 2019). Sentinel-2 MSI data were found to slightly outperform Landsat-8 OLI data (Garcia-Llamas *et al*., 2019; Kurnaz, 2020) and were considered "a more cost-effective approach" than uncrewed aerial vehicle (UAV) imagery, giving similar results (Pádua *et al*., 2020). However, the temporal resolution of Sentinel-2 acquisitions (approximately 5 days), as well as their dependence on clear skies, is a significant limitation, and algorithms for mapping at high spatial resolution have been shown to be more likely to produce false positives (Filipponi, 2019). The combination of Sentinel-2 with other products, such as Landsat-8 images, has been shown by some to be a solution (Mallinis *et al*., 2018; Quintano *et al*., 2018). Another study used daily MODIS hotspots in sub-Saharan Africa as the input to the burned area algorithm applied to Sentinel-2 imagery, thus allowing smaller fires to be detected with greater precision (Roteta *et al*., 2019), and approximately 1.8 times more burned area was identified using the combined approach than using MODIS alone. A small number of studies have combined Sentinel-2 MSI with Sentinel-1 SAR data (e.g. Brown *et al*., 2018; Colson *et al*., 2018). Sentinel-1 has been shown to be a valuable tool for mapping burned areas (Johnston *et al*., 2018; Carreiras *et al*., 2020), but SAR sensors are extremely dependent on the ecosystems and weather conditions of the area. For example, forest fires can be mapped with a higher accuracy than fires in sparse vegetation areas (Belenguer-Plomer *et al*., 2019; Filipponi, 2019), but soil moisture significantly lowers the quality of SAR analysis, reducing the C-band sensitivity to changes resulting from fire events (Tanase *et al*., 2010; Filipponi, 2019). Obtaining clear-sky images often limits the use of optical imagery, but these data can be used to detect change up to several weeks after the fire event, whereas SAR data are most useful immediately after the fire, which can be a significant limitation when the date of the fire event is unknown (Phillipe and Levick, 2020).

2.1.3. *The indices and methods developed to detect and map active fires and burned areas*

Fires destroy features associated with chlorophyll, cell structures and plant components in the visible (0.4–0.7 μm), NIR and SWIR wavelengths. A number of indices have been developed to extract burned areas, with the ones that were found to perform best combining the NIR and SWIR bands. The Normalised Burn Ratio (NBR) and the difference between the pre- and post-fire NBRs (dNBR) are based on the combination of band 8A (0.86 μm) and band 12 (2.19 μm) for Sentinel-2, and band 5 (0.85–0.88 μm) and band 7 (2.11–2.29 μm) for Landsat-8. The NBR has been used in a variety of contexts (Chuvieco *et al*., 2019), with typically relatively low commission errors being associated with dark surfaces, waterbodies and shadows in multi-date approaches (Chuvieco *et al*., 2019). However, image acquisition for multi-date approaches requires that the two images are cloud free, ideally representing the same phenology and moisture content (Quintano *et al*., 2018). Given these limitations, a combination of images from different sensors is often used, with reflectance calibration differences being accounted for (Quintano *et al*., 2018). Given their success, it has been suggested that the discrimination of burned areas and the designation of burn severity using dNBR thresholds has become the reference method (Quintano *et al*., 2018). Some studies suggest that relative dNBR outperforms dNBR (García-Llamas *et al*., 2019; Kurnaz, 2020), while others have shown that indices that estimate chlorophyll content can be effectively used to delineate burned areas (Fernández-Manso *et al*., 2016). Alternatively, an index that exploits the mid-infrared wavelength (the Mid-infrared Burned Index (MIRBI)) can be optimal for shrub/scrubland areas (Brown *et al*., 2018; Roteta *et al*., 2019), and the relative burn ratio can be considered most suitable when the pre-fire biomass is low and variable (Morgan *et al*., 2014).

The most common multi-sensor approaches combine thermal anomalies caused by active fires and reflectance changes attributable to post-fire signals of ash or biomass loss (Chuvieco *et al*., 2019). Such thermal anomalies constitute the seeds for potential burned area regions, thus reducing commission errors, while higher spatial resolution NIR, SWIR and visible bands are used to discriminate actual burned areas and reduce omission errors. These hybrid algorithms have been widely used for many decades and form the basis of most global burned area products (Chuvieco *et al*., 2019), e.g. the ESA CCI MODIS Fire_cci v5.1 product discussed in section 1.2.2; however, the low spatial resolution of many thermal instruments causes small-scale fires to be overlooked.

The vegetation red-edge detectors on the Sentinel-2 MSI offer the opportunity to design and test new spectral indices to discriminate between different levels of burn severity (Filipponi, 2019), with the red-edge region related to chlorophyll content (band 5, 0.705 μm) and variations in leaf structure (band 7, 0.783 μm; band 8A, 0.86 μm) (Fernández-Manso *et al*., 2016). In most cases, the final method relies on a combination of indices and in some instances on classifiers, to further discriminate between different burn severity classes (Brown *et al*., 2018; Colson *et al*., 2018), but it is noted that multi-index methods have the advantage of being significantly quicker to implement than classification methods (Brown *et al*., 2018).

2.2 Burn Scar Detection Method Used in the FLARES Project

2.2.1 Need for a single-image approach at the national level

Many of the indices referred to in section 2.1.3 were trialled, separately and in combination, at different geographical locations across Ireland, encompassing different land cover types, climates and seasons (more information on Irish land cover types can be found at the CORINE Land Cover (CLC) mapping portal (CLMS, 2018) and more information on climate can be found in Walsh (2012)). At a local level for a single fire, very good results were obtained with both Sentinel-2 and Landsat-8 images; however, in considering a method that could be applied on a national scale, the limitations of different indices became apparent. Calculating either the dNBR or the difference MIRBI (dMIRBI) requires a direct comparison between a pre- and post-fire clear-sky image, but in some areas of Ireland in some years these images are scarce, with some regions viewed cloud free only once or twice a year (Figure 2.1). To overcome the need for a direct comparison, a single-image method was developed, relying on calculation of only the NBR, which made processing more efficient, but a number of filtering steps were required to remove potential false positives. Empirical tests were done to determine optimal thresholds for detecting and delineating burn scars in the context of Irish landscapes and burnt vegetation. NBR thresholds are difficult to find in the literature, as most studies use the difference variation of the NBR (i.e. dNBR). Moreover, the use of fixed threshold values is inadequate when the vegetation types and/or the geographical regions differ from those for which they were initially determined (Lasaponara *et al*., 2018). In the context of this study, using a high severity threshold was found to allow the identification of severely burnt pixels (NBR value

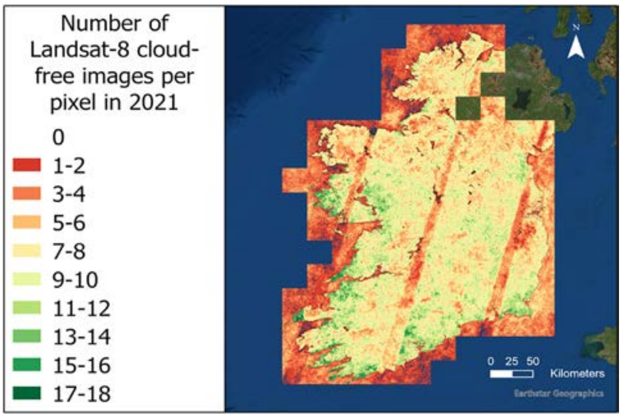

Figure 2.1. Number of Landsat-8 cloud-free images per pixel in 2021. The overlap between adjacent swaths at higher latitudes results in denser coverage, with bands of increasing width in the south, where there are fewer overpasses; upland areas typically have fewer clear-sky images.

of < –0.05) and a low severity threshold was found to best delineate the edges of the burn scar (NBR value of < 0.01 for Sentinel-2 images and < 0.2 for Landsat-8 images). Burn scars that did not contain at least one pixel classified as severely burned (based on the high severity threshold) were removed as potential misclassifications; likewise, potential burn scar areas under 4000 m^2, or 0.4 ha, were removed.

2.2.2 Filtering for potential false positives

Clouds and shadows

Sentinel-2 MSI level 2A (MSIL2A) data are provided with two cloud masks at 20 m and 60 m resolutions, but, owing to the use of inappropriate standard values, these are not adequate to fully mask clouds or their shadows in many Irish scenes. Moreover, the scene classification provided with MSIL2A often classifies burn scars as cloud shadows. However, the Sentinel-2 Water Mask (SWM) developed by Robak *et al*. (2016) was found to effectively filter out clouds and their shadows, as well as water.

Land cover

A national mask was created from a number of datasets relating to land cover and was used to eliminate areas that could be the result of potential misclassifications. It was considered impossible for genuine wildfires to occur on 21 of the CORINE2018 level 3 classes relating to artificial surfaces (1.1, 1.2, 1.3 and 1.4), open spaces (3.3), marshes (4.1.1 and 4.2) and waterbodies (5.1 and 5.2). Similarly, every "skin-of-the-Earth" object within the Ordnance Survey Ireland (OSi), now known as Tailte Éireann, PRIME2 dataset that is not vegetation was integrated into the national mask, as were 22 vegetation classes deemed unlikely to burn, e.g. burial grounds, infrastructure, leisure facilities and arable fields. Pastures and cultivated lands are areas commonly prone to false positives when looking at change in spectral signatures over time, as some agricultural practices involve total or partial clearance of vegetation. However, these are unlikely to be areas where genuine wildfires would happen, as "while single events of crop residue burning cannot be ruled out, it is not common practice in Ireland" (Duffy *et al*., 2022, p. 262). Fire service personnel also confirmed that in general only marginal, low-quality land is burned (pers. comm.). Current datasets for cultivated land in Ireland are both incomplete and inconsistent. CORINE2018 classifies 56% of Ireland's land as "pastures", while, in PRIME2, 87% of the country comes under the "field pasture" function and the "grass/clay surface" form. A conservative approach was adopted to incorporate cultivated land into the national mask by selecting PRIME2 enclosed areas identified as "field allotment", "field pasture" or "not applicable", in addition to CORINE2018 classes of "non-irrigated arable land", "pastures", "complex cultivation pattern" and "land principally occupied by agriculture with significant areas of natural vegetation". The national mask was completed with waterbody boundaries defined by the EU Water Framework Directive.

Remaining false positives

The last processing stage involved comparing the images over multiple years to refine the single-image delineation. Burned areas identified on only one Sentinel-2 image were discarded, to eliminate many of the remaining cloud shadow false positives. For each remaining pixel within the Sentinel-2 time series, the difference between the minimum Normalised Difference Vegetation Index (NDVI) found between 1 January and 30 June and the maximum NDVI for the second half of the year was calculated. Pixels were excluded where the difference between these index values was less than 0.1 or greater than 0.6, to minimise agriculture-related false positives, and the remaining burned area pixels were then merged by year. This final step based on NDVI thresholds, as well as the need for the burned area to be detected on two images, was not applied to the Landsat-8 time series because of a lack of clear-sky images for some locations in some years.

Burned area polygons whose centroid lay within an area defined as a burn scar more than four times in the period 2015–2021 were considered constant false positives and discarded. Likewise, those polygons whose centroid lay within a burn scar detected during the previous year were also discarded, to avoid over-reporting a burn scar that persisted from 1 calendar year to another. Any remaining burned area polygons whose centroid lay within the vegetation classes "arable", "arable mosaic" or "arable land" from the National Parks & Wildlife Service (NPWS) Habitat Asset Register dataset created as part of the Mapping and Assessment of Ecosystems and their

Services project (MAES15) (Parket *et al.*, 2016) were also deleted. The resulting polygons, which were thus definitively categorised as burned areas, were merged by year, and each was time-stamped with the date of first detection in the imagery and its geodesic area calculated.

2.2.3 Future improvements in land cover mapping

During the period of this research, OSi and the EPA created an Irish National Land Cover Map (INLM) based on aerial photography and satellite imagery of high spatial resolution, as well as on existing spatial datasets such as those described above. Released in March 2023, this represents a significant improvement in land cover mapping for Ireland, with a spatial resolution almost 250 times higher than CORINE and a much more detailed and nationally appropriate classification system. Five samples from the INLM, ranging in size from 550 to 1050 km^2 and covering 4200 km^2 in total, were made available to the FLARES project for testing. For these sample areas, burned area polygons that were likely to be false positives, because their centroid fell into classes labelled “bare peat”, “cutover bog”, “raised bog”, “cultivated land”, “improved grassland” or “amenity grassland”, were deleted from the final burned area dataset.

A summary of the full image-processing workflow is shown in Figure 2.2.

2.2.4 Validation

A validation dataset was created from the sources described in sections 1.1.2, 1.1.3 and 1.2.1, representing the most complete knowledge of wildfires in Ireland during the period 2015–2021. For 10 of the 878 km^2 processing tiles located across the country (Figure 2.3) and the five regions for which more detailed land cover data were available from the INLM, Sentinel-2 and Landsat-8 images were explored for each fire report available. Where a burn scar was found it was manually digitised and compared with the automated output, to assess whether it was correct and complete, or an error of commission or omission. Errors of commission are false positives and refer to instances when something is erroneously included for consideration when it should have been excluded; errors of omission are false negatives that result when something is excluded when it should have been included.

2.3 Use of Cloud Services for Data Processing

2.3.1 Copernicus Data and Information Access Service

FLARES utilised a Copernicus Data and Information Access Service (DIAS, https://www.copernicus.eu/en/access-data/dias) cloud computing platform for the duration of the project. Mundi Web Services (https://mundiwebservices.com/) was selected, as it appeared to have the best data offerings, including access to the full Copernicus and Landsat archive, and pay-as-you-use pricing.

The Ubuntu Linux-based cloud computing platform was used to run geoprocessing scripts from command-line interfaces and schedule batch jobs, as well as run an operational PostGIS server, but it became apparent that it is less well suited to remote desktop geoprocessing and analysis functions than professionally managed Microsoft Windows server environments. Moreover, although Mundi’s technical support team was helpful at times, its members failed to understand the needs of scientific researchers, with Mundi’s cloud management system aimed more at cloud computing experts and software developers. In hindsight, this cloud infrastructure was not ideal for the FLARES project.

2.3.2 Data access

In December 2021, the Mundi DIAS changed its Sentinel-2 data access policy from retaining a full archive to maintaining a rolling archive of only the most recent 24 months, as a result of a change in Copernicus DIAS funding. Mundi disseminated this information via its Twitter account, with no email or website notifications, which resulted in the FLARES team being unable to access thousands of scenes directly from Mundi. While Mundi provided an application programming interface (API) to access historical data, this was found to be erroneous, and, after several weeks of attempted contact, it offered to provide any missing data for a fee. A workaround solution was devised to download MSIL2A data directly from Copernicus Open Access Hub

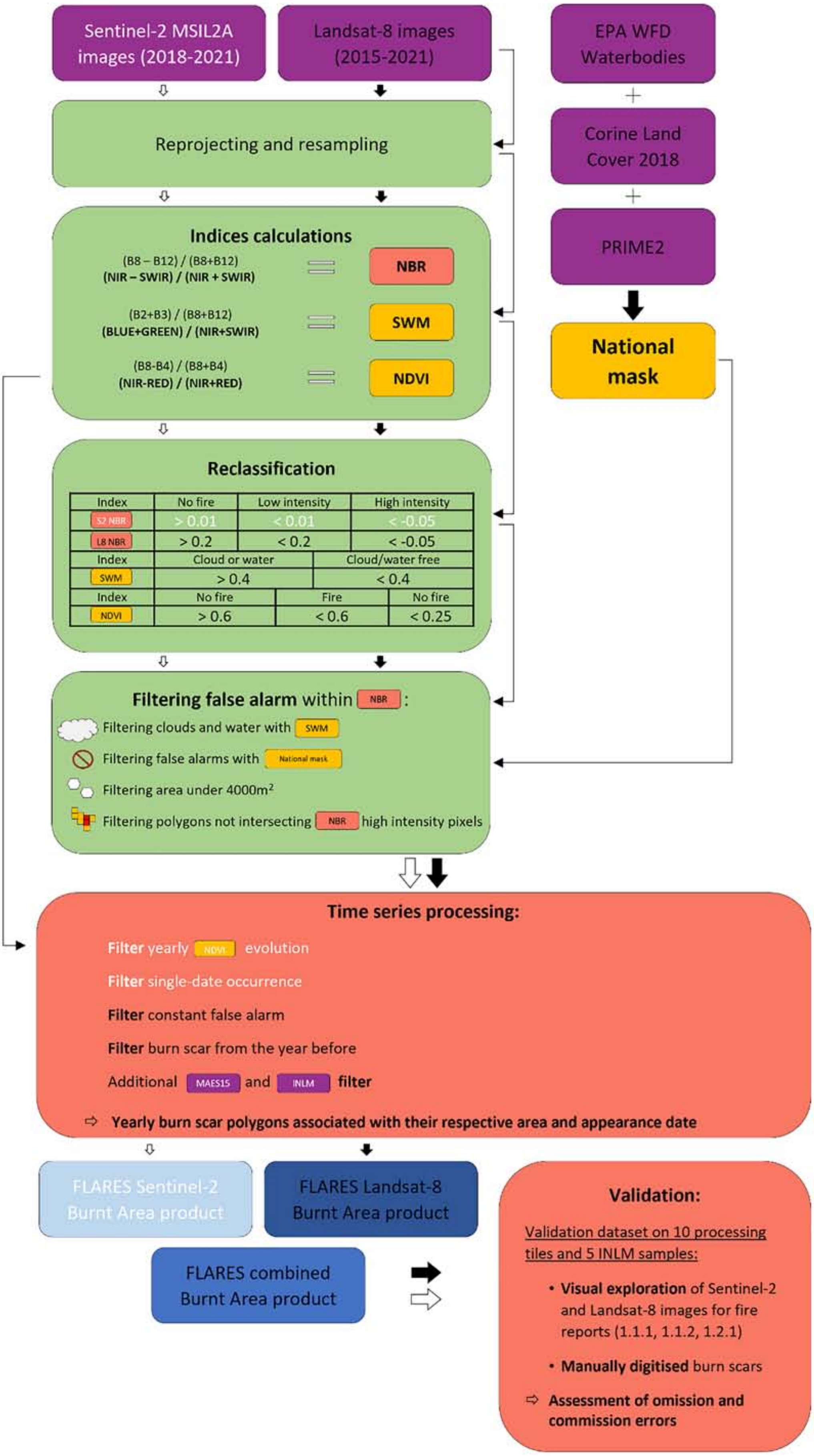

Figure 2.2. Summary of the image-processing steps taken to create the FLARES burned area products.

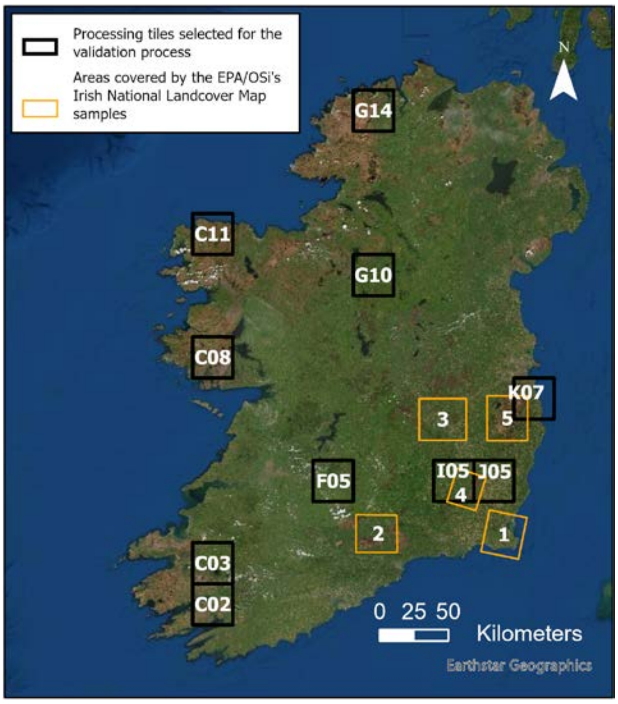

Figure 2.3. The validation areas defined by 10 image-processing tiles and five INLM samples, for which all burn scars were manually digitised.

(https://scihub.copernicus.eu/). However, the Copernicus data retention policy change also resulted in the removal of MSIL2A provisional surface reflectance data prior to April 2017 from the Open Access Hub archive. Given the limited value of the single Sentinel-2A platform and the incomplete data for the first year that the dual platforms operated, namely 2017, it was decided to focus on Sentinel-2 images from the period 2018–2021. The total number of images used per year to derive the burn scars is shown in Table 2.1.

