Three wildfires in England

Best practice and lessons learned

November 2023

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Foreword

Wildfires are episodic events in the UK, generally occurring in association with specific meteorological conditions and anthropogenic activity. One of the many gaps in our understanding of wildfire events in the UK is around the effectiveness of land management interventions aimed at reducing the impact of wildfire events. This report was commissioned as a pilot investigation to begin the process of developing a view of what may be considered good practice, based upon the experience of wildfire at the three sites examined.

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Executive summary

Over the past 15 years, the frequency of wildfire events affecting areas larger than 30 ha is reported to have increased across many European countries. In the UK, large fires have occurred over the past few years, but over the period 2003-2020, no increasing trend in the number of events was identified. Current climate predictions for Europe suggest that there will be a shift towards wetter winter months and drier spring/summer months, with an increased frequency and duration of periods of drought. If a fire occurs under drought conditions, the severity of the fire is likely to be greater, but vegetation does not spontaneously combust. Some wildfires can occur from natural phenomena, but for the UK at least, the majority of wildfire events are started by human activity, either accidentally through negligence, or as deliberate acts of arson.

Monitoring of meteorological and ground conditions enable predictions of fire severity to be created. These enable landowners and land managers to identify times of highest risk when any fires that start would likely become difficult to control. Despite provision of clear warnings of fire risk, wildfires created by human activity continue to occur. These events are thus, to some degree, out of the control of landowners and land managers. However, fire defence and site management strategies can be adopted to mitigate the impact and spread of fires that do occur. In addition, understanding what approaches to controlling wildfires are most effective may improve the way in which future fires are tackled.

This pilot study examined wildfire events at two National Nature Reserves (NNR) and a site designated as a Site of Special Scientific Interest (SSSI) in England. The fire events examined occurred on an area of blanket bog (Winter Hill, West Pennine Moors SSSI, Lancashire; June 2018), a restored lowland raised bog (Hatfield Moors, Humberhead Peatlands NNR; May 2020), and an area of lowland heath with a valley mire (Thursley NNR, Surrey; May 2020). The spread of fire at each site was mapped using cloud-free very high-resolution (VHR) satellite imagery. Information about ignition sources, and interventions undertaken to supress and control the fires, were obtained from local site managers and supplemented with information from Fire and Rescue Services (FRS) where possible. Pre-fire environmental conditions were assessed using meteorological data and level of fire danger in the form of fire weather indices (FWI). Trends in rainfall over the past 60 years were also determined for each site.

Key findings

Although a very low number of wildfire events were examined, several key observations were made:

Fire source/ignition

- The ignition source at all sites resulted from human activity.

- The wildfire events examined at National Nature Reserves were accidental (presumed to arise from disposable barbeques) and occurred on weekends in May. The risk of fires starting at NNRs may therefore increase on days where visitor numbers are typically higher. The fires burned areas covering between 46 to 432 ha.

- The wildfire event examined at Winter Hill occurred in June and comprised three separate ignitions. A relatively small accidental fire (covering 12.2 ha) arose from a disposable barbecue on a Monday. This was followed by two ignitions three days later that were located 4 km apart and resulted in a fire that covered over 700 ha. The latter ignitions were separate acts of arson.

Environmental conditions

- At all three sites, the fires occurred in months with below average rainfall, above average temperatures, and where the level of fire danger (FWI value) was very high.

- The duration of below average rainfall before the fires ranged from one month (Thursley NNR), through two months (Winter Hill), to three months (Hatfield Moors), but all periods were preceded by wetter than average months.

- Fire danger conditions can therefore develop quickly (in as little as one month).

- A trend of increasingly drier spring months (1961-2020) was identified for all sites and may suggest that the risk of fires that occur in spring/early summer becoming uncontrolled is increasing.

  However:

- Two additional fires at Winter Hill, arising from acts of arson, occurred in months with above average (March 2019) or average (March 2020) monthly rainfall, and the FWI values were low.

- No fires occurred at any of these sites in 2022. Thursley NNR and Hatfield Moors received below average rainfall in November 2021 and in January, April, June and July 2022. Winter Hill experienced eight continuous months from February to September 2022 with below average rainfall.

- There was no ignition source at any of the sites in 2022.

Pre-fire measures

- None of the sites examined had any purpose-built fire defences in place prior to the events.

- At Thursley NNR, vegetation adjacent to footpaths is typically managed by cutting or mowing and provides a form of fire defence. Due to resource cuts this activity was not undertaken in 2020.

- A few fires occurred on Hatfield Moors in the 15 years between cessation of peat extraction in 2005, and the fire that occurred in May 2020, but these were small and extinguished by Reserve staff. As a result, Reserve staff admit that the threat of wildfire was not a key consideration.

- At Winter Hill, some fire breaks had been created on the summit of the hill around telecommunication infrastructure, but efforts were focussed on Anglezarke Moor located 4 km to the north as more fires had occurred there historically.

Barriers and interventions

- At Winter Hill, roads appeared to present an effective barrier to spread of fire even when the fire front was moving with the wind, and tracks appeared to offer effective defence to spread of fire when the fire front was moving against the wind, or perpendicular to the direction of wind.

- At Thursley NNR, sandy, non-vegetated footpaths appeared to offer no impedance to spread of fire when the fire front was aligned with the wind, or perpendicular to the direction of wind. There is some evidence that these footpaths may act as a temporary barrier if the fire front is spreading against the direction of wind.

- Fire breaks created by mowing vegetation during the fire at Thursley NNR were successful in containing some fire edges. Much of this work was undertaken by local farmers.

- Some of the fire breaks constructed using bulldozers at Hatfield Moors were effective at preventing spread of fire, but the approach created considerable piles of brash/scrub. These have been cleared since the fire as they represented a future fire risk.

- Fire breaks constructed using bulldozers at Winter Hill were effective at constraining the spread of the fire. However, the fire breaks are on the periphery of a 700 ha burn scar and caused more longer-term local damage to the blanket peat than the fire. No effective fire breaks were created within the burn scar.

- At Winter Hill, a series of water containers were used to create a relay system pumping water from reservoirs up to the fire event. Although the contribution of this approach to tackling the fire on Winter Hill is not clear, it was effective when used on a subsequent fire on Darwen Moor in 2020.

Site access

- Access for FRS vehicles is constrained at all sites.
- Improving accessibility is unlikely to be possible at any of the sites examined here, or at other designated sites, without damaging the habitats.
- Pre-emptive fire control measures need to be in place at all designated sites.

Habitat affected

- All three sites examined are designated SSSI and contain a type of peatland of international importance. Two sites (Hatfield Moors and Thursley NNR) are also protected under European designation: SAC and SPA.
- At each site, fire burned into the peat and presented challenges of peat re-igniting.
- Habitat and vegetation mapping is inconsistent between the sites examined.

Recommendations

The use of disposable barbeques and campfires should be banned from all designated sites. In addition, the sale of barbeques and associated fuels at convenience stores located near designated sites should be reviewed, as the current availability of equipment may be facilitating impromptu barbeques. Site managers may want to explore options for providing safe and controlled fixed barbeque or cooking facilities.