2.4 Results of Burn Scar Mapping from Landsat-8 and Sentinel-2 Platforms

This section summarises some of the key findings from the different platforms, with some geographical locations and temporal periods highlighted where they illustrate important trends or anomalies. For a complete exploration of all the results from fire brigade call-outs, media and social media reports, and EFFIS and FIRMS hotspots, and the results from the Landsat-8 and Sentinel-2 automated approaches to burn scar mapping, the reader is directed to the freely accessible public ArcGIS online portal (https://ucc.maps.arcgis.com/apps/webappviewer/index.html?id=0a192b7e2f384c44b911e9c6eb18b5f6).

2.4.1 Burn scar mapping using Landsat-8 images

The FLARES burned area delineation method was applied to all Landsat-8 images acquired in 2015–2021 over the land mass of Ireland, and evaluated using the validation dataset described in section 2.2.3. Burn scars as small as 0.4 ha were found to be correctly identified, with 46% (or 187) of the validation burned areas perfectly delineated and only 18% fully omitted. These results were improved for areas covered by the INLM samples, where 75% of the burned areas were perfectly delineated and only 10% fully omitted. An average period of 36 days was calculated between the first and last appearance of burn scars. Burn scars created in winter had a longer period of visibility (53 days on average) than summer burn scars, which were detectable for only 25 days on average owing to faster vegetation regrowth. The size of the burn scar also had an impact on the length of time it was visible, ranging from 33 days on average for burned areas under 1 ha to about 54 days for burned areas over 50 ha.

The same validation areas were evaluated for errors of commission, i.e. when a burned area was incorrectly detected, with a national commission error of 39%. The more southerly tiles (C02, C03, I05, J05 and K07) showed commission errors ranging from 0.03% to 27%. By contrast, the north and west coastal tiles (C08, C11 and G14) were located in areas where cloud cover is more prevalent and topographical shadows more pronounced, giving commission errors of up to 91%. In the midlands (tiles F05 and G10),

Table 2.1. Number of images used per sensor per year to derive the burn scars

Sensor	2015	2016	2017	2018	2019	2020	2021	Total
Landsat-8	353	362	358	360	359	345	355	2492
Sentinel-2	–	–	–	3058	2200	3800	4095	13,153
Total	353	362	358	3418	2559	4145	4450	15,645

confusion arose with peat bogs, which have a spectral signature very similar to that of burned areas, leading to commission errors of around 55%. This commission error is reduced to 11% when only the areas covered by the INLM samples are considered.

The amount of land burned each year varied considerably, with a range during the study period of 5206 ha in 2019 to 31,507 ha in 2015 (Figure 2.4). Of the years studied, 2015 was exceptional, as the next highest burned area was 18,179 ha, occurring in 2017; however, the time series is too short to draw any conclusions on longer-term trends. This pattern is not dissimilar to that recorded by other methods and displayed in Figure 1.6, with 2015 and 2017 being identified as the years in which the largest areas of land were burned; however, the magnitude of those areas is estimated to be considerably larger by the FLARES project results, given the ability to create a more complete national map of burned areas, including areas as small as 0.4 ha.

Notably, the largest burned area reported by other methods was in 2017, with the scaling method for the National Inventory Report determining a total burned area of 9516 ha. By comparison, in 2015, the National Inventory Report recorded only 1826 ha of burned area, just 6% of the total estimated by FLARES. When burned areas are considered by county, it is evident that County Kerry had some of the most extensive burned areas each year (yellow bars in Figure 2.4), with nearly 27% of the total burned area in 2015 and 24% in 2021 as a result of large fires in Killarney National Park. In 2017, however, County Galway (dark-purple bars) had a significant burned area, which can be attributed to a fire in Cloosh Valley, with nearly 5000 ha burned, and in County Donegal (mid-green bars) a number of fires led to burned areas in excess of 300 ha.

2.4.2 Burn scar mapping using Sentinel-2 images

The same validation process was applied to the FLARES Sentinel-2 burnt area results for the period 1 January 2018 to 31 December 2021, during which both platforms were fully operational; thus, equivalent results can be compared between years. Prior to inclusion of Sentinel-2B data, omission errors were high, but, after 2018, 47% of the burned areas were perfectly delineated and only 10% were fully omitted on a national scale. These results were improved in INLM areas, where 82% of the burned areas were perfectly delineated and only 0.01% fully omitted. A similar study using Sentinel-2 images to delineate burned areas in Italy in 2017 (Filipponi, 2019) reported a 40% omission error, considerably higher than that achieved by the FLARES method, but the Italian study was reliant on just the single Sentinel-2A platform for some of the year, and therefore the frequency of overpasses was considerably lower than in the period used to validate the FLARES Sentinel-2 results, until Sentinel-2B became operational in summer 2017.

There were 54 days on average between the first and the last appearance of burn scars on Sentinel-2 images. As with the Landsat-8 results, burn scars

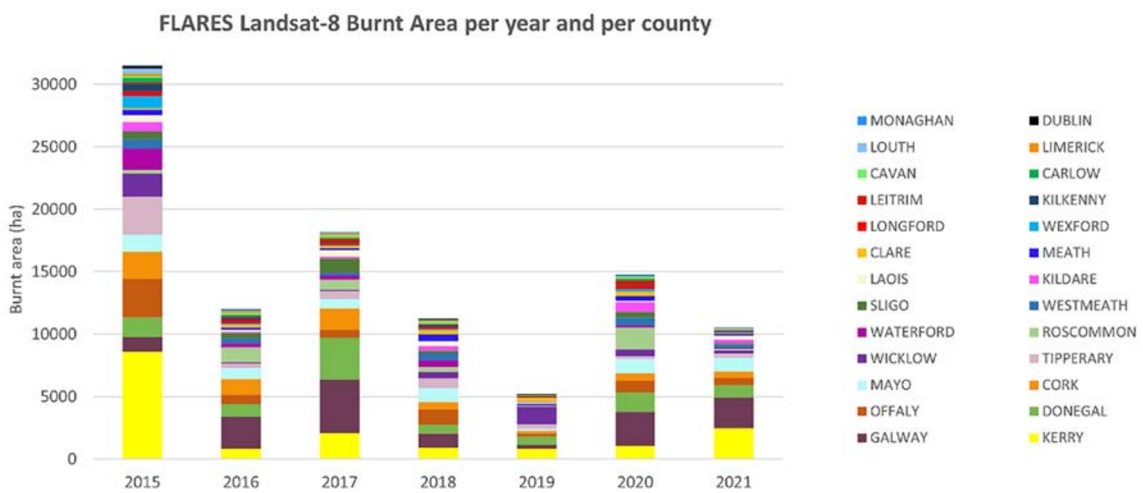

Figure 2.4. The total burned area estimated for each county per year by applying the FLARES method to Landsat-8 images.

appearing in the winter had a longer visibility time, of 101 days on average, than burn scars appearing during the summer, which were detectable for only 33 days on average. For burned areas of less than 1 ha, burn scars persisted for 30 days on average, increasing to about 84 days for burned areas of over 50 ha. While the Landsat-8 and Sentinel-2 results show the same trend, these differences are a function of the higher temporal and higher spatial resolutions of Sentinel-2. With a shorter revisit time, there is a greater likelihood of Sentinel-2 capturing cloud-free images and thus generating a more detailed record of vegetation recovery from the burn event. The higher spatial resolution of Sentinel-2 than of Landsat-8 (effectively nine Sentinel-2 pixels to every one Landsat-8 pixel) allows smaller patches of charred land to be detected, meaning that burn scars are evident for a longer period in Sentinel-2 imagery. Fewer commission errors were identified in the Sentinel-2 dataset than in the Landsat-8 dataset on a national scale, with 23% of the recorded burn scars not genuine products of a fire event. The more southerly tiles (C02, C03, I05, J05 and K07) showed commission errors ranging from 0.09% to 25%. By contrast, the north and west coastal tiles (C08, C11 and G14), which are in areas that are more cloudy and more mountainous, had commission errors of up to 97%. In the midlands (tiles F05 and G10), commission errors were around 46%, with misclassification of peat bogs, as seen in the Landsat-8 results. In the INLM areas, Sentinel-2's commission errors were reduced to only 14%, slightly higher than those seen for Landsat-8.

In summary, Sentinel-2's higher spatial and temporal resolutions enable better detection and delineation of burn scars and fewer false positives on the national scale than Landsat-8. However, the multi-date and thresholding approach taken for the Sentinel-2 data makes it a more conservative product, and, for the INLM samples where false positives arising from misclassification of peat bogs can be eliminated, the Landsat-8 results are slightly more accurate.

The areas burned according to the Sentinel-2 results are similar to those according to the Landsat-8 results for 2018–2021 (Figure 2.5), with 2019 again showing the lowest total extent (5067 ha as opposed to 5267 ha). For 2020 and 2021, however, the more conservative Sentinel-2 product shows only 45–52% of the total burned area defined by the Landsat-8 images, thus making the Sentinel-2 burned area figures more reliable on a national scale than the Landsat-8 values.

When considered by county, the significance of the Killarney National Park fire in County Kerry in April 2021 is again evident, and an even larger total burned area is apparent in 2018, when there were a number of fires in the county in February. These burned areas were not evident when the FLARES method was applied to Landsat-8 images (Figure 2.4), as no clear-sky imagery was available at the time of the event, and, by the time a cloud-free image was acquired from that platform, the vegetation had started to regenerate. The timing and the frequency of satellite overpasses are thus critical for capturing burn scars while they are still fresh.

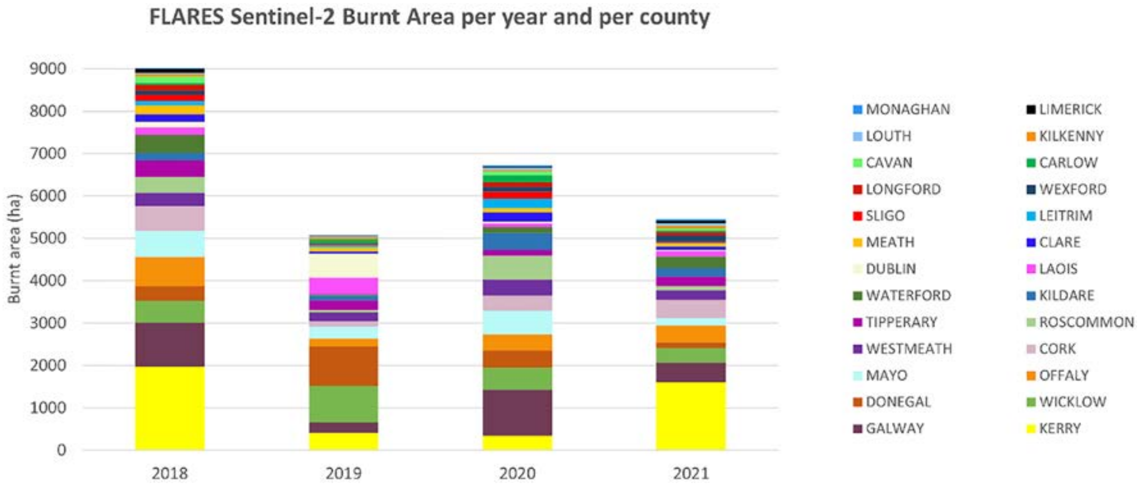

Figure 2.5. The total burned area estimated for each county per year by applying the FLARES method to Sentinel-2 images.

2.4.3 Amalgamation of results from burn scar mapping using Sentinel-2 and Landsat-8 images

When the results from the Sentinel-2 and Landsat-8 image processing were combined (Figure 2.6), 53% of the burned areas were found to be perfectly delineated, and only 0.05% fully omitted on a national scale. Over the INLM areas, the results improved further, indicating that 93% of burn scars were perfectly delineated, with only 0.01% fully omitted. These results further support the observations made about the timing of the Sentinel-2 and Landsat-8 images, and demonstrate that the length of time between the fire and the next cloud-free image is of more importance than spatial resolution when comparing two medium-resolution instruments. Although the number of omissions decreases when the results from the two sensors are combined, the commission errors are similar to those for Landsat-8, with a 39% error rate on a national scale, falling to 11% over INLM areas. The remaining false positives were mainly related to bare peat (eroded peat and commercial bogs), agricultural land cover changes, forest clearcuts and topographical shadows.

Much better results are achieved when only upland areas more than 150 m above sea level are considered. The commission errors for Landsat-8 fall to 27% on a national scale and 0.05% in INLM areas, and for Sentinel-2 they are 11% for both validation datasets. The combination of the two sets of satellite-derived burn scars shows commission errors of 28% and 0.06% on a national scale and in INLM areas, respectively. The EPA/OSi INLM input has proven invaluable to filter out areas of peat bog and cultivated land, which explains the difference between the national validation figures and those relating to the areas covered by the samples provided by the EPA/OSi. When the INLM is available nationally, a further increase in the accuracy of the results is anticipated.

2.4.4 Comparing burned area results from all satellite methods

Table 2.2 and Figure 2.7 summarise the annual burned area estimates using a number of EO approaches. The National Inventory Report, EFFIS and ESA CCI approaches underestimate the total burned area, which is not surprising given that they are based on detecting active fires in excess of 30 ha, whereas the FLARES method can extract burned areas as small as 0.4 ha. The Sentinel-2-derived burned area values are consistently lower than the Landsat-8 values because of the differences in approach adopted for the two datasets, to take into account the fewer overpasses of Landsat-8. As highlighted in section 2.4.2, where INLM data are not available to filter the Landsat-8 results, there are more commission errors and therefore the area defined as burned is larger for those images. Given the lack of national INLM data during the FLARES project, the more conservative Sentinel-2 product was considered more reliable on a national scale.

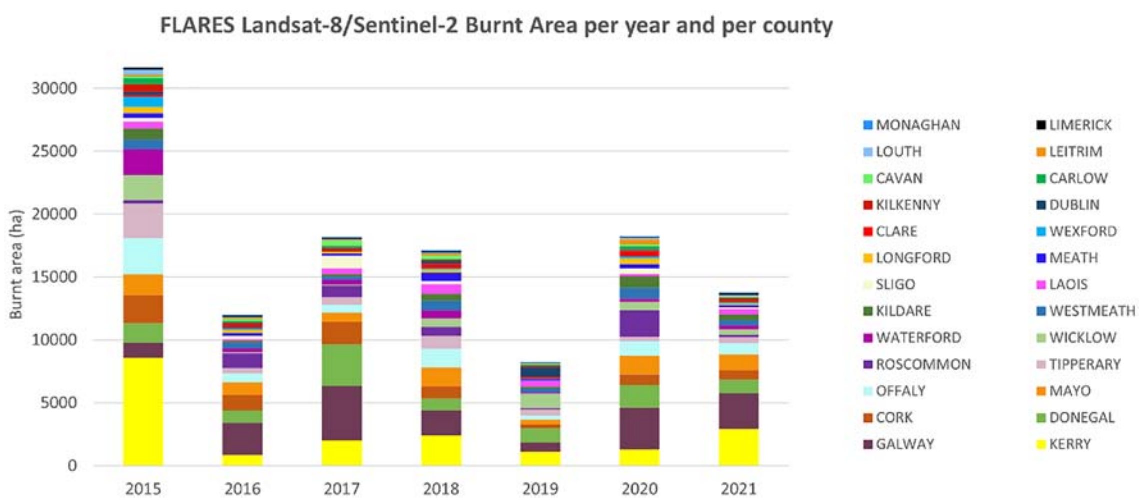

Figure 2.6. The total burned area estimated for each county per year by applying the FLARES method to combined Landsat-8 and Sentinel-2 results.

Table 2.2. National values of burned area per year for the different satellite-based products

	Burnt area (ha)						
Product	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
National Inventory Report (expert judgement)	1826	436	9516	2810	1097	1086	Data not yet available
EFFIS (satellite based)	6807	1177	7241	2868	2898	3262	3609
ESA CCI (satellite based)	8739	752	8333	722	258	1600	Data not yet available
FLARES Landsat-8 product	31,507	12,041	18,179	11,263	5206	14,778	10,517
FLARES Sentinel-2 product	No data	No data	No data	9023	5067	6720	5451
FLARES combined product	No data	No data	No data	17,133	8211	18,263	13,767

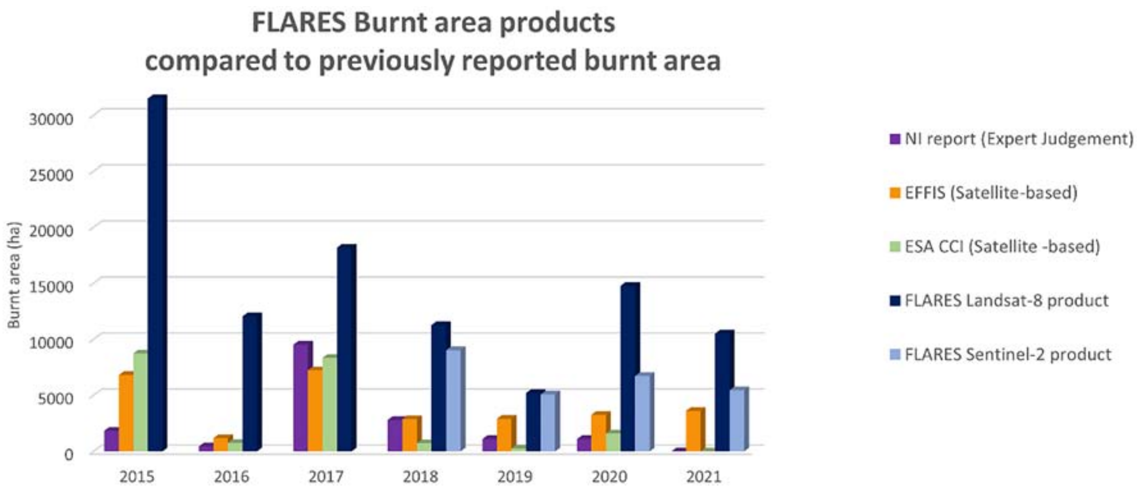

Figure 2.7. Comparison of annual area burned estimates using different methods, illustrating that the FLARES estimates are consistently higher. NI report, National Inventory Report.

2.5 Conclusions

Freely available satellite imagery of medium spatial resolution can be used to successfully map burn scars as small as 0.4 ha. The FLARES project results estimated burned areas to be many times greater than the burned areas estimated by other products, which focus on active, larger fires mapped in near-real time.

3 Estimates of Land Cover Burned

3.1 Mapping Gorse in Ireland

As discussed in sections 1.1.1 and 1.1.3, there is a perception in Ireland that many wildfires occur on land covered by gorse. Yellow gorse (*Ulex europaeus*), also known as *aiteann gallda* in Ireland, is a prolific plant in Irish landscapes and mythologies. This thorny evergreen shrub with bright yellow flowers is abundant in Ireland, and is usually associated with heathland habitats (Rees and Hills, 2001). The main flowering period in Ireland is in April and early May, but flowering can start in February, and some flowers can be found at almost all times (Sutton, 2022). However, gorse is also listed as one of the top 100 most invasive plants by the International Union for Conservation of Nature. Moreover, gorse produces volatile organic compounds (Boissard *et al*., 2001) and has a high concentration of oil within its branches (MacCarter and Gaynor, 1980), making it particularly flammable in dry conditions. Therefore, as well as being an invasive species, it is also considered a fire hazard. Burning is the most common management technique for removing gorse (Rees and Hills, 2001), even though fire may stimulate the germination of seeds present in the ground or remove competing vegetation (Clements *et al*., 2001), and in Irish uplands gorse burning is an established practice of farmers for improving forage, among other benefits (Carroll *et al*., 2021).

While gorse burning is widespread, no habitat maps focus on this species as a specific class, with the only existing dataset being a distribution map from the National Biodiversity Data Centre of the number of *U. europaeus* records within 10 km grid squares. Species mapping on a national scale can be costly and time-consuming; however, remote sensing can play a useful role in discriminating between and mapping the coverage of some species that have distinctive reflectance properties. The bright-yellow flowers of gorse in April and May support discrimination of this shrub from other land cover types on optical satellite images of high spatial resolution. As discussed in section 2.1.2, the MSI sensors on the Sentinel-2 platforms are designed for vegetation mapping, and, for the first time, the potential for creating a national gorse map for Ireland now exists.

A multi-index method was developed relying on thresholds for the NDVI, the Normalised Difference Yellow Index (NDYI), calculated from green and blue wavelengths (band 2, 0.49 µm, and band 3, 0.56 µm, for Sentinel-2), and the Green-Red Vegetation Index (GRVI) (band 3, 0.56 µm, and band 4, 0.67µm, for Sentinel-2). The yellow flowers of gorse are distinguished from other types of vegetation by high NDYI (>0.35) values and low NDVI (<0.7) and GRVI (<0.05) values. Only those images from April and May with less than 30% cloud cover for the period 2018–2021 were processed. Remaining cloud artefacts were filtered out using SWM and MSIL2A scene classification data (both discussed in section 2.2.2), and waterbodies were removed using the EPA's Water Framework Directive dataset (https://data.gov.ie/dataset/water-framework-directive-water-catchments). All gorse polygons that appeared on multiple images within the defined time period were merged to constitute a national gorse map.

To validate this map, gorse patches in six areas across the country, covering 1650 ha in total, were manually digitised using WorldView images of very high spatial resolution in ArcGIS (Figure 3.1), from which 71% of gorse patches above 0.06 ha (six 10 × 10 m Sentinel-2 pixels) were detected. Although 59% of the total gorse area was omitted, this was primarily composed of very small areas or narrow hedgerows not always visible at the spatial resolution of the Sentinel-2 images, owing to the mixture of land cover types in the pixels. A second validation dataset was created by manually digitising gorse patches using Sentinel-2 images for the same six locations. This showed that 70% of gorse patches above 0.04 ha (four Sentinel-2 pixels) were detected, and only 21% of the digitised polygons were omitted. Moreover, only 7% of the patches identified as gorse by the automated approach were found to be areas that contained no gorse on the ground, indicating that this approach is a very reliable indication of the presence of gorse in Ireland. In total,

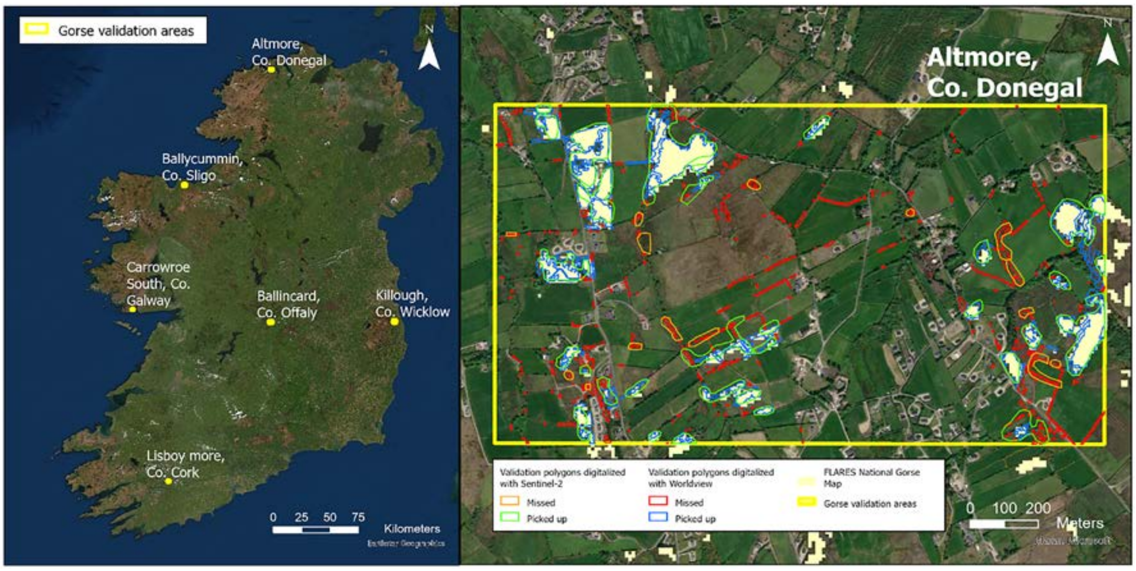

Figure 3.1. Locations selected for validation of the gorse map (left) and an example of the gorse detection results (right). Solid yellow pixels represent locations identified as gorse by the automated method, green outlines represent manually digitised gorse locations from Sentinel-2 imagery and blue outlines represent manually digitised gorse locations from the WorldView imagery, which is of higher spatial resolution. Orange and red outlines represent digitised gorse locations that were not detected by the automated method for Sentinel-2 and WorldView, respectively, most often very small or narrow strips.

the automated approach identified 180 km^2 of gorse in Ireland.

3.2 Vegetation Cover Datasets for Identifying Vegetation Burned

As discussed in section 2.2.4, the EPA/OSi INLM provides a complete and comprehensive land cover map; however, as of the start of 2022, full nationwide coverage was not available, requiring other datasets to be collated to produce the most detailed national vegetation cover map. The datasets chosen, in order of priority where more than one was available for a single location, and their contributions to the final map are shown in Table 3.1 and Figure 3.2.

Table 3.1. Datasets used in creating the national vegetation cover map

Data source (listed in order of priority)	Contribution to final land cover map (%)	Comments	Link to dataset
FLARES national gorse map	0.25	Described in section 3.1	https://ucc.maps.arcgis.com/apps/webappviewer/index.html?id=0a192b7e2f384c44b911e9c6eb18b5f6
EPA/OSi INLM samples	5.64	National map released March 2023	Available from the OSi
EPA TaLAM project ALOS	0.43	EPA project 2013-SL-MS-1	https://www.epa.ie/publications/research/waste/Research_Report_254.pdf
EPA TaLAM project Suir	3.98	EPA project 2013-SL-MS-1	https://www.epa.ie/publications/research/waste/Research_Report_254.pdf
NPWS Habitat Asset Register (MAES15)	84.72	Variety of original sources traceable via the link	https://dahg.maps.arcgis.com/apps/MapSeries/index.html?appid=cb5040a4a19645b6b424bed940c54fff
CORINE 2018	4.93	https://data.gov.ie/dataset/corine-landcover-2018	https://data.gov.ie/dataset/corine-landcover-2018
CORINE 2012	0.05	Used for land in burnt class of CORINE 2018	https://data.gov.ie/dataset/corine-landcover-2012

TaLAM, Towards Land Cover Accounting and Monitoring.

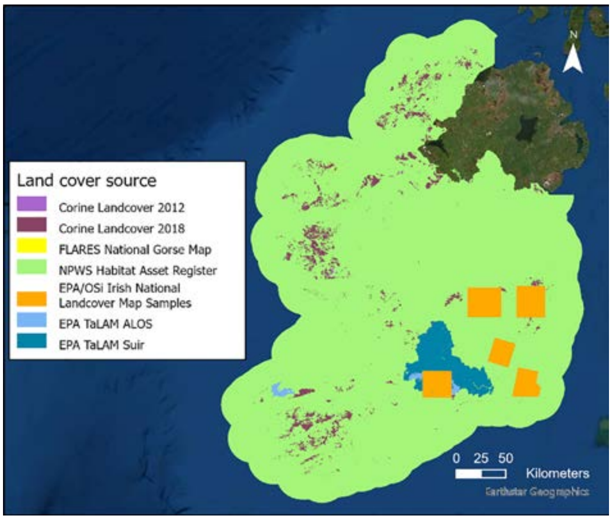

Figure 3.2. Sources of information used to produce the national vegetation cover map.

3.3 Calculation of Annual Burned Land Cover Types from Satellite Data

The environmental impacts of fires can be evaluated based on the nature of the vegetation burned. Each vegetation species or habitat constitutes a different type of biomass, with different physical and environmental properties, for which combustion properties and the resulting emissions will vary. Using the national vegetation cover map presented in section 3.2, annual burned areas of different land cover types were calculated using the FLARES burned area products described in section 2.4. Figure 3.3 shows the area of each vegetation class burned each year from 2015 to 2021, based on the burn scars identified in the Landsat-8 imagery. The proportions of each class burned each year were very similar for the Sentinel-2 and the combined products, with the total proportions for the combined dataset for 2018–2021 shown in Figure 3.4. The vegetation class for which the largest burned area was recorded was the "heavily improved grassland" class from the NPWS Habitat Asset Register (MAES15), accounting for 25% of the total burn scar area. This class constitutes 49% of the national vegetation cover map created for FLARES. The land cover types for which the next largest burned areas were recorded were "peat bog", "raised bog", "blanket bog – active" and "blanket bog – low level", all of which are essential for biodiversity and play a crucial role in sequestering carbon dioxide from the atmosphere and acting as long-term carbon stores. After these, the remaining land cover types for which the largest burned areas were recorded were "moors and heathland" and "sparsely vegetated areas". Similarly to active raised bogs, heath habitats are designated as being of international importance under the 1992 EU Habitats Directive because of their limited distribution in Europe (Coll *et al*., 2016). These upland habitats are critical for ground-nesting birds, such as red grouse and skylarks, which makes these birds very vulnerable to wildfires. Section 40 of the Wildlife Act 1976 makes it an offence to damage vegetation on uncultivated land during the bird nesting season, from 1 March to 31 August each year. However, 70% of the fires in the validation database described in Chapter 1 occurred within this period, although the precise dates

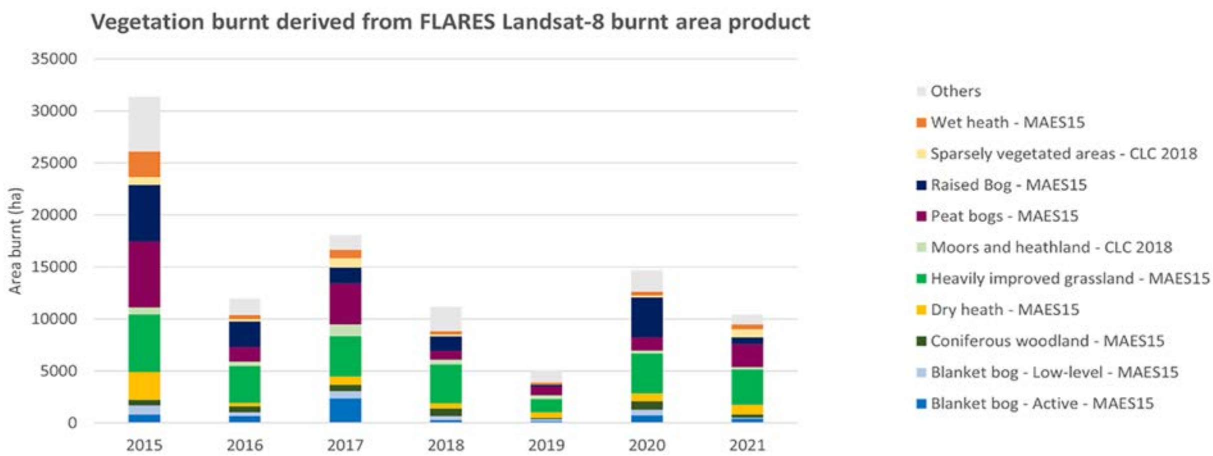

Figure 3.3. Area of land of each vegetation class burned each year from 2015 to 2021 based on the burn scars identified in Landsat-8 imagery.

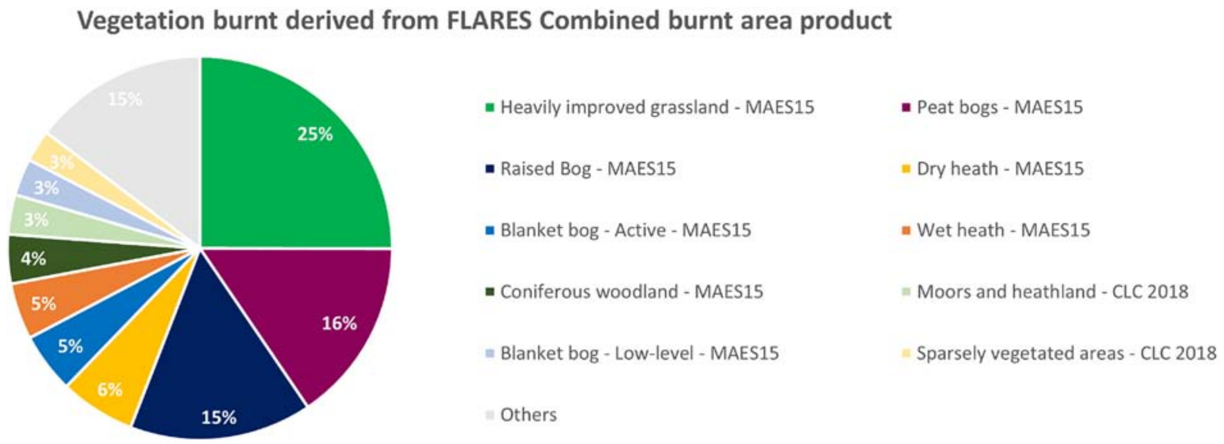

Figure 3.4. Proportions of the total burned area by vegetation class for the burn scars identified using the combined Landsat-8 and Sentinel-2 product for 2018–2021.

of the fires identified from the Landsat-8 and Sentinel-2 imagery are unknown, as the image dates can post-date fire events by up to several weeks.

Forest fires represent a very small minority of Irish wildfires, with coniferous woodland constituting only 4% of the total burned area, and, even in years when significant forest fires have occurred, such as the Cloosh Valley fire in County Galway in 2017, these fires have not significantly affected the overall burned area.

3.4 Habitats Burned in Protected and Upland Areas

The burned areas identified in the Landsat-8, Sentinel-2 and combined datasets were overlaid on maps showing the NPWS boundaries for Natural Heritage Areas, Special Protection Areas and Special Areas of Conservation (downloaded from https://www.npws.ie/maps-and-data). The total combined area protected by these three designations is 1,512,053 ha, of which between 0.2544% and 0.3622% was burned

Table 3.2. Proportion of protected land in Ireland burned each year, and the area and proportion of burned land that lies within protected areas, as calculated from Landsat-8, Sentinel-2 and combined data burn scar mapping

	2015	2016	2017	2018	2019	2020	2021
Total protected area: 1,512,053 ha							
Proportion burnt (%)	–	–	–	0.3573	0.2544	0.3622	0.3442
Landsat-8 dataset							
Total burnt area (ha)	31,507	12,041	18,179	11,263	5206	14,778	10,517
Burnt area in protected areas (ha)	13,335	4141	7486	3114	2629	4598	4222
Proportion of burnt area in protected areas (%)	42.3	34.4	41.2	27.7	50.5	31.1	40.1
Sentinel-2 dataset							
Total burnt area (ha)	–	–	–	9023	5067	6720	5451
Burnt area in protected areas (ha)	–	–	–	3500	2480	2122	2334
Proportion of burnt area in protected areas (%)	–	–	–	38.8	48.9	31.6	42.8
Combined dataset							
Total burnt area (ha)	–	–	–	17,133	8211	18,263	13,767
Burnt area in protected areas (ha)	–	–	–	5403	3847	5477	5204
Proportion of burnt area in protected areas (%)	–	–	–	31.5	46.9	30	37.8

–, no data available.

each year based on the combined Landsat-8 and Sentinel-2 dataset (Table 3.2). However, a relatively large proportion of land burned in Ireland each year lies within protected areas (Table 3.2). According to the Landsat-8 dataset, the area of land burned that lies within protected areas ranges from 2629 ha (2019) to 13,335 ha (2015), whereas, based on the combined product, this area is between approximately 5200 ha and 5500 ha per year, with the exception of 2019 (approximately 3850 ha). The proportion of the total burned area that lies within protected areas varies from year to year, but, interestingly, 2019, which was a year with very low total burned area according to all the methods, saw about half of all burned land lying within areas with protected status. This highlights the potentially deleterious environmental impacts of wildfires in Ireland and the challenge of managing nationally and internationally rare and fragile habitats that are the subject of conservation and protection policies, and often also serve economic and leisure functions.

3.5 Conclusions

Irish wildfires are often referred to as "gorse fires". For the first time, an automated approach to mapping the locations of gorse from satellite imagery has been taken, revealing 180 km^2 of gorse in Ireland. However, while gorse may burn in upland areas, many wildfires do not burn gorse, and one-quarter of the land burned by wildfires each year is classed as "heavily improved grassland" in the NPWS Habitat Asset Register. Significantly, from the perspective of ecosystems services, biodiversity and management, between 30% and 50% of burned land each year lies within the boundaries of Natural Heritage Areas, Special Protection Areas and Special Areas of Conservation.

4 Calculation of Emission Factors

4.1 Use of Standard Values and Limitations for Ireland

Wildfire events convert large amounts of vegetation mass into pollutants that enter the atmosphere. The most notable of these pollutants are carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), methane (CH_4), ozone (O_3), volatile organic compounds (VOCs) and particulate matter (PM). PM contains a mixture of inorganic and organic species, including black carbon (BC) and polycyclic aromatic hydrocarbons (PAHs). CO_2, PM, CH_4 and BC are of concern primarily in terms of their climate-forcing effects, whereas PM, BC, NO_x and PAHs adversely affect air quality and health.

Wildfire emissions depend on vegetation type and combustion conditions. Generally, higher temperatures and greater oxygen availability are associated with more complete combustion and the emission of products that are more highly oxygenated. After release, emission products undergo chemical processing, or "ageing", in the atmosphere. When combustion is inefficient, relatively high amounts of organic matter are emitted as gases (VOCs) and particles (e.g. soot). The atmospheric oxidation of VOCs leads to the formation of secondary PM, which can add significantly to the total particle mass released by a fire.

Total emissions (E_X) from a wildfire (equation 4.1) depend on the area burned (A), fuel loading (FL), combustion completeness (CC) and a fuel-specific emission factor (EF_X):

$$E_X = A \times FL \times CC \times EF_X \quad (4.1)$$

where EF_X is the mass of the pollutant emitted relative to the mass of biomass burned from vegetation X. EFs are measured in units of mass of pollutant emitted (g) per kilogram (kg) of vegetation burned, and vary depending on the specific type of vegetation burnt, fuel moisture and combustion conditions. Fuel moisture is the amount of water in a fuel (vegetation) available to a fire, and is expressed as a percentage of the dry weight of that specific fuel.

4.1.1 Emission factors in the literature

EFs can be determined by field studies that measure the relative concentrations of the target species and of CO_2; however, field measurements are difficult to conduct and may be strongly influenced by factors such as weather conditions. The sampling of controlled burns shows that there can be significant differences in emissions, with wildfires emitting high amounts of PM_1 (particulate matter of diameter $\leq 1\,\mu m$), with an average EF that is more than twice the EF for controlled fires (Liu *et al*., 2017). Alternatively, emissions can be measured directly from a known amount of fuel burned under laboratory conditions, but the accuracy of the calculated EFs depends on how closely laboratory burning simulates wildfire combustion.

A comprehensive summary of EFs can be found in Andreae (2019). Most of the studies on which these EFs are based were conducted in arid regions of Africa, Australia and the Americas (Yokelson *et al*., 2011; Abdulraheem *et al*., 2020), with a smaller number in temperate (Guérette *et al*., 2018), boreal (Singh *et al*., 1994 ; Bertschi *et al*., 2003) and tropical (Andreae *et al*., 1988; Yokelson *et al*., 2007) forests. Studies with a European focus include Alves *et al*. (2010, 2011), on the Mediterranean region and Iberian peninsula, and Iinuma *et al*. (2007), on European conifers and German peat. However, in Ireland, only 4% of the area burned from 2015 to 2021 was coniferous forest (section 3.3). Moreover, the climate in Ireland is typified as temperate oceanic ("Cfb" under the Köppen climate classification system). As a result, the majority of EFs reported in the literature are unsuited to Irish upland fire events.

4.1.2 Emission factors for Irish vegetation species

EFs from a wide variety of fuels found in wildland habitats have been studied in laboratory settings (Cereceda-Balic *et al*., 2017; Abdulraheem *et al*., 2020), but not from species commonly found in Irish upland and heath habitats. Gorse (*U. europaeus*) is a species closely associated with fires in Ireland, as discussed in section 3.1. Other species common to Irish uplands that burn during wildfire events include purple moor grass (*Molinia caerulea*, also called *fionnán* in Ireland), a widespread, deciduous grass species that forms dense tussocks that burn quickly under dry conditions, and heather (*Calluna*), a more woody evergreen species (pers. comm.). EFs for these three common Irish species are needed to more accurately estimate emissions from Irish wildfires, and the FLARES project is the first to derive and report EFs for the fuels characteristic of Irish habitats.

4.2 Laboratory Measurements of Emission Factors for Gorse, Purple Moor Grass and Heather

4.2.1 Experimental set-up

Measurements for the calculation of EFs were conducted in Leipzig, Germany, at the Leibnitz Institute for Tropospheric Research (TROPOS). The facilities enabled the measurement of primary (direct) emissions from the burn experiments and the study of the post-emission atmospheric processing of these emissions in an atmospheric simulation chamber. The Leipzig Biomass Burning Facility (LBBF) consists of a conventional wood stove connected to gas and aerosol sampling instrumentation via a dilution stage (Figure 4.1). Measured concentrations of gases and aerosols were converted into absolute masses by considering sample dilution and the rates of gas flow through the system. The LBBF was connected to a 9 m^3 atmospheric simulation chamber (atmospheric chemistry department chamber (ACD-C)), to study the atmospheric processing of combustion emissions.

Samples of gorse, heather and purple moor grass were collected in County Cork 3 weeks prior to experiments, air dried and shipped to Germany. Heather and gorse were sampled as green branches and purple moor grass was collected from dried tussocks to best represent realistic fuel conditions.