NNRs must be resourced fully so that appropriate management is maintained. Provision of resources.at Thursley NNR in 2022 allowed management to return to levels undertaken in years prior to the fire in 2020. Vegetation is being managed (mown) adjacent to paths and provides a form of fire defence.

For all restoration projects, a fire management plan must be designed and employed from the outset. At Hatfield Moors, a fire prevention strategy is now in place and a series of fire breaks were constructed in 2022.

Vegetation on either side of all roads, tracks and footpaths at any designated site should be managed by cutting or mowing to enhance the level of fire defence these features provide. If this is undertaken, these features may not need intervention during wildfire events, but can be monitored so that fire control and additional fire breaks, if required, can be prioritised elsewhere.

Fire breaks should be created and maintained in areas that are difficult to access. It is not recommended that hard fire breaks are dug or bulldozed, rather that vegetation is mown or cut. The dimensions outlined in the Humberhead Peatlands NNR fire strategy (6 m wide strips) are recommended as a minimum. During any fire events, it is recommended that fire breaks are kept wet, as this appears to enhance their effectiveness. The use of fire wardens and visitor management should also be employed, and this may be a more effective strategy as it reduces the chance of fires starting. To facilitate fires being tackled before they get out of control, a faster, near real-time alert system should also be explored.

For degraded peatlands, rewetting of the peat body should be a key focus of restoration intervention to reduce the impact of any fires. Hydrological recovery is slow, so other fire control measures, such as fire breaks, will need to be employed until water tables are restored.

Installation of infrastructure that allows the relay of water should be considered at all designated sites, particularly any that have a history of wildfires. Pumping water from reservoirs and other surface water sources to fire suppression activities via a series of water containers appears to be an effective strategy, and containers could be mounted on trailers to allow relocation during fire events if required.

For NNRs and designated sites, it is also recommended that suppression of fire using water dropped from helicopters is deployed rapidly and at the onset. Although the control of a wildfire is likely to be the top priority, the water sources used to suppress fires must also be carefully selected. During breeding seasons, significant disturbance, or reduction in available water, could negatively impact other habitats and sensitive species present. Guidance on water sources should be provided in fire management plans for all sites.

It is recommended that routine water quality monitoring is undertaken at all designated sites to enable the impacts of future fires to be quantified. There may be a greater impact on ombrotrophic ecosystems, such as blanket and raised bogs, if externally sourced, nutrient-rich water is used to suppress fires. In addition, a consistent approach to vegetation mapping is needed to better understand habitats affected in future wildfire events.

Contents

List of figures

1 Introduction

1.1 Background

Wildfire events have been defined as “Any uncontrolled vegetation fire which requires a decision, or action, regarding suppression” (Scottish Government, 2013). In the UK, there are two recognised wildfire seasons: spring (peaking in April) and summer (peaking in July; Perry et al., 2022). The greatest frequency of fires typically occurs in spring, linked with the availability of dead vegetation following winter (Albertson et al., 2010). Fire events in summer are generally lower in number, but typically larger in size (Belcher et al., 2021), and are linked with vegetation dried by summer conditions (Albertson et al., 2010). Over the period 2009-2017, the UK Fire and Rescue Service (FRS) attended an average of 32,000 wildfires each year (Forestry Commission, 2019).

The frequency and intensity of fire weather is reported to be increasing (Jones et al., 2022), and shorter-term records of wildfire events, such as those maintained by the European Forest Fire Information System (EFFIS; 2008-2022) may suggest that there is an increasing trend in frequency of wildfire events >30 ha in size. However, slightly longer-term data, such as the burned area recorded by the MODIS satellite (2003-2020), reveal no trend in frequency for the UK, despite a number of large events occurring in the past few years (Perry et al., 2022). Significant wildfire events occurred in 2003, 2011 and 2018, but the number of fires recorded in these years was not as high as the frequency of fires recorded in 1995 or 1976 (Sibley, 2019).

Wildfires in the UK occur on a wide range of land cover types, although half of the incidents recorded between 2009-2017 occurred in built-up areas and gardens (Forestry Commission, 2019). In contrast, the area of land burned is far greater in open habitats (accounting for over 70% of the burnt area each year), particularly in mountain, heath and bog environments (Forestry Commission, 2019). Wildfires can occur from natural phenomena, but for the UK at least, the majority of wildfire events are started by human activity (Glaves et al., 2020), either accidentally through negligence, or as deliberate acts of arson.

The UK Met Office provides a Fire Severity Index (FSI) that quantifies the severity of potential fire according to a range of weather scenarios (Met Office, 2003). The FSI is based on the Canadian Forest Service Fire Weather Index Rating System (FWI), which comprises three fuel moisture codes and three fire behaviour indices derived from temperature, relative humidity, wind speed and precipitation data (Van Wagner, 1987). FSI predictions for up to 5 days are published and enable landowners and land managers to identify times of highest risk when any fires that start would likely become difficult to control. However, despite provision of clear warnings of fire risk, wildfires created by human activity continue to occur. These events are thus, to some degree, out of the control of landowners and land managers. To mitigate the impact and spread of fires that do occur, fire defence and site management strategies need to be adopted.

A recent review of wildfire on heathlands and peatlands in England identified a lack of information highlighting which fire treatments and strategies are most effective in open habitats (Glaves et al. 2020). The current report presents the results of a pilot study examining three wildfire events in England and assesses any pre-fire management techniques and interventions undertaken during the fires.

1.2 Aims and objectives

For the purpose of this study, Natural England identified three wildfire events that occurred at National Nature Reserves (NNR) and sites designated as SSSI in 2018 and 2020. The study sites identified comprise:

- a restored lowland raised bog (Hatfield Moors, Humberhead Peatlands NNR);
- an area of lowland heath with associated valley mire (Thursley NNR, Surrey);
- an area of blanket bog (Winter Hill, West Pennine Moors SSSI).

The aims of the study, as set by Natural England, were: a) to examine the activity that took place prior to and during the wildfire events; b) to identify what actions were effective; and c) to assess how the knowledge gained can be utilised on these and other sites. In addition, the study aimed to examine meteorological and environmental conditions leading up to the time of ignition and to identify any changes or trends in rainfall over the past few decades.

To address these aims, a number of objectives were defined.

For each site:

- obtain meteorological (rainfall and temperature) and environmental (fire danger level) data to understand pre-fire conditions;
- obtain cloud-free VHR satellite imagery captured before, during and after the fire events;
- map the extent of the fires and identify the habitats affected;
- obtain wind data and combine with mapping to understand the spread of the fires;
- liaise with NNR Estate staff, Natural England upland specialists, landowners and Fire and Rescue Services (FRS) to understand what fire control measures were in place before the fire and the type and chronology of interventions employed;

- from satellite imagery and information gained about the events, map any interventions on the ground and explore the position of these in relation to fire progress;
- explore any changes or trends in rainfall over the past few decades.