4.2.2 Results

EFs were established by taking the average of the results of four replicate experiments for each vegetation type (Table 4.1). Primary EFs were determined for CO, CO_2, CH_4, sulfur dioxide (SO_2), NO, $PM_{2.5}$ (particulate matter of diameter ≤ 2.5 µm), total PM (TPM), BC, organic carbon (OC), elemental carbon (EC) and total carbon (TC), and for the molecular markers of biomass burning, namely levoglucosan, mannosan and galactosan.

Initial EFs derived for CO_2 and CH_4 were implausibly high. Subsequent calibration of the instrument showed that initial concentration measurements were 45% higher than the actual concentrations, and a post-measurement correction was applied. EF values based on the corrected concentrations are reported in Table 4.1. These EFs were in broad agreement with those reported by Andreae (2019) for savanna

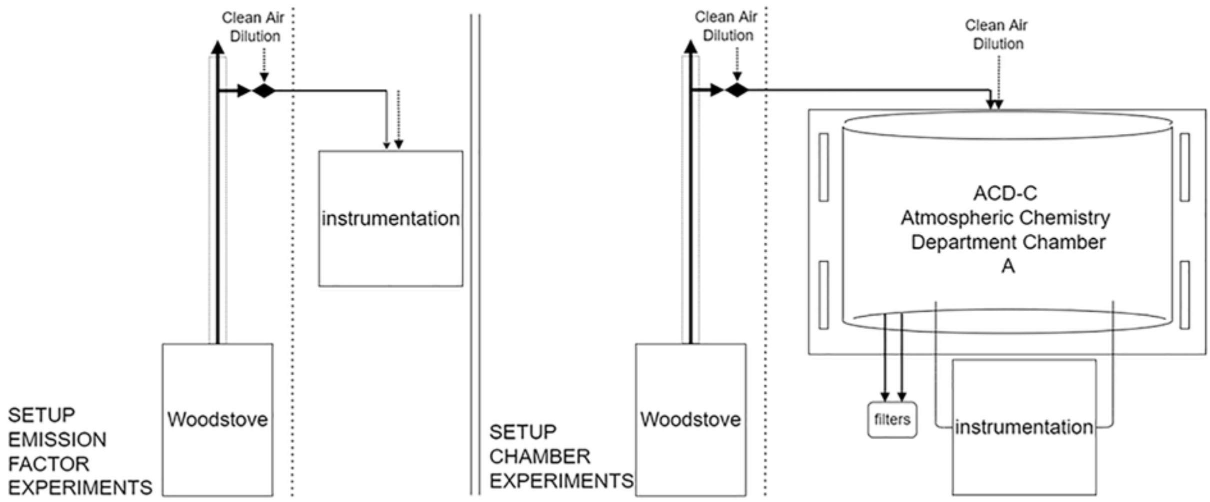

Figure 4.1. Schematic of the LBBF facilities for measurement of primary EFs (left) and atmospheric ageing (right).

Table 4.1. Modified combustion efficiency and pollutant EF values for heather, purple moor grass and gorse established during the FLARES experiments

	Heather (*Calluna*)		Purple moor grass (*M. caerulea*)		Gorse (*U. europaeus*)		Savanna and grassland (Andreae, 2019)[a]		
Derived value	Average	SD	Average	SD	Average	SD	Average	SD	Number sampled
MCEs	0.97	0	0.98	0	0.95	0	*0.94*	*0.02*	*49*
Pollutant EFs ($g\ kg^{-1}$)									
CO	42	6	27	2	80	7	*69*	*20*	*50*
CO_2	1167[b]	51[b]	1558[b]	54[b]	1442[b]	87[b]	*1660*	*90*	*31*
CH_4	NA	NA	0.21[b]	0.06[b]	2.52[b]	0.38[b]	*2.7*	*2.2*	*49*
SO_2	1.38	0.46	1.08	0.58	1.68	0.39	*0.47*	*0.44*	*12*
NO_x as NO	4.46	0.39	5.51	0.35	6.85	0.56	*2.5*	*1.3*	*18*
$PM_{2.5}$	3.35	0.71	1.37	0.17	7.73	0.97	*6.7*	*3.3*	*20*
TPM	4.35	0.4	4.26	0.58	14.33	0.15	*8.7*	*3.1*	*11*
BC	0.23	0.06	0.18	0.05	0.5	0.08	*0.53*	*0.4*	*18*
OC	1.44	0.16	1.26	0.37	5.43	0.81	*3*	*1.5*	*15*
EC	0.89	0.25	0.81	0.19	2.23	0.44	*0.53*	*0.4*	*18*
TC	2.33	0.36	2.07	0.28	7.65	0.39	*3.2*	*1.5*	*10*
Levoglucosan	0.69	0.22	1.27	0.51	1.38	0.31	*0.05*	*NA*	*1*
Mannosan	0.06	0.02	0.09	0.04	0.05	0.01	*NA*	*NA*	*NA*
Galactosan	0.08	0.03	0.09	0.04	0.13	0.04	*NA*	*NA*	*NA*

[a]Values from Andreae (2019) for savanna and grassland (in italics) are included for comparison.
[b]EF measured but not used for total emission calculations.
NA, not available; SD, standard deviation.

and grassland, the category closest to the three Irish vegetation types in terms of their relatively low amount of woody material. The CO_2 EFs for purple moor grass ($1558\ g\ kg^{-1}$) and gorse ($1442\ g\ kg^{-1}$) were close to the value of $1660\ g\ kg^{-1}$ reported by Andreae (2019), but the value for heather ($1167\ g\ kg^{-1}$) was lower than for the other fuel and grassland values. This difference may have arisen from the large amount of fuel left unburnt during the experiments. Gorse emitted more pollutants than heather and purple moor grass. It was the woodiest fuel, and had a relatively high VOC content. This is consistent with firefighter observations (pers. comm.) that gorse burns fiercely with large flames, probably owing to its high oil content.

How complete a burn is can be quantified using the modified combustion efficiency (MCE) equation (equation 4.2):

$$MCE = (C)CO_2/(C)CO_2 + (C)CO \qquad (4.2)$$

where C is the concentration of CO_2 or CO (Ward and Radke, 1993). High MCE values (> 0.95) are associated with flaming combustion conditions and lower values (< 0.95) are indicative of smouldering combustion conditions. MCE values during the FLARES experiments ranged from 0.95 to 0.99. High MCE values are expected for thin leaves and minimally woody vegetation with relatively low moisture content (as seen for the samples used for this experiment). The high burning efficiency of the wood stove promoted flaming combustion conditions, and the values measured are at the upper end of the biomass MCE values found in the literature. High MCE values have been observed for some wildfires (Korontzi *et al*., 2003), but MCE values during a real-world fire would typically be lower, and emissions would vary accordingly.

Biomass burning emits a wide variety of gases and aerosols, of which a significant portion is organic (primary organic aerosols). Depending on the time of day or night, the amount of ultraviolet (UV) radiation and the presence of other chemical species, reactions involving VOCs will lead to the formation of secondary organic aerosols (SOAs), contributing to PM levels.

To determine the amount of SOAs formed, daytime and night-time atmospheric ageing were simulated for each fuel. Three types of ageing experiments were conducted: (i) daytime ageing (UV lights); (ii) daytime ageing under more reactive conditions (UV lights + OH radical as an oxidising species); and (iii) night-time ageing (no lights + O_3). The 4–5 hours of ageing in the chamber was considered to represent accelerated ageing, equivalent to several days of chemical processing in the atmosphere.

PM mass concentrations increased by 2–9% under daytime ageing conditions and by 5–11% under night-time ageing conditions (Figure 4.2). Gorse experiments showed the highest increase in secondary PM. This finding is important, as considering primary EFs alone to calculate total emissions would underestimate the amount of PM resulting from the burn by an average of 6.7%. Such secondary emissions therefore need to be included in the total amount of PM produced by a fire. Furthermore, notwithstanding the above point, the increase in SOAs was relatively modest and indicates a low proportion of incompletely burned material. A limitation of this work is that real-world wildfire conditions such as fuel moisture, oxygenation and fuel spread cannot be fully reproduced in an experimental setting, and, as already noted, laboratory-derived MCE values tend to be higher than MCE values for real-world wildfires (Andreae, 2019). These values are therefore a best estimate of EFs for Irish wildfires.

4.3 Association of Irish Land Cover Types with Emission Factors

As indicated by equation 4.1, the total emissions from a wildfire depend on the area burned, fuel loading, combustion completeness and a fuel-specific EF. Every vegetation cover can be associated with biomass, measured in tonnes per hectare. Numerous experiments have been reported to associate individual species and assemblages of species in a habitat, with standard values of above-ground dry matter biomass. Chapter 2 of the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories – Volume 4: Agriculture, Forestry and Other Land Use* represents the most comprehensive and up-to-date source of information on methods to estimate emissions from biomass burning, with standard values for global habitats (Ogle *et al*., 2019). The *EMEP/EEA Air Pollutant Emission Inventory Guidebook 2019* of the European Environment Agency (EEA) provides additional guidelines and biomass standard values (San-Miguel-Ayanz *et al*., 2019). Standard values for combustion factors, which are used to scale the biomass lost to account for that not combusted, have also been determined for each vegetation class.

Determination of the areas burned by Irish wildfires is described in section 2.4, and the association with vegetation cover is described in section 3.3. The 128 vegetation classes identified within the national vegetation dataset (section 3.2) were associated with the closest biomass standard value and combustion factor extracted from the scientific literature, Ogle *et al*. (2019) or San-Miguel-Ayanz *et al*. (2019) (Table 4.2). The EF values for CO_2 and CH_4 for all species and vegetation covers were derived from Andreae (2019); the EF values for heather, gorse and purple moor grass for all other emissions were derived from the FLARES values (Table 4.2).

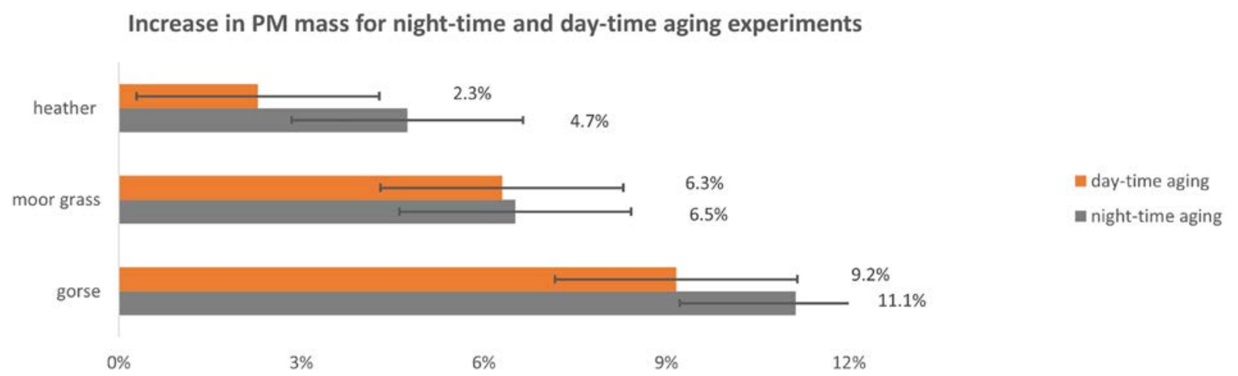

Figure 4.2. Increase in PM mass concentrations during night-time and daytime ageing experiments.

Table 4.2. Association of vegetation classes with biomass standard values, combustion factors and EFs

Vegetation		Biomass standard value		Combustion factors		
Class	Source	Source	Value (tonnes ha^{-1})	Source	Value	EF source
Alpine heath	NPWS MAES15	*Calluna* heath – IPCC	11.5	IPCC	0.71	*Calluna* – FLARES
Amenity grassland	NPWS MAES15	Grassland vegetated by perennial grasses – EEA	2.24	EEA	0.5	Grassland – Andreae (2019)
Arable/arable – arable mosaic	NPWS MAES15	Grassland vegetated by perennial grasses – EEA	2.24	EEA	0.5	Grassland – Andreae (2019)
Arable land	EPA TaLAM	Grassland vegetated by perennial grasses – EEA	2.24	EEA	0.5	Grassland – Andreae (2019)
Bare ground/bare ground – rock	NPWS MAES15	Non-forest class – EEA	1.57	EEA	0.5	Grassland – Andreae (2019)
Bare peat	EPA/OSi INLM	Sparsely vegetated areas – EEA	10.1	EEA	0.5	Shrubland – Andreae (2019)
Bare rock	EPA TaLAM	Non-forest class – EEA	1.57	EEA	0.5	Grassland – Andreae (2019)
Bare rocks	CLC 2018	Non-forest class – EEA	1.57	EEA	0.5	Grassland – Andreae (2019)
Bare soil	EPA TaLAM	Non-forest class – EEA	1.57	EEA	0.5	Grassland – Andreae (2019)
Bare soil and disturbed ground	EPA/OSi INLM	Grassland vegetated by perennial grasses – EEA	2.24	EEA	0.5	Grassland – Andreae (2019)
Beaches, dunes, sands	CLC 2018	Fixed dunes – Beaumont *et al.*	12.21	EEA	0.5	Grassland – Andreae (2019)
Blanket bog	EPA/OSi INLM	Sparsely vegetated areas – EEA	10.1	EEA	0.5	Shrubland – Andreae (2019)
Blanket bogs	NPWS MAES15	Sparsely vegetated areas – EEA	10.1	EEA	0.5	Shrubland – Andreae (2019)
Bracken	EPA/OSi INLM	Sparsely vegetated areas – EEA	10.1	EEA	0.5	Shrubland – Andreae (2019)
Broadleaved forest	EPA/OSi INLM	Broadleaved forest – EEA	6.72	EEA	0.2	Temperate forest – Andreae (2019)
Broadleaved forest	CLC 2018	Broadleaved forest – EEA	6.72	EEA	0.2	Temperate forest – Andreae (2019)
Broadleaved woodlands	NPWS MAES15	Broadleaved forest – EEA	6.72	EEA	0.2	Temperate forest – Andreae (2019)
Coastland	EPA TaLAM	Non-forest class – EEA	1.57	EEA	0.5	Grassland – Andreae (2019)
Complex cultivation patterns	CLC 2018	Grassland vegetated by perennial grasses – EEA	2.24	EEA	0.5	Grassland – Andreae (2019)
Coniferous forest	EPA/OSi INLM	Shrubland understory and pine overstory – EEA	19.1	EEA	0.2	Boreal forest – Andreae (2019)
Coniferous woodlands	NPWS MAES15	Shrubland understory and pine overstory – EEA	19.1	EEA	0.2	Boreal forest – Andreae (2019)
Cultivated land	EPA/OSi INLM	Grassland vegetated by perennial grasses – EEA	2.24	EEA	0.5	Grassland – Andreae (2019)
Cutover bog	EPA/OSi INLM	Sparsely vegetated areas – EEA	10.1	EEA	0.5	Shrubland – Andreae (2019)
Dense bracken	EPA TaLAM	Sparsely vegetated areas – EEA	10.1	EEA	0.5	Shrubland – Andreae (2019)
Dry heath	NPWS MAES15	*Calluna* heath – IPCC	11.5	IPCC	0.71	*Calluna* – FLARES
Dry humid grassland	EPA TaLAM	Grassland vegetated by perennial grasses – EEA	2.24	EEA	0.5	Molinia – FLARES
Dry siliceous heath	EPA TaLAM	*Calluna* heath – IPCC	11.5	IPCC	0.71	*Calluna* – FLARES

Table 4.2. Continued

Vegetation		Biomass standard value		Combustion factors		
Class	**Source**	**Source**	**Value (tonnes ha⁻¹)**	**Source**	**Value**	**EF source**
Exposed rock and sediments	EPA/OSi INLM	*Calluna* heath – IPCC	11.5	IPCC	0.71	*Calluna* – FLARES
Exposed siliceous rock	EPA TaLAM	*Calluna* heath – IPCC	11.5	IPCC	0.71	*Calluna* – FLARES
Gorse	FLARES	Transitional woodland shrub – EEA	12.3	EEA	0.5	Gorse – FLARES
Heath	EPA TaLAM	*Calluna* heath – IPCC	11.5	IPCC	0.71	*Calluna* – FLARES
Heavily improved grassland	NPWS MAES15	Grassland vegetated by perennial grasses – EEA	2.24	EEA	0.5	Grassland – Andreae (2019)
Hedgerows	EPA/OSi INLM	Transitional woodland shrub – EEA	12.3	EEA	0.5	Gorse – FLARES
Improved grasslands	NPWS MAES15	Grassland vegetated by perennial grasses – EEA	2.24	EEA	0.5	Grassland – Andreae (2019)
Inland marshes	CLC 2018	Inland and coastland marshes – EEA	15.7	EEA	0.5	Grassland – Andreae (2019)
Land principally occupied by agriculture	CLC 2018	Grassland vegetated by perennial grasses – EEA	2.24	EEA	0.5	Grassland – Andreae (2019)
Limestone pavement	NPWS MAES15	Non-forest class – EEA	1.57	EEA	0.5	Grassland – Andreae (2019)
Lowland blanket bog	EPA TaLAM	Sparsely vegetated areas – EEA	10.1	EEA	0.5	Shrubland – Andreae (2019)
Machair	NPWS MAES15	Machair – Beaumont *et al.*	12.21	EEA	0.5	Grassland – Andreae (2019)
Marsh	NPWS MAES15	Inland and coastland marshes – EEA	15.7	EEA	0.5	Grassland – Andreae (2019)
Mire/fen	NPWS MAES15	Inland and coastland marshes – EEA	15.7	EEA	0.5	Grassland – Andreae (2019)
Mixed forest	EPA/OSi INLM	Average – EEA	12.91	EEA	0.2	Temperate forest – Andreae (2019)
Mixed woodland/ planted	NPWS MAES15	Average – EEA	12.91	EEA	0.2	Temperate forest – Andreae (2019)
Montane heath	EPA TaLAM	*Calluna* heath – IPCC	11.5	IPCC	0.71	*Calluna* – FLARES
Moors and heathland	CLC 2018	*Calluna* heath – IPCC	11.5	IPCC	0.71	*Calluna* – FLARES
Natural grasslands	CLC 2018	Grassland vegetated by perennial grasses – EEA	2.24	EEA	0.5	Molinia – FLARES
Non-irrigated arable land	CLC 2018	Grassland vegetated by perennial grasses – EEA	2.24	EEA	0.5	Grassland – Andreae (2019)
Orchard	NPWS MAES15	Broadleaved forest – EEA	6.72	EEA	0.2	Temperate forest – Andreae (2019)
Pastures	CLC 2018	Grassland vegetated by perennial grasses – EEA	2.24	EEA	0.5	Grassland – Andreae (2019)
Peat bogs	NPWS MAES15	Sparsely vegetated areas – EEA	10.1	EEA	0.5	Shrubland – Andreae (2019)
Raised bogs	NPWS MAES15	Sparsely vegetated areas – EEA	10.1	EEA	0.5	Shrubland – Andreae (2019)
Rocky shore	NPWS MAES15	Non-forest class – EEA	1.57	EEA	0.5	Grassland – Andreae (2019)
Salt marshes	CLC 2018	Saltmarsh – Beaumont *et al.*	4.7	EEA	0.5	Grassland – Andreae (2019)
Salt meadows	NPWS MAES15	Saltmarsh – Beaumont *et al.*	4.7	EEA	0.5	Grassland – Andreae (2019)

Table 4.2. Continued

Vegetation		Biomass standard value		Combustion factors		
Class	Source	Source	Value (tonnes ha⁻¹)	Source	Value	EF source
Saltmarshes	NPWS MAES15	Saltmarsh – Beaumont *et al.*	4.7	EEA	0.5	Grassland – Andreae (2019)
Sand dune – fixed	NPWS MAES15	Fixed dunes – Beaumont *et al.*	12.21	EEA	0.5	Grassland – Andreae (2019)
Sand dune – humid dune slack	NPWS MAES15	Dune slacks – Beaumont *et al.*	12.57	EEA	0.5	Grassland – Andreae (2019)
Sand dune – marram	NPWS MAES15	Fixed dunes – Beaumont *et al.*	12.21	EEA	0.5	Grassland – Andreae (2019)
Sand dune – mobile	NPWS MAES15	Mobile dunes – Beaumont *et al.*	13.75	EEA	0.5	Grassland – Andreae (2019)
Sand dune – with scrub	NPWS MAES15	Transitional woodland shrub – EEA	12.3	EEA	0.5	Gorse – FLARES
Scattered woodland	NPWS MAES15	Transitional woodland shrub – EEA	12.3	EEA	0.5	Gorse – FLARES
Scrub	NPWS MAES15	Transitional woodland shrub – EEA	12.3	EEA	0.5	Gorse – FLARES
Scrub/transitional	EPA TaLAM	Transitional woodland shrub – EEA	12.3	EEA	0.5	Gorse – FLARES
Semi-improved grassland	EPA TaLAM	Grassland vegetated by perennial grasses – EEA	2.24	EEA	0.5	Grassland – Andreae (2019)
Semi-natural grasslands	EPA/OSi INLM	Grassland vegetated by perennial grasses – EEA	2.24	EEA	0.5	Grassland – Andreae (2019)
Semi-natural grasslands	NPWS MAES15	Grassland vegetated by perennial grasses – EEA	2.24	EEA	0.5	Grassland – Andreae (2019)
Sparsely vegetated areas	CLC 2018	Sparsely vegetated areas – EEA	10.1	EEA	0.5	Shrubland – Andreae (2019)
Swamp	EPA/OSi INLM	Inland and coastland marshes – EEA	15.7	EEA	0.5	Grassland – Andreae (2019)
Transitional forest	EPA/OSi INLM	Transitional woodland shrub – EEA	12.3	EEA	0.5	Temperate forest – Andreae (2019)
Transitional woodland – shrub	CLC 2018	Transitional woodland shrub – EEA	12.3	EEA	0.5	Temperate forest – Andreae (2019)
Treelines	EPA/OSi INLM	Transitional woodland shrub – EEA	12.3	EEA	0.5	Temperate forest – Andreae (2019)
Turlough	NPWS MAES15	Grassland vegetated by perennial grasses – EEA	2.24	EEA	0.5	Grassland – Andreae (2019)
Upland blanket bog	EPA TaLAM	Sparsely vegetated areas – EEA	10.1	EEA	0.5	Shrubland – Andreae (2019)
Urban greenspace – amenity grassland	NPWS MAES15	Grassland vegetated by perennial grasses – EEA	2.24	EEA	0.5	Grassland – Andreae (2019)
Vegetated rocky sloped – calcareous	NPWS MAES15	Non-forest class – EEA	1.57	EEA	0.5	Grassland – Andreae (2019)
Vegetated scree – calcareous/siliceous	NPWS MAES15	Non-forest class – EEA	1.57	EEA	0.5	Grassland – Andreae (2019)
Wet grassland	EPA TaLAM	Grassland vegetated by perennial grasses – EEA	2.24	EEA	0.5	Grassland – Andreae (2019)
Wet heath	NPWS MAES15	*Calluna* heath – IPCC	11.5	IPCC	0.71	*Calluna* – FLARES
Woodlands	NPWS MAES15	Average – EEA	12.91	EEA	0.2	Temperate forest – Andreae (2019)

EEA refers to San-Miguel-Ayanz *et al.* (2019); IPCC refers to Ogle *et al.* (2019).

TaLAM, Towards Land Cover Accounting and Monitoring.

4.4 Annual Emissions Based on Satellite-derived National Burn Scar Maps

Using equation 4.1 and the values in Table 4.2, the total GHG and air pollutant emissions generated each year from wildfires were calculated using the full Landsat-8 dataset, the shorter, more conservative Sentinel-2 time series and the combined results. A scaling factor of 6.7% determined during chamber experiments was applied to the $PM_{2.5}$ and TPM values to account for SOA formation (Table 4.3).

For the longer Landsat-8 time series, 2015 saw 73.6% more burned land than the next closest year of 2017. However, the importance of including vegetation-specific biomass and EF values is apparent in that there was 77.8% more biomass burned in 2015, and 86.2% more CO_2 and 101.1% more SO_2 emitted. A total of 1131.3 t of TPM was released from wildfires in 2015 according to the Landsat-8 burned area, 77.6% more than in 2017 and more than seven times as much as in 2019, the year with the lowest TPM emitted. Although Landsat-8 indicated that there was about 2% more burned area in 2019 than derived from Sentinel-2, almost 23% more TPM was emitted from 20% more biomass burned, but, in terms of GHGs, Sentinel-2 estimated 11% more than Landsat-8.

In reporting GHG emissions, it is common for the different gases to be summed as CO_2 equivalent, a measure of how much a gas contributes to global atmospheric warming, relative to CO_2. Using the global warming potential values from the IPCC's Fourth Assessment Report (IPCC, 2007, Table 2.14) to enable direct comparison with the National Inventory Reports, Figure 4.3 presents a comparison of the different satellite-derived burned areas when converted to CO_2 equivalent emission values, as well as the values reported in the Irish National Inventory Reports for the same period. The smaller burned areas reported by the National Inventory Reports led to a significant underestimate of the amount of CO_2 equivalent emitted compared with satellite methods, the notable exception being 2017 when a number of large active fires were detected (Figure 1.6).

Based on average emissions per car and per year in the National Inventory Report (Duffy *et al.*, 2022), which were converted to CO_2 equivalent values as described above, Figure 4.4 highlights that, depending on the dataset used, wildfire emissions equate to the average annual distance driven by 20,000–40,000 cars per year.

4.5 Conclusions

Laboratory methods are essential for refining species-specific EFs, although these figures need to be treated with caution given the very different burning conditions from natural wildfire events. Depending on the vegetation cover ascribed to the burned areas, the emissions calculated can significantly vary, highlighting the need for accurate, up-to-date spatially detailed information on vegetation cover.

Table 4.3. Burnt area identified from the Landsat-8, Sentinel-2 and combined datasets, the biomass lost from the wildfires, and estimated emissions (tonnes) calculated using EFs presented in Table 4.2

Year	Area burnt (ha)	Biomass lost (t)	CO_2 (t)	CO (t)	CH_4 (t)	N_2O (t)	NO_x (t)	SO_2 (t)	$PM_{2.5}$ (t)	TPM (t)	TC (t)	OC (t)	BC (t)	Levoglucosan (t)	$PM_{2.5}$ – SOA (t)[a]	TPM – SOA (t)[a]
Landsat-8																
2015	31,358.6	279,328.5	252,454.0	9253.8	420.3	26.1	493.6	124.1	883.5	1131.3	472.1	394.3	104.0	49.6	942.7	1207.1
2016	11,961.4	95,915.3	78,966.8	3153.2	135.9	8.3	140.4	33.5	316.3	392.7	163.7	137.8	30.2	13.3	337.4	419.0
2017	18,064.3	156,995.4	135,610.9	5168.7	228.5	14.1	252.7	61.7	503.5	637.0	264.4	221.4	53.6	24.2	537.2	679.6
2018	11,170.0	83,616.0	67,639.7	2728.7	121.4	7.3	128.1	32.5	284.4	343.8	152.0	125.0	28.0	16.3	303.4	366.8
2019	5140.3	39,712.9	37,105.6	1298.9	62.4	3.9	78.7	20.6	123.4	158.6	69.2	55.8	16.4	9.7	131.6	169.3
2020	14,689.5	123,231.9	99,724.6	4037.5	172.9	10.5	175.8	41.8	408.5	505.1	211.5	177.8	38.1	16.9	435.9	538.9
2021	10,449.0	79,755.0	70,743.9	2624.2	118.6	7.3	138.1	34.7	252.6	322.4	136.0	112.0	29.4	14.4	269.6	344.0
Sentinel-2																
2018	8991.0	75,174.8	62,325.1	2430.1	110.4	6.6	121.0	31.3	248.5	302.2	134.1	108.4	26.2	15.4	265.1	2018.0
2019	5045.0	47,809.5	41,217.6	1568.8	72.7	4.4	82.6	21.7	159.5	194.9	86.5	71.0	17.7	10.7	170.1	2019.0
2020	6698.4	59,008.0	46,950.5	1883.4	83.7	5.0	87.1	22.2	194.2	234.0	103.4	82.7	19.0	10.6	207.2	2020.0
2021	5431.2	47,942.6	41,118.0	1521.3	72.0	4.4	84.6	22.8	152.0	185.8	84.6	65.7	18.2	11.4	162.2	198.2
Combined																
2018	17,019.7	130,406.2	105,098.3	4251.2	188.3	11.3	196.8	49.5	442.4	535.4	235.2	194.0	43.0	24.5	472.0	571.3
2019	8132.7	67,730.3	59,373.4	2212.7	103.3	6.3	120.8	31.4	221.0	274.2	121.1	98.7	25.6	15.5	235.8	292.6
2020	18,160.5	151,774.0	121,530.0	4951.2	212.3	12.9	214.5	51.3	504.6	620.2	262.2	218.7	46.8	21.6	538.4	661.7
2021	13,683.8	108,350.5	93,327.4	3525.0	159.7	9.8	181.9	46.2	347.0	434.4	187.3	152.2	39.0	20.5	370.2	463.5

[a]Values scaled to account for SOAs.

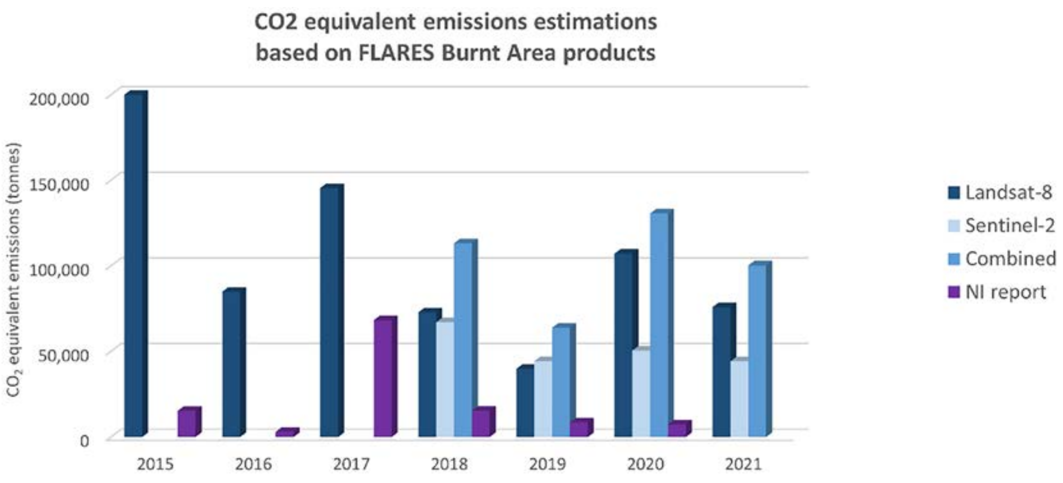

Figure 4.3. Wildfire emissions converted to CO_2 equivalent emission values for the satellite-derived burned areas and emissions reported in the National Inventory Report.

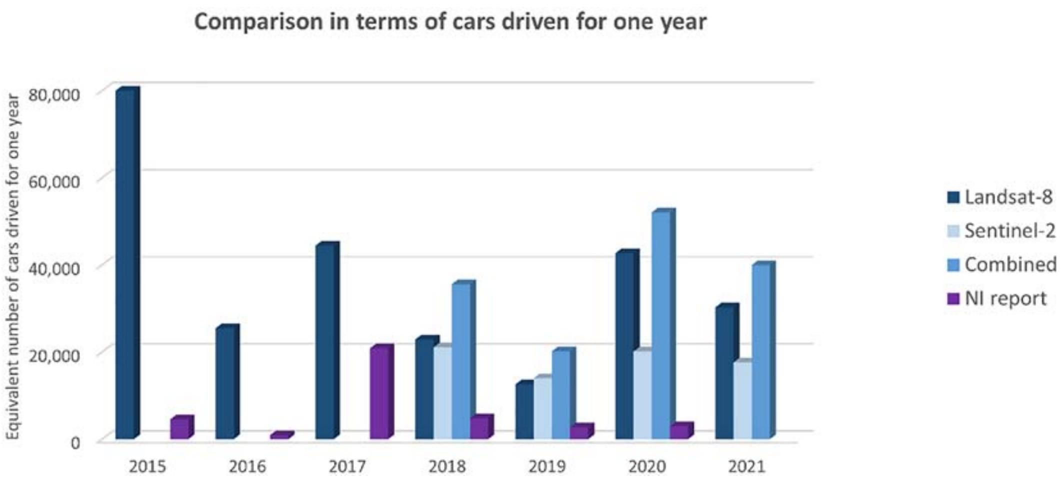

Figure 4.4. Conversion of CO_2 equivalent emissions to equivalent number of Irish cars driven (2020 vehicle emission data were used for 2021 calculations owing to the absence of data for 2021).

5 Estimates of Emissions

5.1 Air Quality Measurement Network

The air pollutants of greatest concern in Ireland are PM (TPM, $PM_{2.5}$ and PM_{10} (particulate matter of diameter ≤10 µm)), which is produced mostly by residential solid fuel combustion, and NO_x, which is largely associated with transport emissions. High PM levels are of concern in many populated areas, with exceedances of World Health Organization (WHO) air quality guidelines being recorded at 38 of 67 monitoring stations in 2020 (EPA, 2021). Ireland's air quality is monitored by a network of 102 stations, situated mostly in cities and larger towns, managed by the EPA. Only three stations are in rural locations: Kilkitt, County Monaghan (measuring NO_2, SO_2 and O_3), Claremorris, County Mayo (measuring $PM_{2.5}$ and PM_{10}), and Emo, County Laois (measuring NO_2 and O_3). Upland fires are often distant from larger population centres, and, as a result, there are limited opportunities to directly measure the impacts of wildfires on nearby air quality through the current monitoring network. While the laboratory methods described in Chapter 4 are useful in refining annual emission estimates, the values obtained are averaged based on standards, with actual values for a wildfire being potentially very different because of the unique characteristics of that fire event.

5.2 Field Measurements of Emissions

To overcome these data limitations, a two-fold approach was taken: (i) the deployment of a mobile air monitoring station over a 2 month period at a rural site with a high likelihood of being affected by fire events and (ii) a rapid response approach, to sample air during an accessible fire event.

5.2.1 Two month rural measurement campaign

Instrumental deployment

Based on the FLARES fire database (sections 1.1.2 and 1.1.3), the Glencree Centre for Peace and Reconciliation (Co. Wicklow) was identified as a suitable monitoring site, in a location that had historically been affected by upland fires over multiple years during April and May. The Glencree Centre is located in the northern Wicklow Mountains, and the site has electricity and road access (Figure 5.1). Glencree is near the Wicklow–Dublin border, 25 km from Dublin city (population about 1.4 million) and 20 km from Bray, County Wicklow (population 30,000). A few houses are in the vicinity of the sampling site, and the nearest settlements are Glencullen (9 km away, population 238), Enniskerry (13 km away, population 1889) and Manor Kilbride (19 km away, population 272). The R115 "Old Military Road" runs through the area and receives local and tourist traffic, especially at weekends. The mobile air monitoring station was deployed in this location from 31 March to 31 May 2021.

The mobile laboratory included instrumentation to quantify $PM_{2.5}$ and PM_{10} concentrations, carbonaceous aerosol optical properties and chemical tracers specific to biomass burning. BC and brown carbon (BrC), two absorbing aerosol components relevant to global warming, were measured continuously with an AE33 Aethalometer (Magee Scientific). This optical method differentiates aerosols by their respective wavelength dependence, allowing estimation of the relative contributions of biomass burning and fossil fuel combustion to the total amount of BC measured. The relative contribution of biomass burning to total BC produced is shown in the right-hand panel of Figure 5.2 as "BB%".

PM in size fractions from 0.3 µm to 10 µm was measured in real time using PurpleAir (PA-II-SD) sensors, which are based on a laser particle counter (Plantower PMS5003). The PurpleAir sensor is a low-cost PM monitor, but of inferior accuracy to the instruments of the national air quality monitoring network calibrated based on European Committee for Standardization (CEN) standards. For this study, only the size fractions below 2.5 µm were considered, i.e. $PM_{2.5}$. Filter samples (Pallflex Tissuquartz) of ambient air were collected over 24 hour intervals with a DHA-80 High Volume Aerosol Sampler (DIGITEL) using a sampling head with a 2.5-µm-size cut-off. These filters were analysed at TROPOS Leipzig for

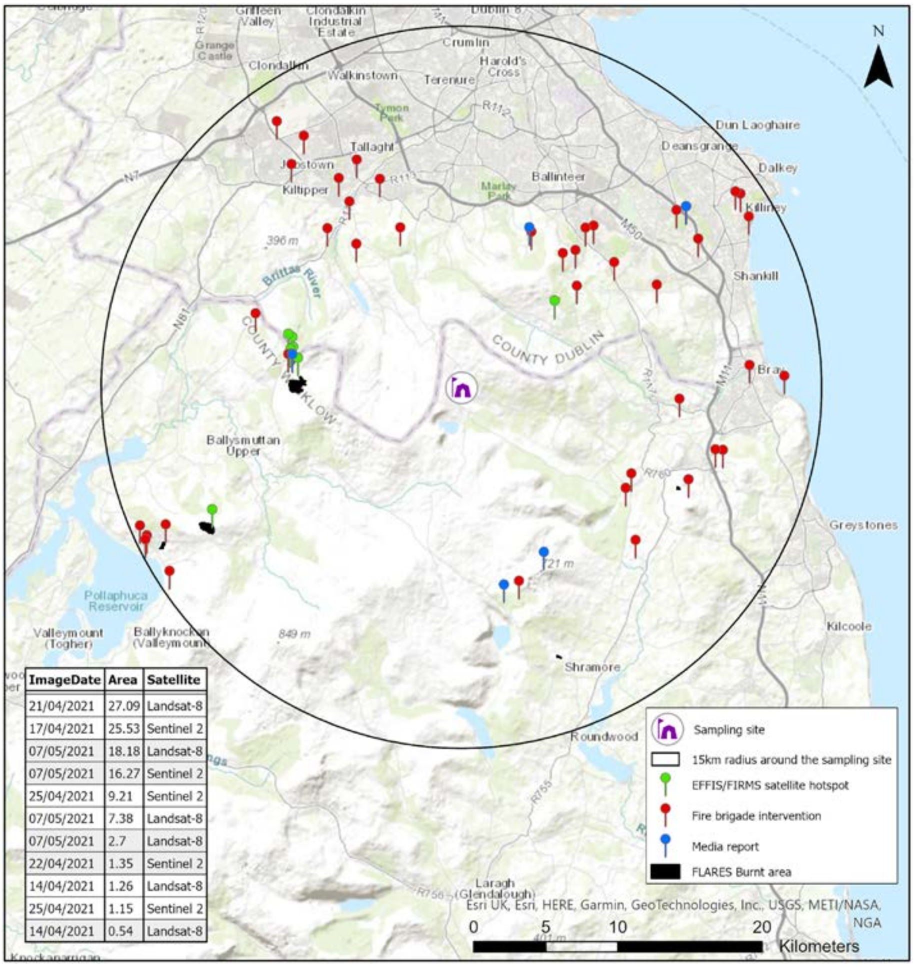

Figure 5.1. Glencree monitoring site and locations of fire events during the campaign.

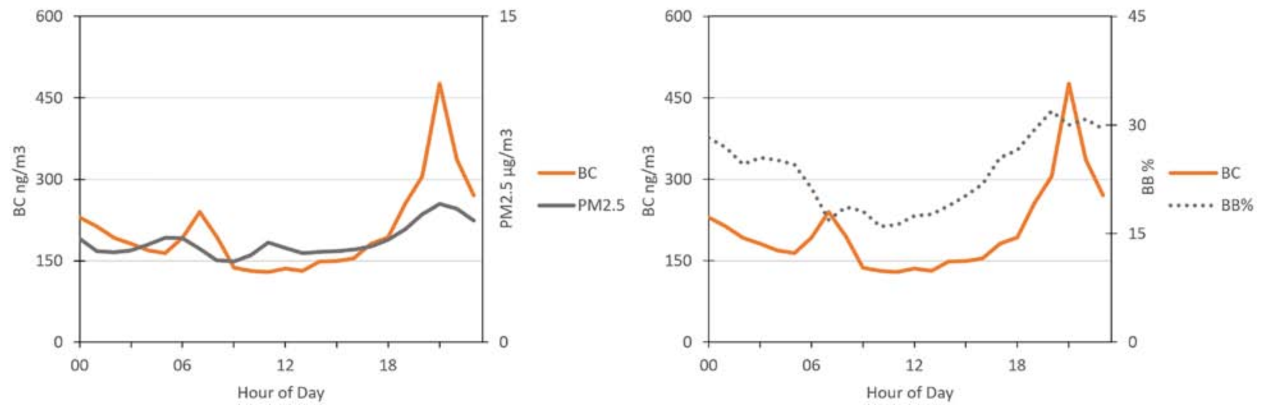

Figure 5.2. Diurnal profiles of $PM_{2.5}$ and BC (left) and BC and BB% (right) at Glencree.

the OC and EC content of carbonaceous aerosol and molecular markers. OC and EC measurements are related to aethalometer BrC and BC measurements, but determined using different measurement principles. EC is emitted during the incomplete combustion of carbon-containing fuels, whereas OC can be emitted directly or produced during atmospheric ageing reactions, indicating the extent of smoke processing.

Fossil fuel burning during monitoring period

Human activity has a notable impact on air quality in Glencree, with peaks in the $PM_{2.5}$ and BC daily profiles attributable to vehicle traffic (morning) and domestic solid fuel use (evening) (Figure 5.2).

The impact of solid fuel use for residential heating was clearly visible in the BC and $PM_{2.5}$ trends over the 2 month period, with a decline in average values observed with progression through spring.