It was beyond the scope of the project to assess habitat damage and recovery across the sites.

2 Site descriptions

2.1 Thursley National Nature Reserve

Thursley NNR covers an area of 322.6 ha and is located in the south-east of England, approximately 1 km west of Godalming within the Surrey Hills Area of Outstanding Natural Beauty (AONB; Figure 1). The NNR is part of the Thursley, Hankley and Frensham Commons Site of Special Scientific Interest (SSSI; Figure 1) and is also covered by European designation lying within Thursley, Ash, Pirbright and Chobham Special Area for Conservation (SAC) and Thursley, Hankley and Frensham Commons Special Protection Area (SPA). Natural England manage the NNR along with areas on Elstead and Ockley Commons (Figure 1).

Thursley NNR contains wet and dry heath that is reported to be one of the largest remaining fragments of heathland in Surrey (Giles et al., 2012). The NNR also contains areas of broadleaved and coniferous woodland (Figure 2) and a valley mire complex. The mire complex is recognised as an internationally important wetland and designated as the Thursley & Ockley Bog Ramsar site (Joint Nature Conservation Committee (JNCC), 2007). Thursley and Ockley Bog covers an area of 265 ha, although the valley mire likely covers an area of approximately 52 ha (Figure 2). The latter area was estimated from 1 m resolution Environment Agency Lidar data collected in 2020 and 12.5 cm resolution aerial photography captured in May 2018. Hydrology tools in ArcGIS were used to model surface water and the extent of the bounding polygon was created where there was topographic change or vegetation visibly transitions to heath. The extent of the valley mire is indicative for the purpose of this study and the true extent of the mire will require ground truthing.

Elstead and Ockley Commons in the north of the SSSI are relatively flat, ranging from 60-65 m asl, but Thursley Common contains significant changes in topography, ranging from 60-110 m asl (Figure 2). This topographic variation is reflective of the underlying geology which comprises sands and sandstones of the Lower Greensand Group. The geology underlying Elstead and Ockley Commons is predominantly fine sands, silts and silty clays from the Sandgate Beds, whereas Thursley Common lies on medium- and coarse-grained sands and sandstones from the Folkstone Beds (Figure 2). The hills on the southern edge of Thursley Common divert rainwater to the north and a series of springs at the base of these hills form the start of the valley mire system.

Although the mire contains deep peat (JNCC, 2007), this is not recognised in national soil mapping (www.landis.org.uk) or in Natural England peaty soils mapping

(Natural England, 2013). The soils across the NNR are described as humic-ferric podzols (Avery, 1980). Numerous footpaths (not mapped) cross the site, and three sections of boardwalk, totalling 1.3 km in length, have been installed across sections of the mire (Figure 3). A dense network of bridleways that can be driven on by 4x4 vehicles is also present across the site and can be accessed from at least 13 locations on roads or residential tracks (Figure 3).

The LTM annual rainfall (1962-1990) recorded at Alice Holt Lodge (10 km west) is 776.5 mm (see section 3). A seasonal pattern of monthly rainfall is evident and aligns with the hydrological year, but the mean rainfall totals recorded in February and April are notably lower than the trend and comparable to the total rainfall recorded in the summer months of June and July (Figure 4).

The LTM monthly mean temperatures (1962-1990) range from 3.4°C in January to 16.2°C in July (Figure 4). The lowest LTM monthly minimum temperature is recorded for February (0.52°C) and the highest LTM monthly maximum temperature is recorded for July (21.2°C).