Wildfire analysis

Data on fire activity within a 15 km radius of the Glencree sampling site during the field campaign were obtained from the FLARES fire events database. This distance was selected based on local experience and consideration of the topography, with more distant fires considered unlikely to have a significant impact on the monitoring site. During the campaign (31 March–31 May), fires occurred on 22 days within the 15 km zone, with most in April (18 fires over 15 days), and just five fires over 6 days occurring in May and one fire on 1 day occurring in March.

Atmospheric composition and meteorological data from days with wildfire events were analysed to investigate how local air composition was affected. Of the 22 fire days, only four fire events were noticeable at the monitoring site. Data from 1 April 2021 suggest some wildfire influence (Figure 5.3), with a large, rapid increase in BC observed in the early morning, deviating from the normal pattern (shown in Figure 5.2). This event coincided with a fire reported at Old Long Hill (53.1598°N, 6.18629°W), and a south-east wind from the direction of the fire.

Overall, it was not possible to identify wildfire events with certainty. A *t*-test showed a statistically significant difference in $PM_{2.5}$ and BC between wildfire and non-wildfire days, but this difference cannot be unequivocally attributed to upland fires because the profiles of $PM_{2.5}$ and BC showed large fluctuations over the monitoring period as part of a general and widespread trend (Figure 5.4).

Comparison of Glencree $PM_{2.5}$ measurements with a nearby EPA monitoring station in suburban Tallaght (Co. Dublin) is useful, despite differences in the instrumentation accuracy. Tallaght has a CEN-standard-calibrated monitoring station maintained by the EPA, and thus more accurate measurements of the PM levels than the indicative PurpleAir sensors. Comparison of data from co-located PurpleAir devices with data from reference instrumentation similar to that in Tallaght, at the air quality monitoring station at University College Cork (station 21), indicates that PurpleAir devices are highly correlated with the reference instrument (Met One BAM), with r^2 values above 0.9, but are subject to a positive bias, on average by a factor of 1.8. So, for the purpose of comparing $PM_{2.5}$ values measured at Glencree and in Tallaght, the measurements at Glencree were first reduced by a factor of 1.8.

Comparison of the corrected values showed that, although usually lower in Glencree, $PM_{2.5}$ followed the same trends in both locations, indicating that they experience similar sources of air pollution, despite their different settings and population densities. Air quality in Glencree could be affected more by topography and non-applicability of the smoky coal

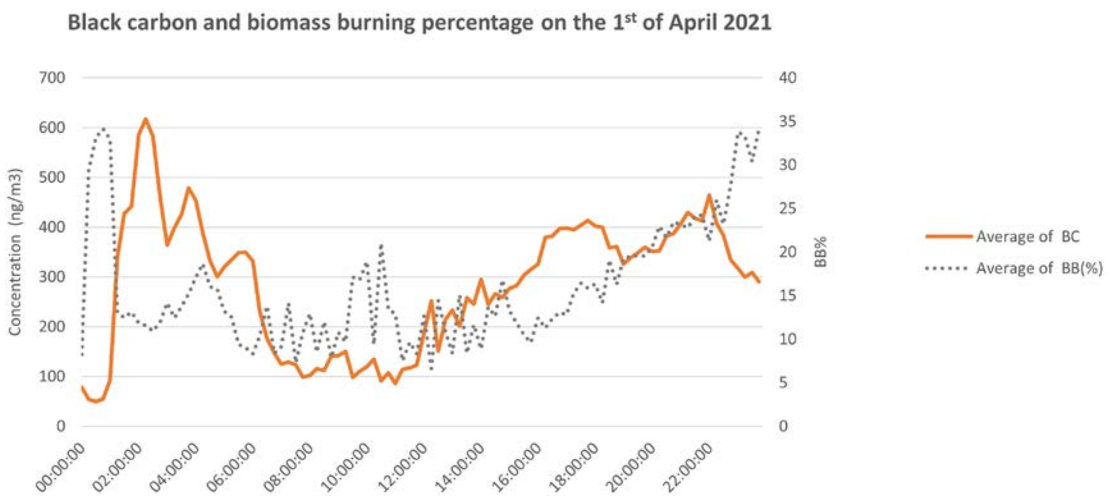

Figure 5.3. BC concentrations and BB% at different times on 1 April 2021, suggesting wildfire influence.

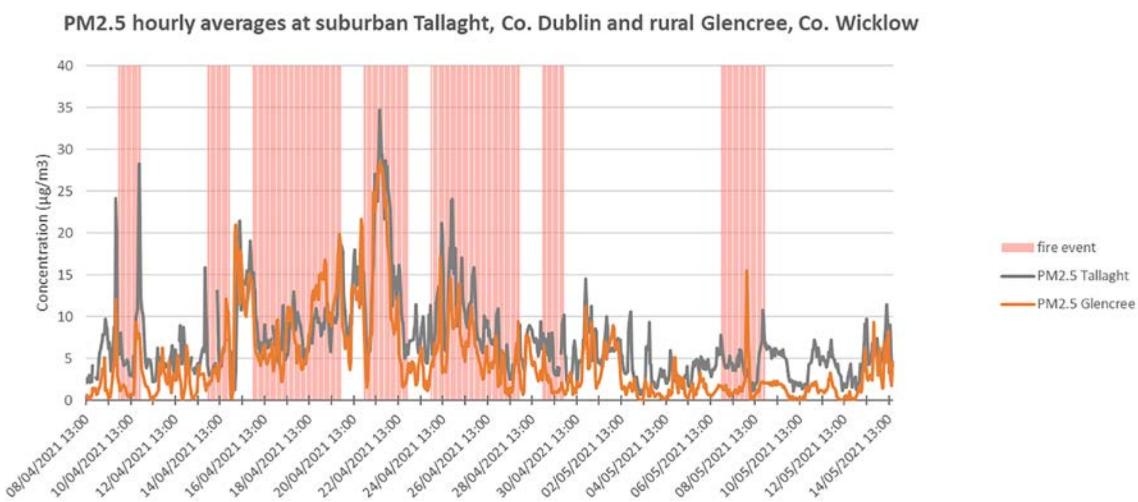

Figure 5.4. $PM_{2.5}$ hourly average concentrations at suburban Tallaght, Co. Dublin, and rural Glencree, Co. Wicklow.

ban than by wildfires, as the dates when these occur (in red on Figure 5.4) do not coincide with peaks in $PM_{2.5}$. Compared with other years in the fire event database, 2021 was unusual, with no major wildfires in the Wicklow region, but the local influence of topography and meteorology highlights the importance of monitoring air quality in rural areas, which are under-represented in the national monitoring network but are affected by similar air quality issues as large population centres.

5.2.2 Rapid response sampling during a fire event

Plume samples were taken at two fire events – a large fire in Killarney National Park, County Kerry (25 April 2021), and a small-scale fire in Cobh, County Cork (6 May 2021) (Figure 5.5). A TSI DustTrak II Aerosol Monitor 8532 with a $PM_{2.5}$ inlet was used to measure $PM_{2.5}$ concentrations within the smoke plume in reasonable proximity to the fire. Maximum $PM_{2.5}$ values measured reached 6930 $\mu g\,m^{-3}$ in Cobh (approximately 30 m from the fire) and 874 $\mu g\,m^{-3}$ in Killarney (approximately 30 m from the fire). As of September 2021, the WHO 24 hour average limit for $PM_{2.5}$ has been 15 $\mu g\,m^{-3}$.

5.3 The Human Impacts of Wildfire Events

5.3.1 Fires occurring upwind of population centres

While attending fire events, the measurement team observed that many local residents seemed unaware of the health impacts of wildfire smoke, and how

Figure 5.5. Sampling $PM_{2.5}$ in smoke in Cobh, Co. Cork (left), and near Killarney, Co. Kerry (right). Photographs: Clara Felberbauer.

they could modify their behaviour to protect their health. Wildfire smoke might be more harmful for human health than other types of smoke (Aguilera *et al*., 2021). The fire attended in Cobh, County Cork (section 5.2.2), affected air quality in a nearby residential area for the fire duration. The Killarney National Park fire of April 2021 had a limited impact on settlements, as the easterly wind blew smoke predominantly over uninhabited areas. Had the wind been from the south-west, residents of Killarney would have been severely affected.

Each of the burned areas in the Landsat-8, Sentinel-2 and combined datasets described in section 2.4, which damaged at least 30 ha and lay within 15 km of a settlement of at least 10,000 inhabitants, was identified. For each of these wildfires, information from media, social media and fire brigade reports was sought to ascribe an exact time and date to the event, and the wind direction was determined from the ERA5 dataset described in section 5.4.2, to identify settlements lying downwind of the fire. Using the methods described in section 4.4, the levels of CO_2 equivalent, $PM_{2.5}$ and TPM emissions, and SOAs, were calculated (Table 5.1).

In total, 21 fires met the required criteria between 2015 and 2021, with Killarney and Clonmel each affected on three occasions, and Dublin city and suburbs affected on four occasions. Notably, even though the area burned in 2019 was smaller than in any of the other years in the time series (Table 2.1), more urban areas (six) were affected in this year than in any other. In addition, almost half of the fires occurred in the May–September period, i.e. outside the controlled burning period. At the times of approximately 75% of the fires, the wind was from an easterly direction (north-east through to south-east), which corroborates comments from fire service personnel that drier, easterly winds tend to drive some of the largest fires. In terms of PM affecting population centres, three fire events were notable for their very high PM emission levels: Kilcummin in County Kerry (in 2015, 551.7 ha burned, emitting 17.7 t $PM_{2.5}$), Meenagleragh in County Sligo (in 2017, 297.1 ha burned, emitting 12.3 t $PM_{2.5}$) and Castlekelly in County Dublin (in 2019, 385.1 ha burned, emitting 12.0 t $PM_{2.5}$). All of these fires occurred predominantly on peat bogs, with coniferous woodland also affected at Meenagleragh. When SOAs are included, a total of 44.9 t $PM_{2.5}$ is estimated to have been released from the three bog fires, compared with a total of 43.7 t $PM_{2.5}$ from the other fires combined, emphasising how very large fires can have a very significant impact on populations – namely those of Killarney (population approximately 13,500), Ballina (population approximately 45,700), and Dublin city and suburbs (population approximately 1,263,000).

The fieldwork highlighted how short-lived the impacts of wildfires on $PM_{2.5}$ can be (Figure 5.3) but, equally, how the instantaneous values can be extremely high (section 5.2.2) in a local area. While the existing EPA air quality monitoring network can capture general trends (Figure 5.4), the number of stations is insufficient to capture information on the emissions from every fire, and an alternative approach to estimating the impacts of individual fire events from modelled data was explored.

5.4 Approach to Estimating Emissions from Modelled Data

5.4.1 The Copernicus Atmosphere Monitoring Service

The Copernicus Atmosphere Monitoring Service (CAMS), managed by the European Centre for Long-Range Weather Forecasts (ECMWF), is one of six thematic services of Copernicus, the EU's EO programme. The service provides access to large quantities of historical and near-real-time (NRT) data at various temporal and spatial resolutions that can be used to address environmental and related issues on different scales (Copernicus, 2022). A variety of data products related to air quality, emissions, solar radiation and surface fluxes (Peuch *et al*., 2018) are available on a global scale, as well as regional data products focused solely on the European continent.

The European air quality forecast and analysis, also known as ENSEMBLE, comprises a 4 day (96 hour) air quality forecast and a daily air quality analysis product that merges 1-day-old observations with the forecast for a more accurate output. Currently, ENSEMBLE forecasts the concentration levels over Europe of the pollutants CO, NO, NO_2, SO_2, O_3, $PM_{2.5}$, PM_{10} and atmospheric dust, ranging from the surface level up to 5000 m.

A single ENSEMBLE forecast and analysis (Marécal *et al*., 2015) are derived by combining the forecasts and analysis products of a collection of nine European

Table 5.1. Primary and secondary emissions associated with wildfire events over 30 ha, less than 15 km upwind of a settlement of at least 10,000 inhabitants

Wildfire location	Date	Settlement affected	Distance to settlement affected (km)	Wind direction	Area burnt (ha)	Biomass lost (t)	Primary emissions		Secondary emissions	
							$PM_{2.5}$ (t)	TPM (t)	$PM_{2.5}$ – SOA (t)[a]	TPM – SOA (t)[a]
Mount Leinster, Co. Carlow	21/03/2015	Enniscorthy	14.5	NW	151	1735.2	4.2	5.4	4.4	5.8
Kilcummin bog, Co. Kerry	07/04/2015	Killarney	6	NE	551.7	5427.6	17.7	23	18.9	24.5
Gortagullane, Co. Kerry	08/04/2015	Killarney	1.8	SE	107.8	933.6	3.1	4	3.3	4.3
Aghamore Far, Co. Sligo	10/04/2015	Sligo	2.6	SE	48.4	549.2	1.3	1.7	1.4	1.8
Slievenamon, Co. Tipperary	07/05/2016	Clonmel	8	NE	39.9	420	1.2	1.6	1.3	1.7
Bray Head, Co. Wicklow	16/08/2016	Bray	0.3	SE	60.3	682.1	1.9	2.8	2.1	3
Bray Head, Co. Wicklow	16/08/2016	Dublin city and suburbs	3.5	SE	60.3	682.1	1.9	2.8	2.1	3
Meenagleragh, Co. Sligo	07/05/2017	Ballina	13.8	NE	297.1	3200.2	12.3	15.2	13.2	16.3
Derrymore East, Co. Clare	18/05/2018	Ennis	13.2	SE	38.6	389.4	1.3	1.7	1.4	1.8
Cloonaddron, Co. Roscommon	19/05/2018	Athlone	13.6	SW	47.3	468.9	1.6	2	1.7	2.2
Glenmore, Co. Roscommon	19/05/2018	Athlone	12.6	SW	96.8	920.4	3.1	4	3.3	4.3
Bray Head, Co. Wicklow	14/07/2018	Bray	1	SE	70.2	776.1	2.8	4.6	3	4.9
Bray Head, Co. Wicklow	14/07/2018	Dublin city and suburbs	4.7	SE	70.2	776.1	2.8	4.6	3	4.9
Carrigbrack, Co. Waterford	26/02/2019	Clonmel	13.5	SE	30.3	336.2	0.9	1.1	0.9	1.2
Castlekelly, Co. Dublin	26/02/2019	Dublin city and suburbs	5.5	SW	385.1	4023.8	12	15.6	12.8	16.6
Carrigaveema, Co. Kerry	27/02/2019	Killarney	11.6	SE	43	145.7	0.5	0.6	0.5	0.6
Ballynultagh Woods, Co. Wicklow	27/02/2019	Naas	14.8	SE	172.5	1897.1	5.2	6.8	5.6	7.2
Ballyhiernaun, Co. Mayo	13/04/2019	Ballina	2.6	SE	32.7	313.6	1	1.3	1.1	1.4
Seefingan, Co. Wicklow	20/04/2019	Dublin city and suburbs	6.3	SW	120.8	1331.7	3.6	4.6	3.8	5
Cloroge Beg, Co. Wexford	11/04/2020	Enniscorthy	13.2	NW	61.3	704.5	1.7	2.2	1.8	2.3
Culleens, Co. Sligo	03/06/2020	Ballina	11.1	NE	33.6	363.9	1.2	1.3	1.2	1.4
Anna More Bog, Co. Kerry	24/04/2021	Tralee	14.7	SE	62.6	246.2	0.8	1.1	0.9	1.2
Comeragh Mountains, Co. Waterford	07/09/2021	Clonmel	10.7	SE	30.2	335.1	0.8	1.1	0.9	1.2

[a]Values scaled to account for SOAs.

air quality models, for which the median value per 0.1° latitude/longitude grid cell is taken to produce the final ENSEMBLE forecast. To produce the *a posteriori* analysis, each model has a custom method that assimilates air quality observations, which are provided by the EEA, from the previous day (ECMWF, 2023).

Depending on the models, satellite observations of NO_2 and SO_2 column retrievals from Aura (Ozone Monitoring Instrument) and MetOp (Global Ozone Monitoring Experiment-2), CO profiles from Terra (Measurement of Pollution in the Troposphere) and CO partial column measurements from MetOp (Infrared Atmospheric Sounding Interferometer) are assimilated. By taking the median value of values from a multitude of models, outliers within the single models can be corrected, resulting in a better end product (Galmarini *et al*., 2004). CAMS also publishes retrospective analyses (reanalyses), which make use of only a single forecasting and assimilation system and are therefore consistent throughout the entire time period covered by the dataset (Dee *et al*., 2011).

In situ observations provided by the European Environment Information and Observation Network (EIONET) are incorporated into the modelling process of the ENSEMBLE models. The stations used in the analysis are updated every year, so there are no fixed lists of Irish ground stations incorporated into the product. According to the ECMWF (pers. comm.), the ground stations that were used in 2021 measured NO_2 (eight stations), O_3 (nine stations), $PM_{2.5}$ (two stations) and PM_{10} (five stations).

CAMS uses Moderate Resolution Imaging Spectroradiometer (MODIS) data to produce Global Fire Assimilation System (GFAS) version 1.2, which is an analysis system that produces estimates of EFs based on the energy of the observed fire and the land cover of its surroundings (Di Giuseppe *et al*., 2017). The GFAS product calculates estimates of emissions based on the fire radiative power (FRP), a measure generated from the MODIS observations used to detect fire events. Based on the conversion factors for the biome where a fire event takes place, the dry matter burned is estimated, and emission fluxes of 40 smoke constituents are calculated using EFs derived from field measurements (Andela *et al*., 2013). The partner models for the ENSEMBLE forecast and analysis take the GFAS product as an input representing an influx of emissions caused by fires (Marécal *et al*., 2015; Collin, 2020). It is important to note, as discussed in section 1.2.1, that, because of cloud cover, the low spatial resolution of the observations and the revisit time of the satellites, many of the fires that occur across Ireland are not recorded by MODIS instruments, and therefore are not included in the GFAS product.

5.4.2 CAMS, meteorological and other datasets used for emission estimates

To cover the period 2015–2021 as comprehensively as possible, a combination of the CAMS NRT analysis and reanalysis products was used; however, to understand the atmospheric dynamics of the gases and particulates, data on the prevailing weather conditions are also needed.

Researchers at Met Éireann produced a reanalysis dataset of climatological data, known as MÉRA (Met Éireann ReAnalysis), for the period 1981–2019. MÉRA offers a three-dimensional numerical representation of the Irish climate based on meteorological models and weather observations. It has a spatial resolution of approximately 2.5 km and a temporal resolution of 3 hours. For this project, the longitudinal and latitudinal axis components of the 10 m wind (the wind 10 m above ground level), from which wind speed and direction can be derived, as well as total precipitation and the 2 m air temperature data, were used. Reanalysis data were not available for total precipitation, so the first 24 hours for each daily 33 hour total precipitation forecast product were used. The MÉRA data were reprojected and resampled to the same resolution as the CAMS ENSEMBLE NRT analysis product.

As MÉRA covers only up until August 2019, the ERA5 dataset (the fifth-generation reanalysis dataset for global climate and weather produced by the ECMWF (2022)) was used for the period August 2019 to December 2021. The ERA5 dataset is published within 5 days of real time, and a quality-checked version is published 2 months later. However, in practice it is very rare that adjustments are made to the original ERA5 dataset (Hersbach *et al*., 2020). While the original ERA5 dataset has a spatial resolution of 0.25° × 0.25° (roughly 25 km), for the purposes of the analyses these data were resampled to match the 0.1° resolution of the CAMS ENSEMBLE.

To better understand the influence of topography, the EU-DEM v1.1 digital elevation model (DEM) with a spatial resolution of 25 m (CLMS, 2022) was clipped to the extent of the study area, after which the slope was derived for the area of interest. The CLC map for 2018 was used to indicate the land cover types (CLMS, 2018).

5.5 Estimation of Emissions Using CAMS Products

5.5.1 Comparing CAMS with ground station observations

To assess the accuracy of the CAMS product for ground-level measurements in Ireland, a validation exercise was performed comparing measurements of CO, O_3, $PM_{2.5}$ and PM_{10} from the Mace Head, County Galway, ground station with the nearest pixel in the CAMS air quality analysis product. Significant correlations ($p < 0.01$) were found for all measurements, ranging between 0.44 and 0.87, with the highest correlations observed for O_3 and CO.

5.5.2 Determining emission baselines

When quantifying the emissions from a fire event, it is necessary to have information about the background concentration level for each of the pollutants observed, to understand the extent to which fire events contribute to total pollutant concentration levels (Gao *et al*., 2018). The background concentration level is the portion of a pollutant in the air that is not directly attributable to a local pollutant source but caused by natural processes or human activity (US EPA, 2005; Tchepel *et al*., 2010; Gao, *et al*., 2018, 2019). The background concentration is not a single fixed value, but is influenced by spatial and temporal factors such as seasonal and regional fluctuations. Moreover, meteorological factors such as wind direction and speed can affect background concentrations (McNabola *et al*., 2011; Gao *et al*., 2018).