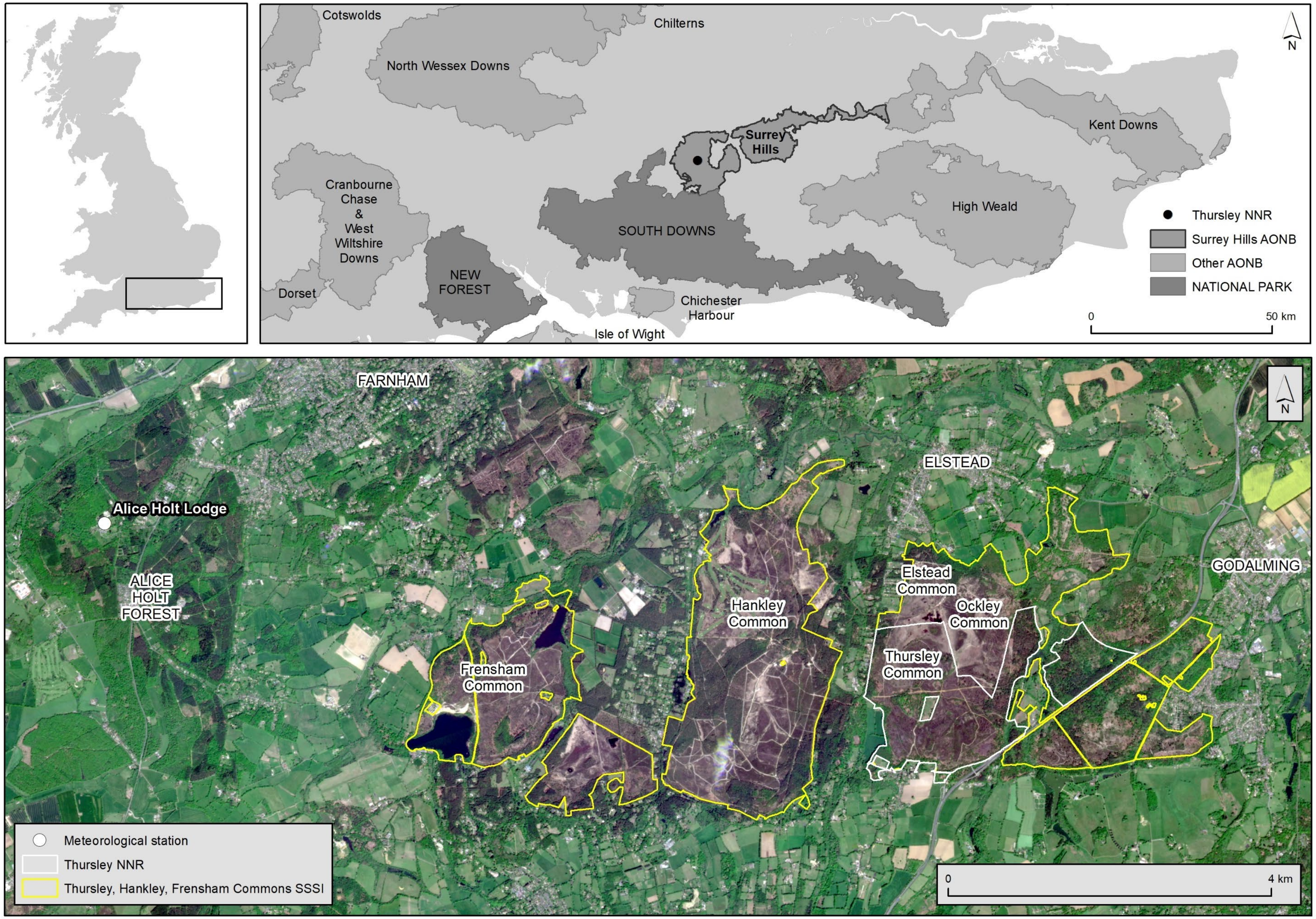


Figure 1. Location of Thursley NNR. Imagery: © Planet 13 May 2019

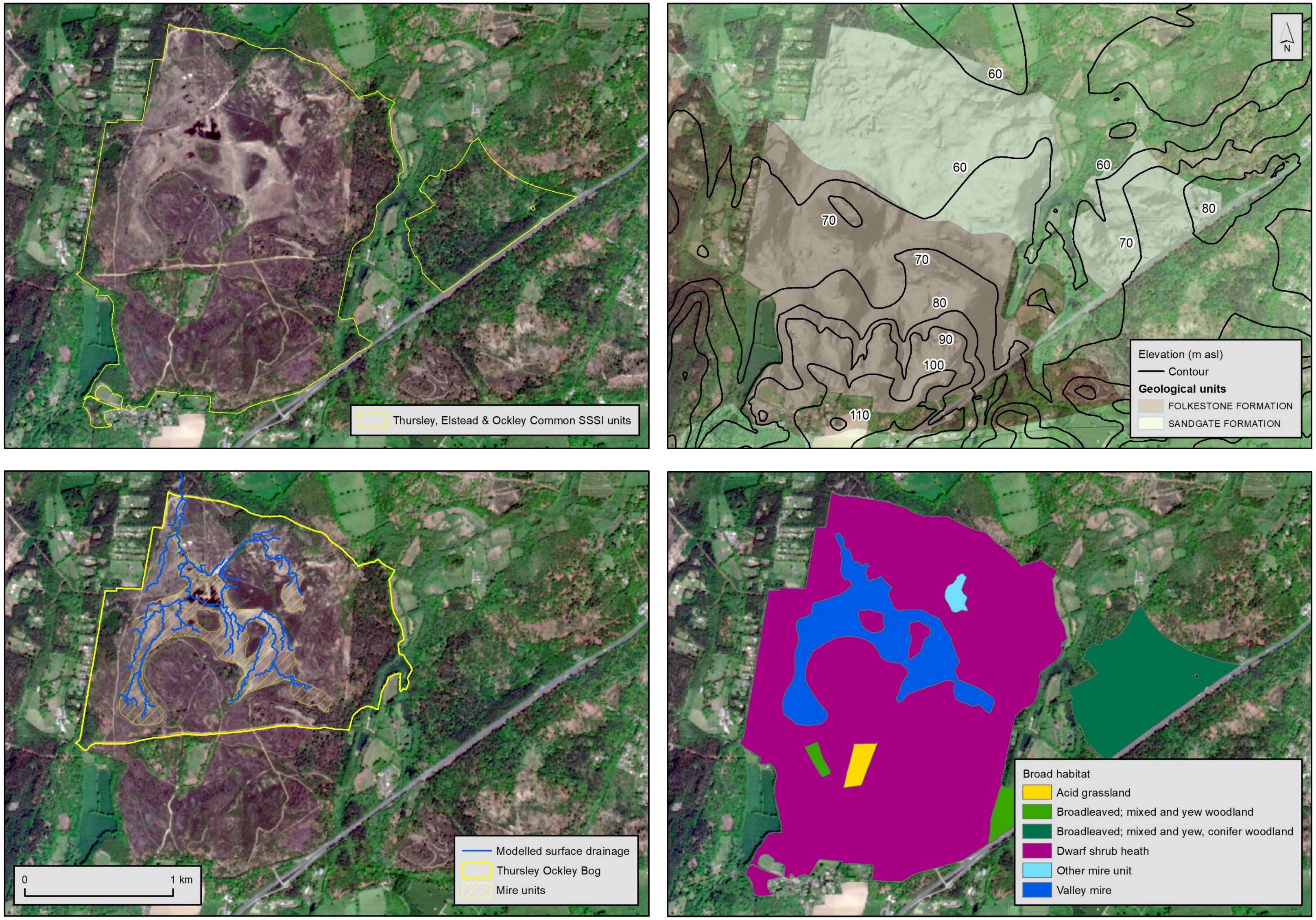


Figure 2. Site designations, geology and broad habitats across Thursley NNR (note: Broad habitat are NVC assigned to component SSSI units). Imagery: © Planet 13 May 2019. Geological Map Data BGS © UKRI 2022