To estimate the atmospheric background concentrations at the location of fire events, baseline-derivation methods were developed to establish three baselines: a temporal, a spatial and a spatio-temporal baseline. A short explanation of the method used for each baseline is given below. Figure 5.6 provides a schematic representation of the methods used.

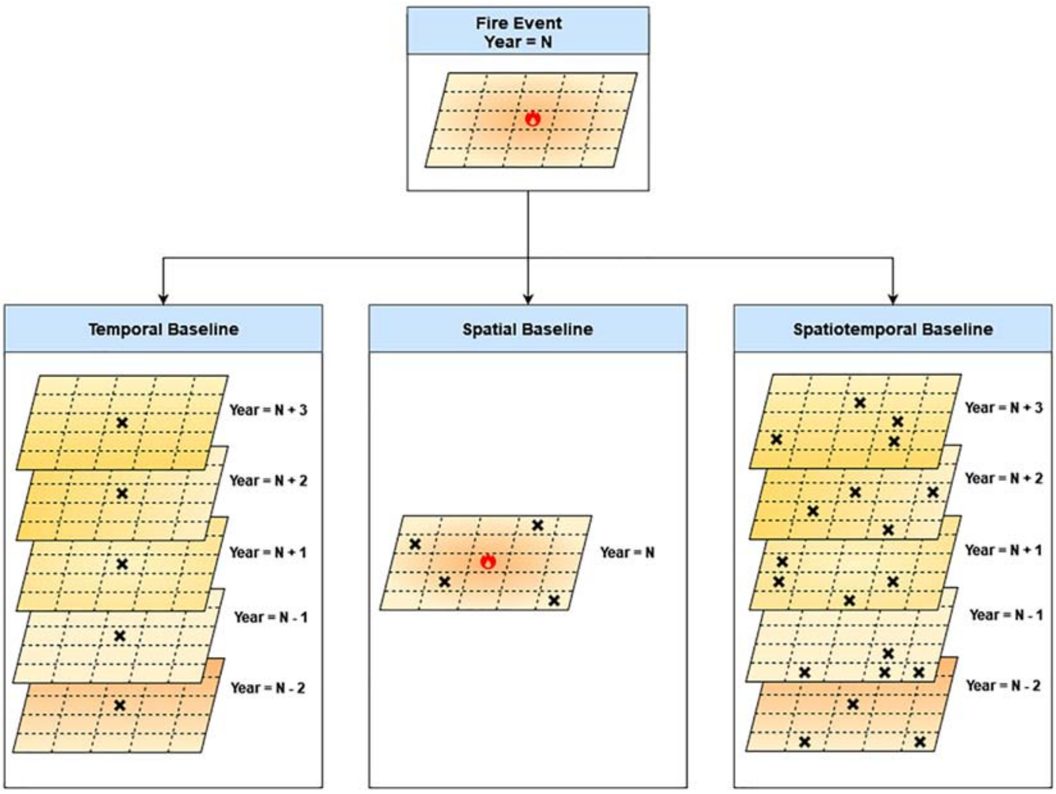

Figure 5.6. The different baseline methods, where X represents a pixel that is selected for the baseline calculation for each method.

Temporal baseline

The goal of using a temporal baseline was to capture the typical concentration range for a fire event by comparing the pollutant concentrations in the ENSEMBLE dataset at the location of the fire with the concentrations recorded at that location in years in which a fire did not take place. To prevent other fire events from contaminating the data, an area of 100 km by 100 km was masked from ENSEMBLE data for a period of 48 hours for all other fire events reported by MODIS. Next, pollutant concentration levels for the ENSEMBLE pixel that overlaps with the location of the fire event were selected for each available year, excluding the year during which the fire took place. This results in a collection of pixel values, which are then used to calculate descriptive statistics such as the mean, median, standard deviation, and upper and lower quartiles. These statistics were then used as an indication of the temporally derived background concentration levels for a fire event.

Spatial baseline

The spatial baseline was derived to attempt to examine the background concentration levels during the time of the fire event itself, using the pollutant concentrations for ENSEMBLE pixels with similar physical and meteorological characteristics to the ENSEMBLE pixel overlapping the fire event. The selection of the most similar pixels was done using the scikit-learn Python library's nearest neighbour algorithm, which selects the closest data points in the feature space. The feature space refers to the number of dimensions in which the data points of a training set are based, where the number of features of the data point determines the number of dimensions. There are many ways in which the distance for the feature space can be calculated, but most commonly the Euclidean distance is used.

The average, median, 25th and 75th percentile elevations, and slope were calculated for the area covered by each ENSEMBLE pixel based on EU-DEM v1.1. The dominant land cover class for each ENSEMBLE pixel was determined from the CORINE2018 land cover dataset. Using the meteorological data (MÉRA up to August 2019; ERA5 from August 2019), the average, median, standard deviation, and 25th and 75th percentile values were calculated for temperature, precipitation and wind speed, as well as average wind direction. These features were used to determine the pixels most similar to the ENSEMBLE pixel overlapping the fire event. For this study, the 50 most similar pixels located over land within 50–250 km of the fire event were selected. Just as with deriving the temporal baseline, the pollutant concentration of the selected pixels was used to calculate descriptive statistics such as the mean, median, standard deviation, and upper and lower quartiles.

Spatio-temporal baseline

The method used to derive the spatio-temporal baseline combined the methods used for the spatial and temporal baselines, to create a more robust version of the temporal baseline. One of the disadvantages of using the temporal baseline was that it was based on a single pixel value per year, giving a very small sample set to use for the calculation of the baseline concentration range. To remedy this, for the spatio-temporal baseline for each year, excluding the year of observation, a collection of pixels was selected, using the same nearest neighbour algorithm as used for the spatial baseline, that were most similar to the ENSEMBLE pixel overlapping the location of the fire event.

5.5.3 Exploring fire events using CAMS data

The initial exploration of the CAMS data focused on single fire events identified for the validation database described in sections 1.1 and 1.2. The results were very inconsistent, with some fire events showing strong peaks in constituent concentrations and other fire events not showing any considerable increases in pollutant concentrations at all. The emissions associated with the known fire events can be explored at the FLARES project interactive web portal (https://www.flares.randbee.com).

To assess the impact of fire events on the ENSEMBLE product in a methodical way, the deviation from the baseline was calculated for each fire event reported between 2015 and 2021. The graphs in Figure 5.7 show the median deviation by baseline type for all fires reported by MODIS over Ireland for each of the pollutants analysed. The values were smoothed using a 6 hour window moving average for visualisation purposes. The graphs show that the deviations for

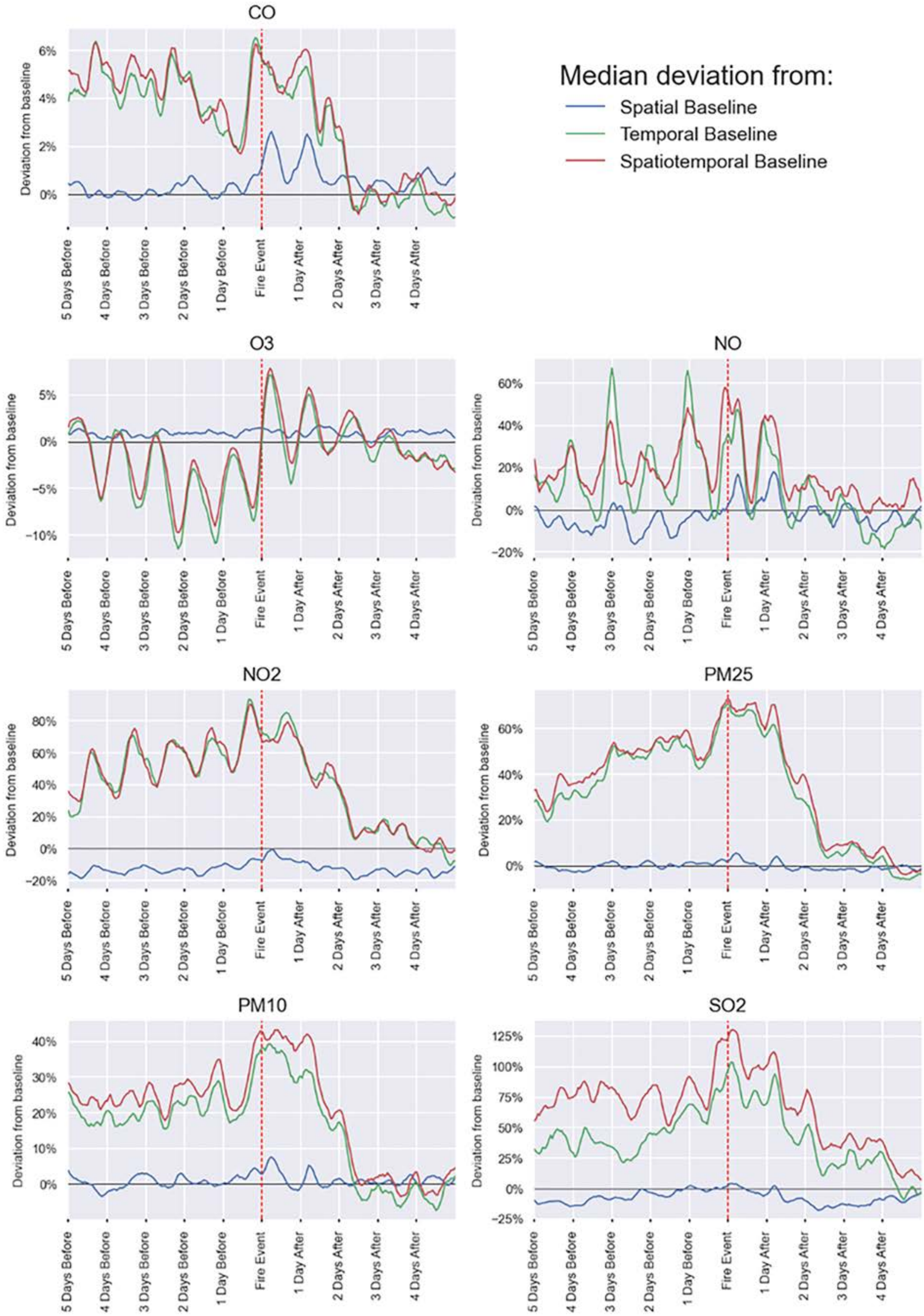

Figure 5.7. The median deviation by baseline type for all fires reported by MODIS between 2015 and 2021 for each of the pollutants analysed.

all pollutants are much higher for the temporal and spatio-temporal baselines than for the spatial baseline. Moreover, the difference between the deviations from the spatio-temporal and temporal baselines is minimal. There are also noticeable differences between pollutants, with CO showing a relatively small median deviation from the baseline (approximately 6% around the time of detection of the fire event) and O_3 showing a negative deviation before the report of the fire event that quickly peaks at about 6% immediately after the fire is reported. For other pollutants, there is a gradual increase in pollutant levels in the days leading up to the report of the fire event, peaking between the report of the fire event and 2 days after, and then quickly decreasing. Some of the pollutants show a very clear diurnal signal before the fire, which is modified after the fire event, possibly due to human activity, for example emissions of NO and NO_2, which, as discussed in section 5.1, are the product of traffic emissions.

Given that the temporal and spatio-temporal baselines give very similar results, further analysis of fire events was performed using the temporal baseline, which was the least computationally expensive. The graphs in Figure 5.8 show the value range between the 25th and 75th percentiles for deviations from the temporal baseline for all Irish fires reported by MODIS between 2015 and 2021 for each of the pollutants analysed. For all pollutants, the 25th percentile line follows or is below the line indicating a 0% deviation from the baseline, i.e. for 25% of the fires reported by MODIS, there was no noticeable, and in some instances even a negative, deviation from the temporal baseline values at the time of the fire.

5.5.4 Evaluation of CAMS data for quantifying vegetation fire emissions over Ireland

The analysis performed by calculating the percentage difference between the three baselines and the pollutant concentrations reported by the CAMS product during the time of a fire shows a pattern of increasing deviation from the baseline in the days leading up to, during and shortly after a fire event. The percentage differences between the temporal and spatio-temporal baselines from the values reported by the CAMS product are much higher than for the spatial baseline, while the difference between the deviation from the temporal baseline and the deviation from the spatio-temporal baseline is minimal. This suggests that, even though emissions from fire events affect the ENSEMBLE model outputs, the spatial variability over Ireland is relatively low. The lack of precision of the spatial distribution of the pollutant concentrations related to fire events confirms that the low spatial resolution of the ENSEMBLE product is better suited to assessing pollution on the pan-European or regional scale, rather than on the local scale (Marécal *et al*., 2015).

Considering that many ENSEMBLE models incorporate emissions for 2 days after detection, it is interesting to note that there is a gradual increase in deviation from the baseline in the days leading up to the detection of a fire event (Figure 5.8). By contrast, for O_3 a negative deviation from the baseline is seen in the days before the detection of the fire event and a positive deviation after. A possible explanation for the increase in deviation from the baseline in the days before the fire event is detected by MODIS could be that the *in situ* measurements, which are used to produce the analysis product, detect emissions from the initial fire ignition before it is sufficiently large to be detected by the satellite sensors. It could also be attributable to the grouping of FIRMS fire reports in the validation database to prevent multiple reports for the same fire event. The strong decrease in the percentage deviation from the baseline 48 hours after the report of the fire event is in line with the period of incorporation of the GFAS fires as emission sources into the ENSEMBLE modelling.

Figure 5.8 shows the range of deviations from the temporal baseline for only those fire events detected by the MODIS sensors on Aqua and Terra. These can be compared with deviations from the baseline for the VIIRS sensors on NOAA-20 and Suomi NPP shown in Figure 5.9. The deviation from the baseline is less pronounced for the VIIRS sensors, but the median deviation shows the same trend as seen for the fire events reported by MODIS. This similarity could be attributed to an overlap in fire events reported by VIIRS and MODIS, meaning that the ENSEMBLE partner models incorporated emissions from the fire indirectly. When a fire event is not detected by MODIS satellites, the other correcting factor would be information from *in situ* measurements.

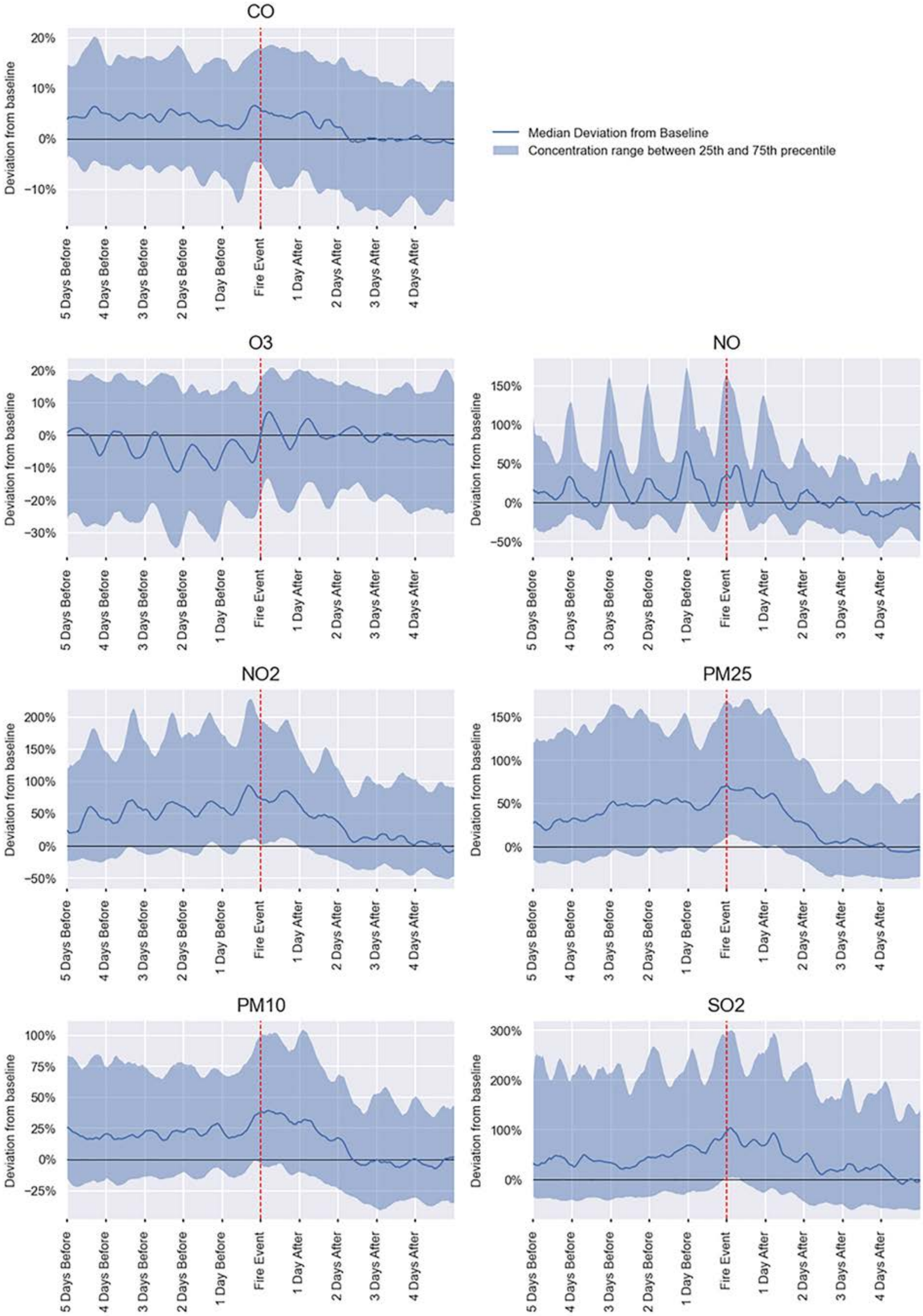

Figure 5.8. The range between the 25th and 75th percentiles and median deviations from the temporal baseline for all fires reported by MODIS between 2015 and 2021 for each of the pollutants analysed.

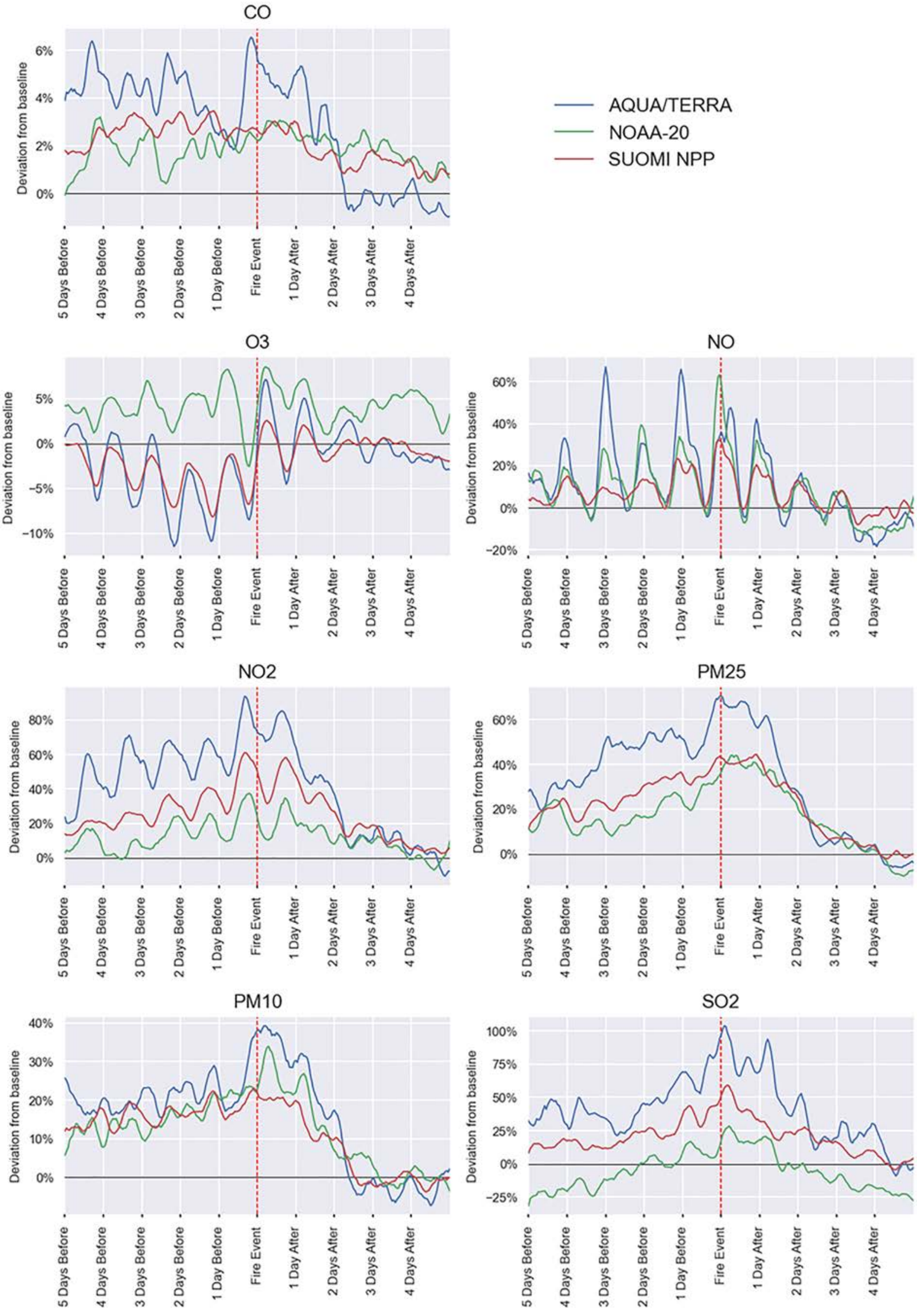

Figure 5.9. The differences in deviation from the temporal baseline for fires reported by different satellite sources between 2015 and 2021 over Ireland for each of the pollutants analysed.