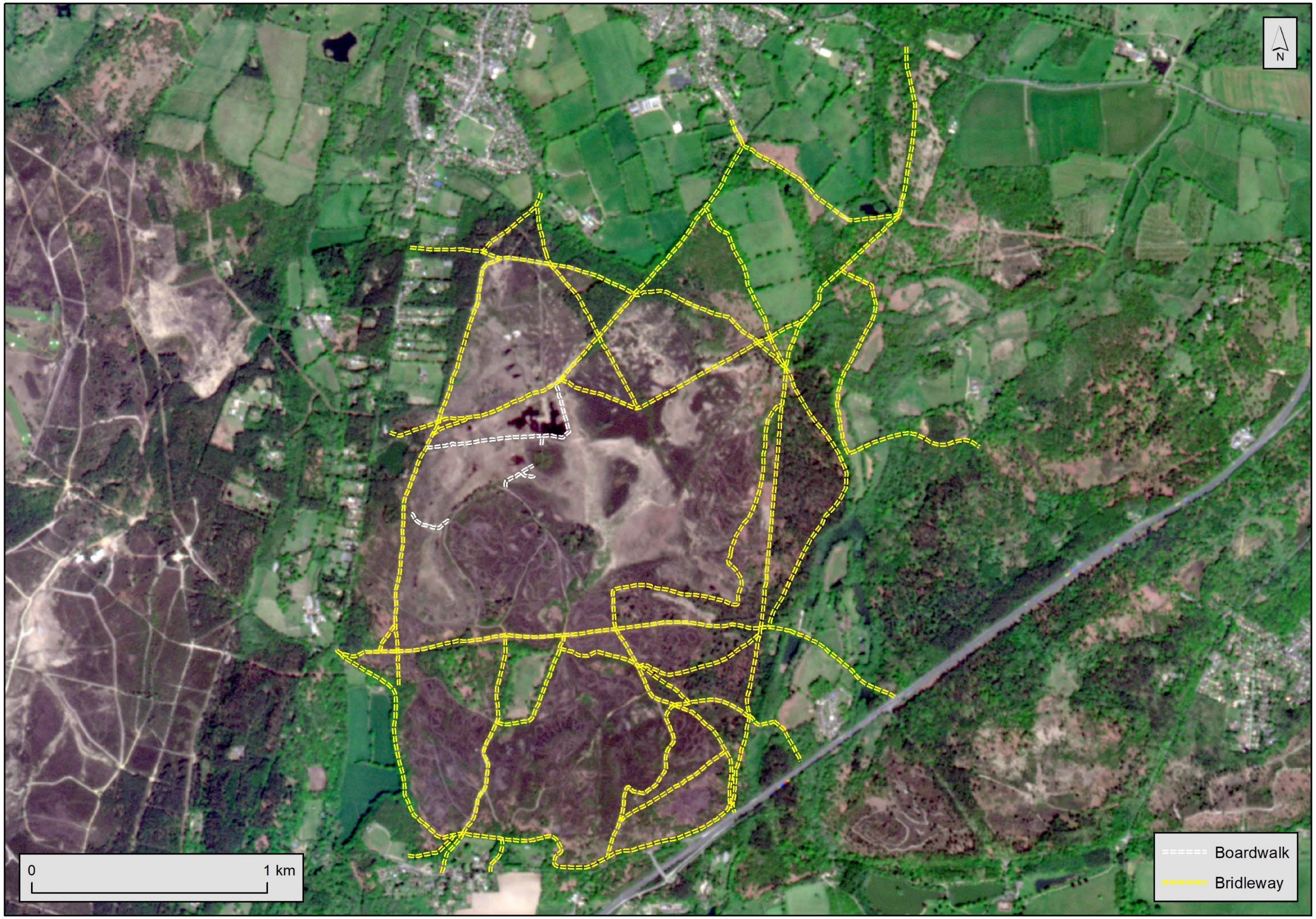


Figure 3. Location of boardwalks and bridleway access across Thursley, Elstead and Oxley Commons (bridleways have been digitised from points of road access). Imagery: © Planet 13 May 2019

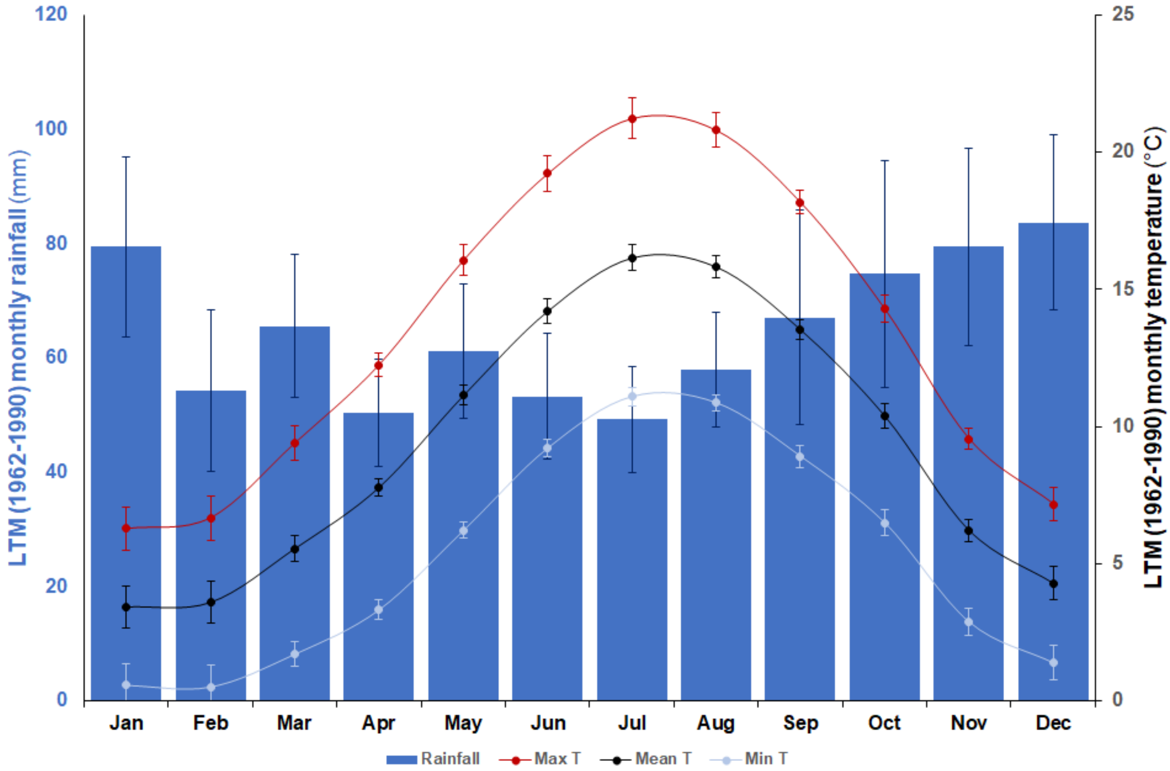


Figure 4. Long term mean (1962-1990) monthly rainfall and temperature recorded at Alice Holt Lodge meteorological station (error bars show 1.96 * s.e.)

2.2 Winter Hill

Winter Hill is located in the north-west of England, approximately 5 km north-west of Bolton (Figure 5). At 456 m asl, the summit of Winter Hill is the highest peak within the West Pennine Moors SSSI and is utilised as a site for television and telecommunications masts. Although there is a steep scarp just north of the summit (Figure 6), and numerous tracks and small roads dissect the terrain, Rivington and Smithills Moors on the flanks of Winter Hill form the southerly part of a blanket mire landscape that extends through Anglezarke Moor to the north and Darwen Moor to the north-east (Figure 5). In contrast to the two other sites examined in this study, Winter Hill does not fall under any European designation.

The extent of Winter Hill is not clearly defined, but land ownership parcels within the SSSI referring to Winter Hill cover an area of 1,118.9 ha, of which 70% (792.7 ha) is owned by United utilities and the remaining 326.2 ha is owned by the Woodland Trust (Figure 7). The Woodland Trust also own a further 153.4 ha of land that extends beyond the limit of the SSSI. Within the section of SSSI owned by United Utilities and the Woodland Trust, the dominant habitats (94% by area) are mapped as blanket bog (65%; 732.4 ha), upland heathland (198 ha; 18%) and acid grassland (Figure 8; 125.2 ha; 11%). Soil mapping indicates that Winter Hill is predominantly covered by deep peat soil (Figure 9), and depths of up to 4 m have been recorded near the summit by Penny Anderson Associates. The soil series 10.11b (Winter Hill) described as mixed *Eriophorum* and *Sphagnum* peat (Clayden & Hollis, 1984) was named after soil surveys undertaken at this location.

The surface geology of Winter Hill is predominantly comprised of sandstone, interleaved with siltstones and mudstones (Geological Map Data BGS © UKRI 2022). Deeper strata in Winter Hill contain several coal seams which have been exploited over the past. Numerous sandstone quarries, kilns, mounds, shafts, tunnels and coal pits are marked on historical OS mapping (dated 1853), along with two collieries (Wildesmoor Colliery and Holdens Colliery; Figure 10). Due south of Wilder's Moor is the currently active Montcliffe stone quarry.

The historical access road to Wildesmoor Colliery has been extended and provides the only vehicular access to the masts on the summit of the hill. The route of Coal Pit Road leading to Holdens Colliery and the Miners' track running north-east from the masts are visible in aerial imagery (Figure 10), but both are only accessible on foot.

The LTM annual rainfall (1961-1990) recorded at Cranberry Moss (located approximately 6 km north-east) is 1417.5 mm, highlighting that this site receives the most rainfall of all sites examined. A seasonal pattern of monthly rainfall is evident and aligns approximately with the hydrological year, but the mean rainfall totals recorded in February and April are comparable to, and lower than, the total rainfall recorded in summer months, particularly in August (Figure 11).

The LTM monthly mean temperatures (1962-1990) recorded at Preston (located approximately 20 km north-west) range from 3.9°C in February to 15.5°C in July (Figure 11). The lowest LTM monthly minimum temperature is recorded for February (1.3°C) and the highest LTM monthly maximum temperature is recorded for July (19.2°C).

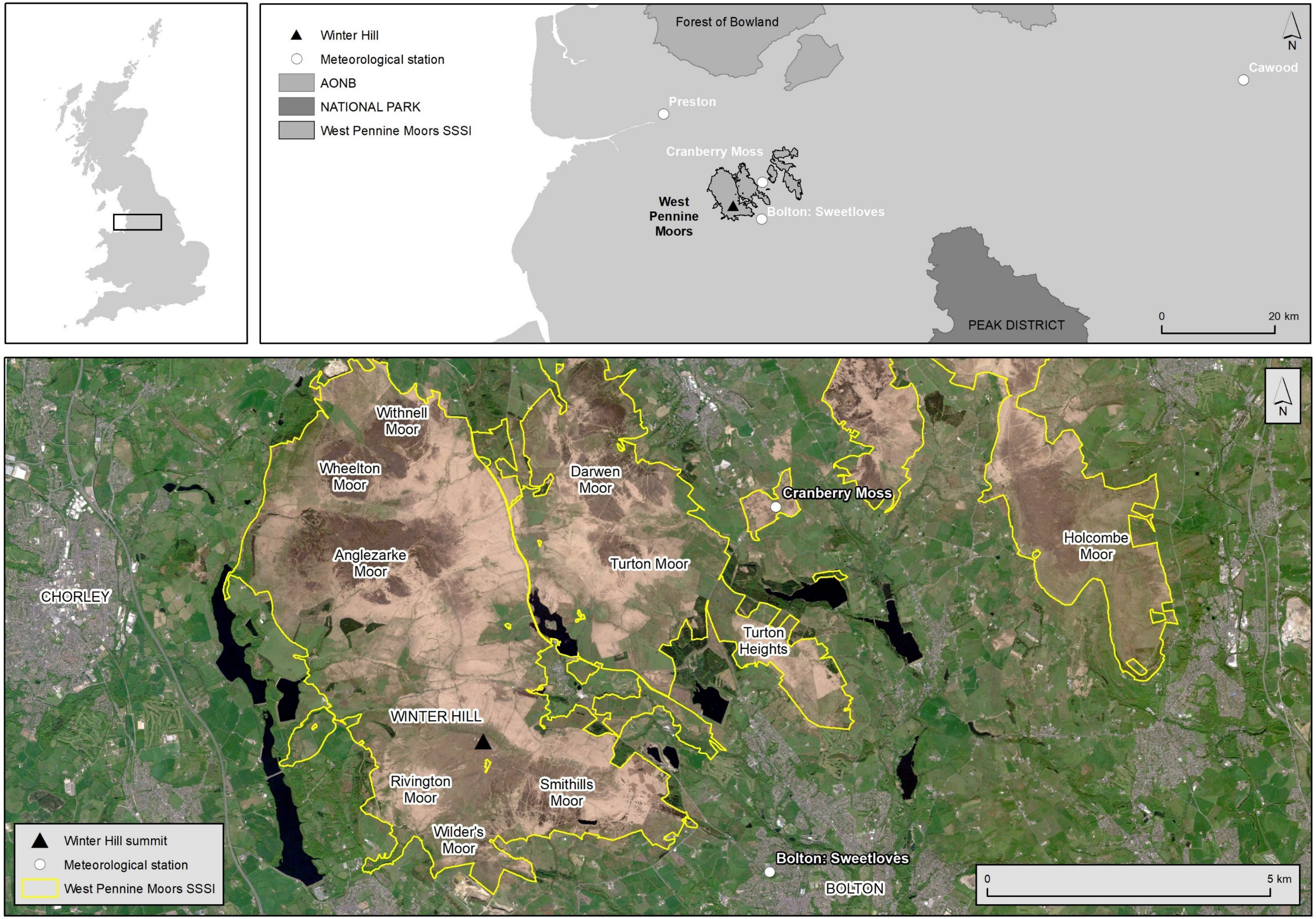


Figure 5. Location of Winter Hill. Imagery: © Planet 07 May 2017

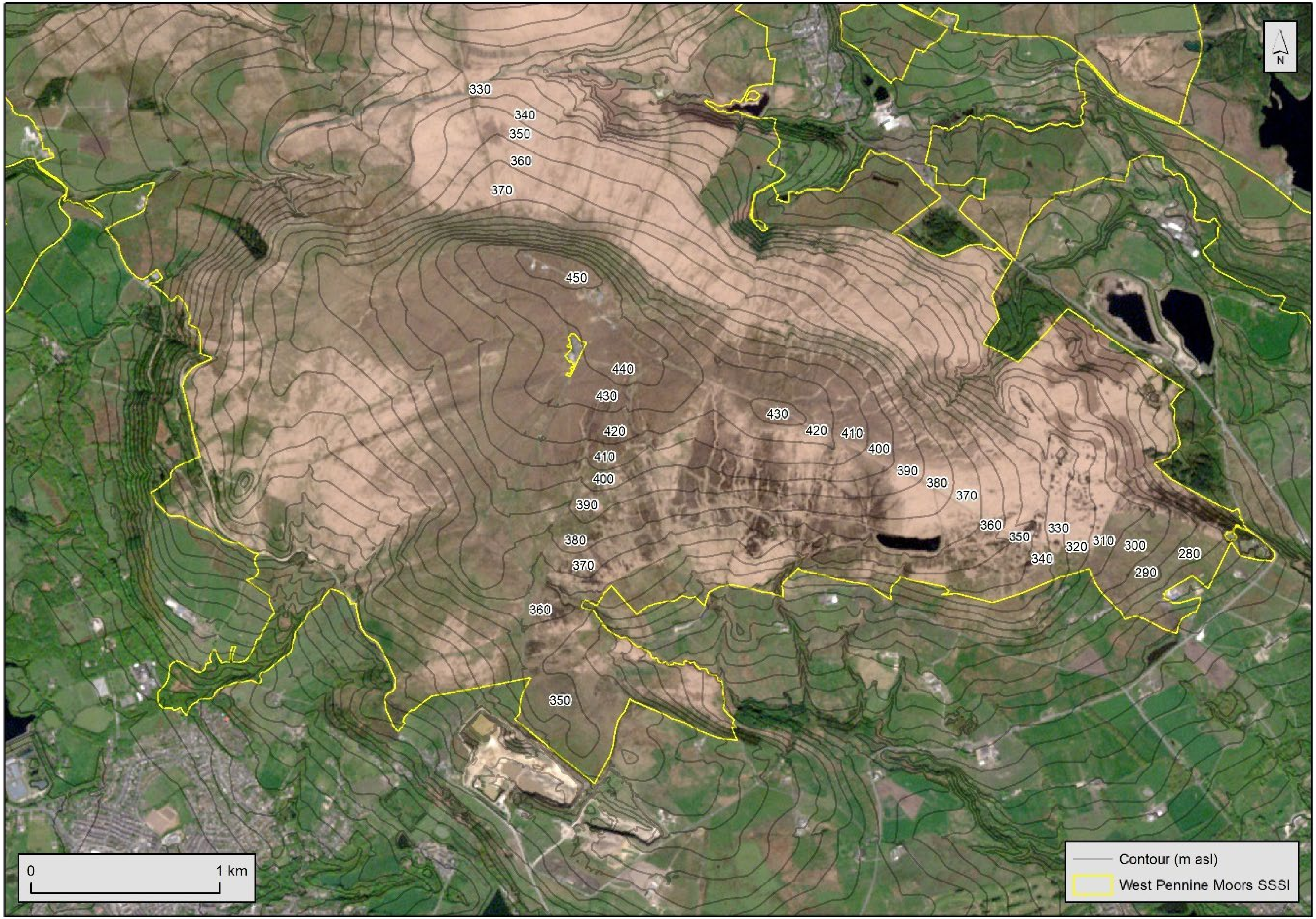


Figure 6. Topography of Winter Hill. Imagery: © Planet 07 May 2017

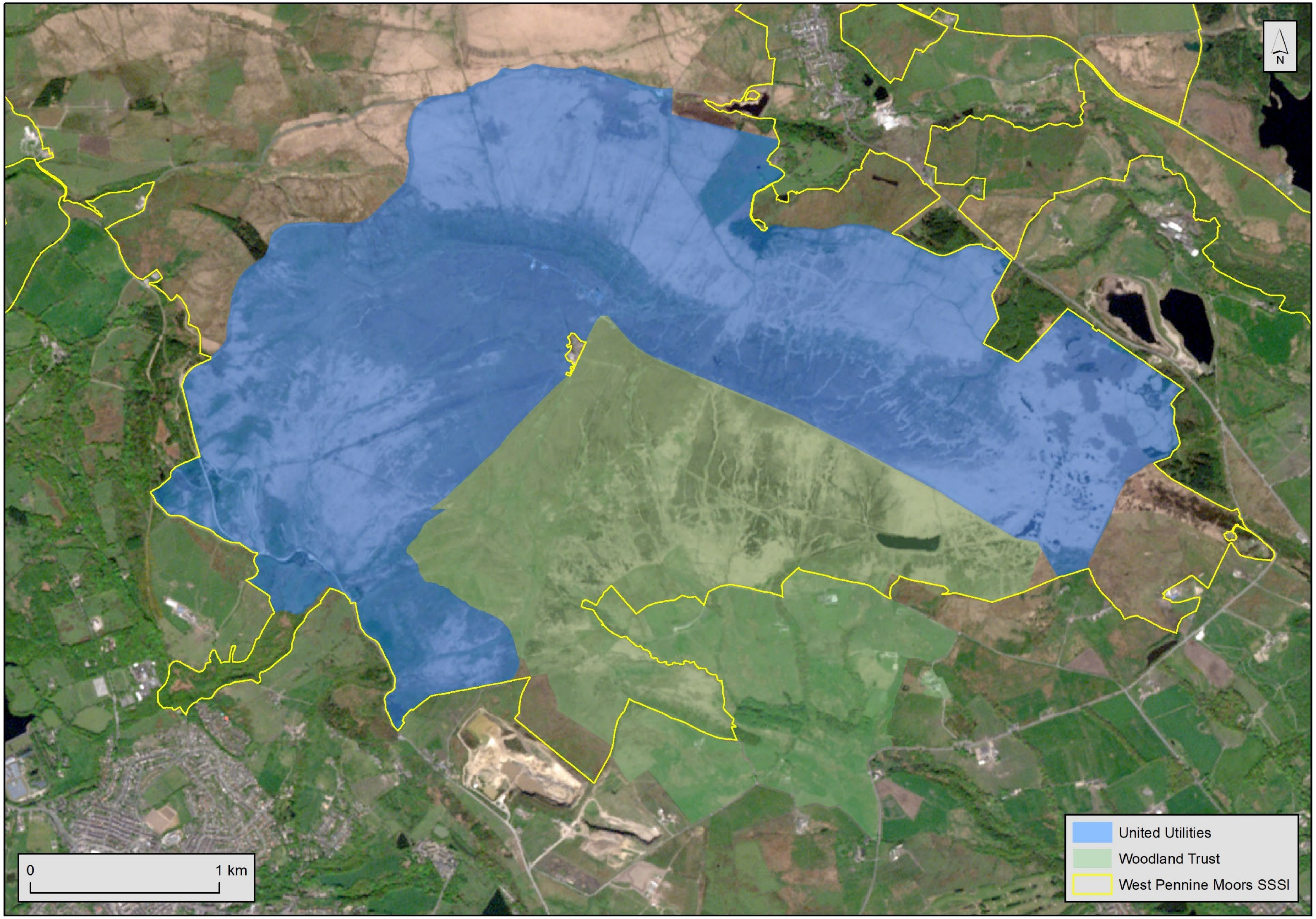


Figure 7. Ownership of SSSI parcels on Winter Hill. Imagery: © Planet 07 May 2017