It is anticipated that the future GFAS product will include fire events reported by the VIIRS sensors, which would be a considerable improvement given their higher spatial resolution, of 375 m, enabling smaller fire events to be detected. Moreover, potential future planned improvements to the CAMS ENSEMBLE product could make it better suited to quantifying emissions from fire events in Ireland. For example, one potential improvement would be to include hourly data from Sentinel-4, which is anticipated for launch as a geostationary platform in 2024, for several atmospheric constituents.

5.5.5 The potential of Sentinel-5P

The Sentinel-5 precursor satellite (Sentinel-5P) was launched in 2017, carrying the TROPOspheric Monitoring Instrument (TROPOMI). The main goal of this mission is to map daily global atmospheric composition with a spatial resolution of 7 km (Hu *et al.*, 2018) and use these measurements for air quality, O_3, UV radiation and climate monitoring and forecasting (ESA, 2020). Combined with hourly data from Sentinel-4, data from these missions will allow for improved analysis of pollution levels at a local level and from specific events. At present, however, although the spatial resolution of Sentinel-5P data is higher than that of the CAMS ENSEMBLE data, Sentinel-5P data have a low temporal resolution and this satellite does not provide daily observation data, with cloud cover further limiting consistent data acquisition. Sentinel-5P data could potentially complement the CAMS data, with average values based on 7–10 day periods, but analysis of the data did not demonstrate any significant ability to detect the relatively short duration of fires that occurred in Ireland during the period of study.

5.6 Conclusions

The air quality network in Ireland is able to detect some wildfire events, but it is very dependent on local topography and prevailing meteorological conditions, with the potential for large fire events to go completely undetected. While these events may not have significant consequences for urban and suburban centres, the very high short-term emission levels can affect the local population, and there may be no record of the event for use in calculating national emission levels. Modelled data from the CAMS product reveal an influence of fire events on pollutant concentration levels, but the delineation and quantification of emissions attributable to fire events are unrealistic. At present, the only fires that are evident in the product are those that are reported by MODIS, which is a very small proportion of the total number of fires in Ireland.

6 Conclusions and Recommendations

6.1 Conclusions

6.1.1 Detection and mapping of burn scars from satellite images

The FLARES project results indicate significantly more burned area and emissions related to wildfires in Ireland than all other estimates, which focus on active fires mapped in near-real time. This project has developed a methodology for detecting and mapping smaller, more short-lived fires that may occur under conditions of cloud and heavy smoke and were thus not captured in these previous estimates. This new methodology has proven that optical satellite imagery of medium spatial resolution from Sentinel-2 and Landsat-8 can successfully map burn scars as small as 0.4 ha, and that active C-band Sentinel-1 microwave imagery cannot reliably identify burned areas in Ireland owing to surface backscatter changes arising from events other than wildfires. Depending on the location and season, burn scars are evident on these optical images on average for 36–54 days, although this depends on the sensor and the location and timing of the fire, with vegetation regenerating most quickly after spring fires. All sources of information indicate that the majority of fires occur between March and June, with fire occurrence peaking in April, highlighting the need for as short a period of time as possible between the fire and the first cloud-free image, to enable detection. This can be achieved through a combination of multiple sensors from the same family, e.g. Sentinel-2A and -2B, and from 2022 onwards Landsat-8 and -9, and by combining the results from different sensors. Sentinel-2's higher temporal and spatial resolutions enable better detection and delineation of burn scars and fewer false positives than can be achieved with Landsat-8. However, the multi-date and thresholding approach taken for the Sentinel-2 data makes it a more conservative product. This approach was required because false positives are generated from agricultural activities, such as harvesting, and from peat bogs, cloud and cloud/topographical shadows, but many false positives can be eliminated using the EPA/OSi INLM, based on the samples made available during the project's lifetime.

Irish wildfires are often referred to as "gorse fires", and, for the first time, the location of 180 km^2 (18,000 ha) of gorse has been mapped from satellite imagery. However, while gorse may be burned in upland areas, many wildfires affect other habitats. Up to half of the burned area each year lies within designated protected areas, about one-quarter of which is classed as heavily improved grassland in the NPWS Habitat Asset Register. Forest fires meanwhile account for less than 4% of the burned land.

6.1.2 Measurement of greenhouse gas and particulate emissions from wildfires

Combustion chamber experiments demonstrated that EFs for three Irish vegetation species (gorse, heather and purple moor grass) can be determined and are in line with published values for other species. Although some caution is required, as conditions in a chamber encourage more complete combustion, with flaming, than might be seen in a real wildfire event, these values can be used to produce more refined estimates of emission levels. Likewise, chamber experiments are essential to understand how primary products age to secondary products in the atmosphere after a fire, with the amount of PM (TPM, $PM_{2.5}$ and PM_{10}) from the three Irish vegetation species increasing by up to 10% when these secondary products are included in the emission estimates.

Field measurements demonstrated that emissions from individual wildfire events can be distinctive, and instantaneously extremely high, highlighting the importance of the fixed air quality network but also its inadequacy, given that the vast majority of the monitoring stations are in population centres that are not necessarily close to a fire event. The lack of evidence of a fire event in air quality records during the period of the Killarney National Park fire in April 2021 illustrates how a significant wildfire that emits large amounts of GHGs and PM can be completely overlooked by the current air quality monitoring network (where GHGs are not routinely measured).

6.1.3 Modelling of wildfire emissions

Fire events have a notable influence on the pollutant concentration levels in the CAMS product when analysing temporal trends, most notably for $PM_{2.5}$, PM_{10}, SO_2, NO_2 and NO. However, spatial analysis of the ENSEMBLE pollutant concentrations during the fire event shows minimal differences, making delineation and quantification of emissions attributable to fire events unrealistic. The main limiting factor of ENSEMBLE is its reliance on the GFAS product to model fire emissions, as this product currently includes only fire events reported by MODIS. ENSEMBLE analysis and reanalysis products rely mostly on *in situ* observations to correct for any fires missing in the GFAS product, but the small number of stations used in Ireland, in combination with the coarse resolution of the ENSEMBLE product, make it hard to properly attribute emissions directly to fire events.

6.2 Recommendations

6.2.1 Implementation of a national reporting system based on the FLARES methodology

The foremost recommendation of this report is to develop a system that is managed by a responsible agency that can use the FLARES automated method to identify burn scars and calculate vegetation loss and emissions generated on an annual basis, and incorporate this information into emission inventory reports for more refined estimates of wildfire emissions. Current reporting of wildfire events by local authority fire services could be further improved and harmonised, with national guidelines for more accurate spatial information on fire events being made available and fires being labelled more informatively. However, this would still not account for unattended wildfires.

6.2.2 Refinements of the FLARES methodology based on additional land cover data and sensors

If it is to be performed on an operational basis, the FLARES method for burn scar mapping would have to be repeated when the full EPA/OSi INLM becomes available, with improved results being anticipated to result from the removal of agricultural and peat bog false positives. The multi-date and thresholding approach taken for the Sentinel-2 data, making it a more conservative product, would need to be reviewed, given that these steps are designed to remove false positives. Similarly, improving cloud, cloud shadow and topographical shadow identification could result in the elimination of some of the thresholding steps. The FLARES results indicated high fire activity in peat bog areas, some of which are false positives, and, while the INLM will help to eliminate some of these errors, investigation is recommended into whether the thermal bands from Landsat-8 and -9 could help to discriminate peat from combusted vegetation.

6.2.3 Extending the time series of burn scars for the 30 m Landsat data archive (1982 to present)

Subsequent to the completion of data collection for the FLARES project, Landsat-9 was launched with the same sensors as on Landsat-8, enabling a doubling of the frequency of Landsat data collection. A significant improvement was seen in the capability of Sentinel-2 to capture the burn scars after two platforms were operational, and it is highly likely that a similar improvement will be evident with the use of two Landsat platforms. Furthermore, the Landsat archive (Landsat-4 to -7) from 1982 to 2015, with 30 m spatial resolution, could be used to explore spatial and temporal trends and patterns in fire events. From the 7 year sample considered in this project, it is not possible to determine the influence of climate change, land management and policy, and human activities on wildfire patterns in Ireland. Progress towards the attribution of wildfire events to either anthropogenic or natural causes could be advanced with a better understanding of these influences.

6.2.4 Accurate information on Irish land cover, biomass values and emission factors

The EPA/OSi INLM samples proved to be extremely beneficial in eliminating false positives and in characterising the types of vegetation that burned in the years analysed, emphasising the enormous potential that will be offered by a dedicated Irish land cover map over the generic CORINE classes. It is imperative that this dataset is kept up to date, with changes in land cover updated annually. The FLARES methodology could prove to be a useful input to such updates, as it will highlight areas of potential change and allow only areas of change to be revised.

Knowing the mass of biomass burned is essential in calculating emissions, but there are very few biomass standard values and very few EFs have been determined specifically for Irish habitats or species. As noted for land cover, the use of global or European standards is inappropriate for the unique and fragmented Irish habitats, and calculating biomass and EF values for Ireland's main habitats and species should be a priority, to remove the remaining key uncertainties in FLARES emission estimations.

6.2.5 Additional capacity in the Irish air quality monitoring network

Currently, the EPA-managed national air quality monitoring network focuses on monitoring for compliance and regulatory purposes, and on providing information on ambient air quality to the Irish public. Additional capacity, beyond the criteria set by the EU directive on ambient air quality and cleaner air for Europe (CAFE Directive 2008/50/EC), would support the acquisition of data for other domains of national importance. This includes more detailed measurements of wildfire emissions as discussed here, but also data for the validation of remotely sensed products and air quality nowcasting and forecasting models in areas that, in the opinion of the authors, are currently poorly served by ground-based measurements. The locations of future stations, especially in rural areas, which are under-represented in the national monitoring network, could in part be determined by identifying sites of repeated burn scars using the FLARES methodology, or where population centres are affected.

6.2.6 Closer collaboration with the CAMS development team

The outputs from the FLARES project with respect to identification of small-scale fires and species-specific EFs can support the improvement of CAMS products for mid-latitude fire emission quantifications via refinement of the GFAS product. The extended *in situ* monitoring network referred to in section 6.2.5 and Irish researchers working in air quality and atmospheric dynamics could strengthen engagement with the CAMS development team, leading to the generation of more reliable atmospheric air quality information and forecasts for use in Ireland.

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Abbreviations

BC	Black carbon
CAMS	Copernicus Atmosphere Monitoring Service
CCI	Climate Change Initiative
CEN	European Committee for Standardization
CLC	CORINE Land Cover
CORINE	Coordination of Information on the Environment
DEM	Digital elevation model
DIAS	Data and Information Access Service
dNBR	Differenced Normalised Burn Ratio
EC	Elemental carbon
ECMWF	European Centre for Medium-Range Weather Forecasts
EEA	European Environment Agency
EF	Emission factor
EFFIS	European Forest Fire Information System
EO	Earth observation
ESA	European Space Agency
EU	European Union
FIRMS	Fire Information for Resource Management System
FLARES	Fires, Land and Atmospheric Remote Sensing of Emissions
GFAS	Global Fire Assimilation System
GHG	Greenhouse gas
INLM	Irish National Land Cover Map
IPCC	Intergovernmental Panel on Climate Change
LBBF	Leipzig Biomass Burning Facility
MAES15	Mapping and Assessment of Ecosystems and their Services project
MCE	Modified combustion efficiency
MÉRA	Met Éireann ReAnalysis
MIRBI	Mid-infrared Burned Index
MODIS	Moderate-resolution imaging spectroradiometer
MSI	Multispectral instrument
MSIL2A	Sentinel-2 multispectral instrument level 2A
NASA	National Aeronautics and Space Administration
NBR	Normalised Burn Ratio
NDVI	Normalised Difference Vegetation Index
NDYI	Normalised Difference Yellow Index
NIR	Near-infrared
NOAA	National Oceanic and Atmospheric Administration
NPWS	National Parks & Wildlife Service
NRT	Near-real-time
OC	Organic carbon
OLI	Operational Land Imager
OSi	Ordnance Survey Ireland
PM	Particulate matter
PM_1	Particulate matter of diameter $\leq 1\,\mu m$
$PM_{2.5}$	Particulate matter of diameter $\leq 2.5\,\mu m$

PM_{10}	Particulate matter of diameter ≤ 10 µm
RCC	Regional control centre
SAR	Synthetic aperture radar
Sentinel-5P	Sentinel-5 precursor satellite
SOA	Secondary organic aerosol
Suomi NPP	Suomi National Polar-orbiting Partnership
SWIR	Shortwave-infrared
SWM	Sentinel-2 Water Mask
TC	Total carbon
TPM	Total particulate matter
TROPOS	Leibniz Institute for Tropospheric Research
UNFCCC	United Nations Framework Convention on Climate Change
UV	Ultraviolet
VIIRS	Visible Infrared Imaging Radiometer Suite
VOC	Volatile organic compound
WHO	World Health Organization

An Ghníomhaireacht Um Chaomhnú Comhshaoil

Tá an GCC freagrach as an gcomhshaol a chosaint agus a fheabhsú, mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ar thionchar díobhálach na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialáil: Rialáil agus córais chomhlíonta comhshaoil éifeachtacha a chur i bhfeidhm, chun dea-thorthaí comhshaoil a bhaint amach agus díriú orthu siúd nach mbíonn ag cloí leo.

Eolas: Sonraí, eolas agus measúnú ardchaighdeáin, spriocdhírithe agus tráthúil a chur ar fáil i leith an chomhshaoil chun bonn eolais a chur faoin gcinnteoireacht.

Abhcóideacht: Ag obair le daoine eile ar son timpeallachta glaine, táirgiúla agus dea-chosanta agus ar son cleachtas inbhuanaithe i dtaobh an chomhshaoil.

I measc ár gcuid freagrachtaí tá:

Ceadúnú

- Gníomhaíochtaí tionscail, dramhaíola agus stórála peitril ar scála mór;
- Sceitheadh fuíolluisce uirbigh;
- Úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe;
- Foinsí radaíochta ianúcháin;
- Astaíochtaí gás ceaptha teasa ó thionscal agus ón eitlíocht trí Scéim an AE um Thrádáil Astaíochtaí.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Iniúchadh agus cigireacht ar shaoráidí a bhfuil ceadúnas acu ón GCC;
- Cur i bhfeidhm an dea-chleachtais a stiúradh i ngníomhaíochtaí agus i saoráidí rialáilte;
- Maoirseacht a dhéanamh ar fhreagrachtaí an údaráis áitiúil as cosaint an chomhshaoil;
- Caighdeán an uisce óil phoiblí a rialáil agus údaruithe um sceitheadh fuíolluisce uirbigh a fhorfheidhmiú
- Caighdeán an uisce óil phoiblí agus phríobháidigh a mheasúnú agus tuairisciú air;
- Comhordú a dhéanamh ar líonra d'eagraíochtaí seirbhíse poiblí chun tacú le gníomhú i gcoinne coireachta comhshaoil;
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Dramhaíola agus Ceimiceáin sa Chomhshaol

- Rialacháin dramhaíola a chur i bhfeidhm agus a fhorfheidhmiú lena n-áirítear saincheisteanna forfheidhmithe náisiúnta;
- Staitisticí dramhaíola náisiúnta a ullmhú agus a fhoilsiú chomh maith leis an bPlean Náisiúnta um Bainistíocht Dramhaíola Guaisí;
- An Clár Náisiúnta um Chosc Dramhaíola a fhorbairt agus a chur i bhfeidhm;
- Reachtaíocht ar rialú ceimiceán sa timpeallacht a chur i bhfeidhm agus tuairisciú ar an reachtaíocht sin.

Bainistíocht Uisce

- Plé le struchtúir náisiúnta agus réigiúnacha rialachais agus oibriúcháin chun an Chreat-treoir Uisce a chur i bhfeidhm;
- Monatóireacht, measúnú agus tuairisciú a dhéanamh ar chaighdeán aibhneacha, lochanna, uiscí idirchreasa agus cósta, uiscí snámha agus screamhuisce chomh maith le tomhas ar leibhéil uisce agus sreabhadh abhann.

Eolaíocht Aeráide & Athrú Aeráide

- Fardail agus réamh-mheastacháin a fhoilsiú um astaíochtaí gás ceaptha teasa na hÉireann;
- Rúnaíocht a chur ar fáil don Chomhairle Chomhairleach ar Athrú Aeráide agus tacaíocht a thabhairt don Idirphlé Náisiúnta ar Ghníomhú ar son na hAeráide;
- Tacú le gníomhaíochtaí forbartha Náisiúnta, AE agus NA um Eolaíocht agus Beartas Aeráide.

Monatóireacht & Measúnú ar an gComhshaol

- Córais náisiúnta um monatóireacht an chomhshaoil a cheapadh agus a chur i bhfeidhm: teicneolaíocht, bainistíocht sonraí, anailís agus réamhaisnéisiú;
- Tuairiscí ar Staid Thimpeallacht na hÉireann agus ar Tháscairí a chur ar fáil;
- Monatóireacht a dhéanamh ar chaighdeán an aeir agus Treoir an AE i leith Aeir Ghlain don Eoraip a chur i bhfeidhm chomh maith leis an gCoinbhinsiún ar Aerthruailliú Fadraoin Trasteorann, agus an Treoir i leith na Teorann Náisiúnta Astaíochtaí;
- Maoirseacht a dhéanamh ar chur i bhfeidhm na Treorach i leith Torainn Timpeallachta;
- Measúnú a dhéanamh ar thionchar pleananna agus clár beartaithe ar chomhshaol na hÉireann.

Taighde agus Forbairt Comhshaoil

- Comhordú a dhéanamh ar ghníomhaíochtaí taighde comhshaoil agus iad a mhaoiniú chun brú a aithint, bonn eolais a chur faoin mbeartas agus réitigh a chur ar fáil;
- Comhoibriú le gníomhaíocht náisiúnta agus AE um thaighde comhshaoil.

Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéil radaíochta agus nochtadh an phobail do radaíocht ianúcháin agus do réimsí leictreamaighnéadacha a mheas;
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha;
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta;
- Sainseirbhísí um chosaint ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Ardú Feasachta agus Faisnéis Inrochtana

- Tuairisciú, comhairle agus treoir neamhspleách, fianaise-bhunaithe a chur ar fáil don Rialtas, don tionscal agus don phobal ar ábhair maidir le cosaint comhshaoil agus raideolaíoch;
- An nasc idir sláinte agus folláine, an geilleagar agus timpeallacht ghlan a chur chun cinn;
- Feasacht comhshaoil a chur chun cinn lena n-áirítear tacú le hiompraíocht um éifeachtúlacht acmhainní agus aistriú aeráide;
- Tástáil radóin a chur chun cinn i dtithe agus in ionaid oibre agus feabhsúchán a mholadh áit is gá.

Comhpháirtíocht agus Líonrú

- Oibriú le gníomhaireachtaí idirnáisiúnta agus náisiúnta, údaráis réigiúnacha agus áitiúla, eagraíochtaí neamhrialtais, comhlachtaí ionadaíocha agus ranna rialtais chun cosaint chomhshaoil agus raideolaíoch a chur ar fáil, chomh maith le taighde, comhordú agus cinnteoireacht bunaithe ar an eolaíocht.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an GCC á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóir. Déantar an obair ar fud cúig cinn d'Oifigí:

1. An Oifig um Inbhunaitheacht i leith Cúrsaí Comhshaoil
2. An Oifig Forfheidhmithe i leith Cúrsaí Comhshaoil
3. An Oifig um Fhianaise agus Measúnú
4. An Oifig um Chosaint ar Radaíocht agus Monatóireacht Comhshaoil
5. An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tugann coistí comhairleacha cabhair don Ghníomhaireacht agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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