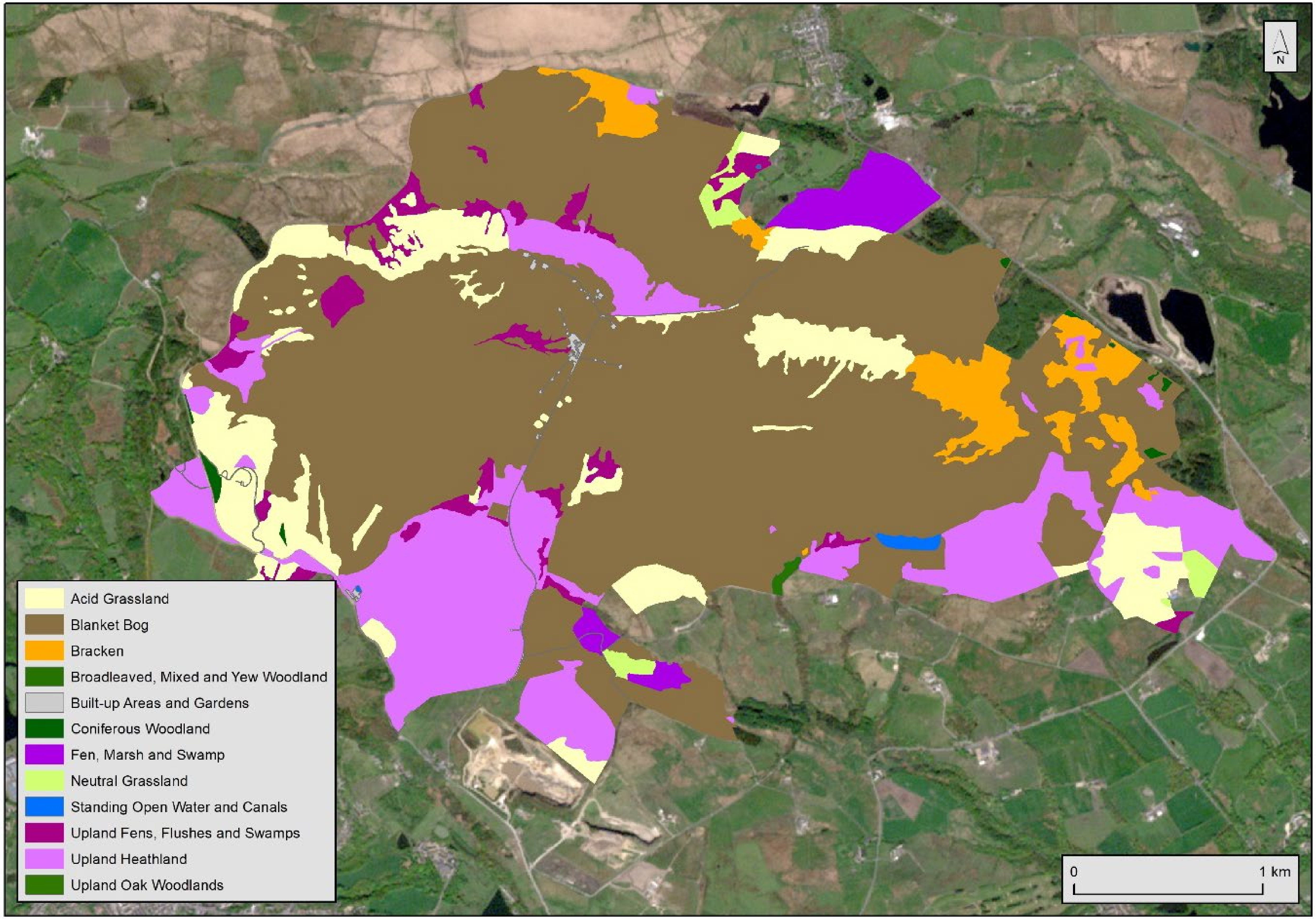


Figure 8. NVC mapping of Winter Hill (provided by Penny Anderson Associates). Imagery: © Planet 07 May 2017

Figure 9. Cover of peat soils on Winter Hill. Imagery: © Planet 07 May 2017. Natural England Peaty Soils Location (England) © BGS & NSRI

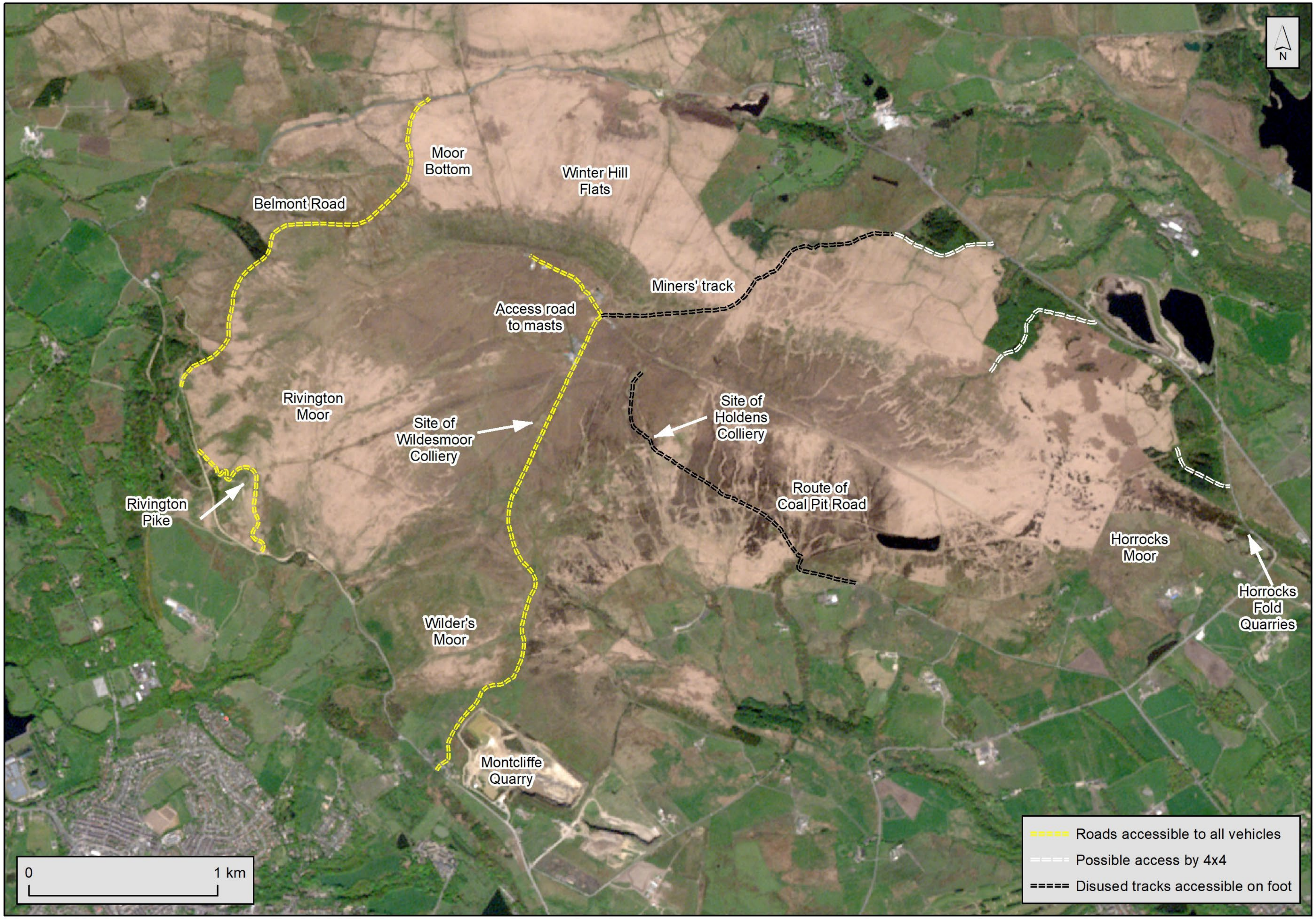


Figure 10. Access to Winter Hill and location of mining infrastructure. Imagery: © Planet 07 May 2017

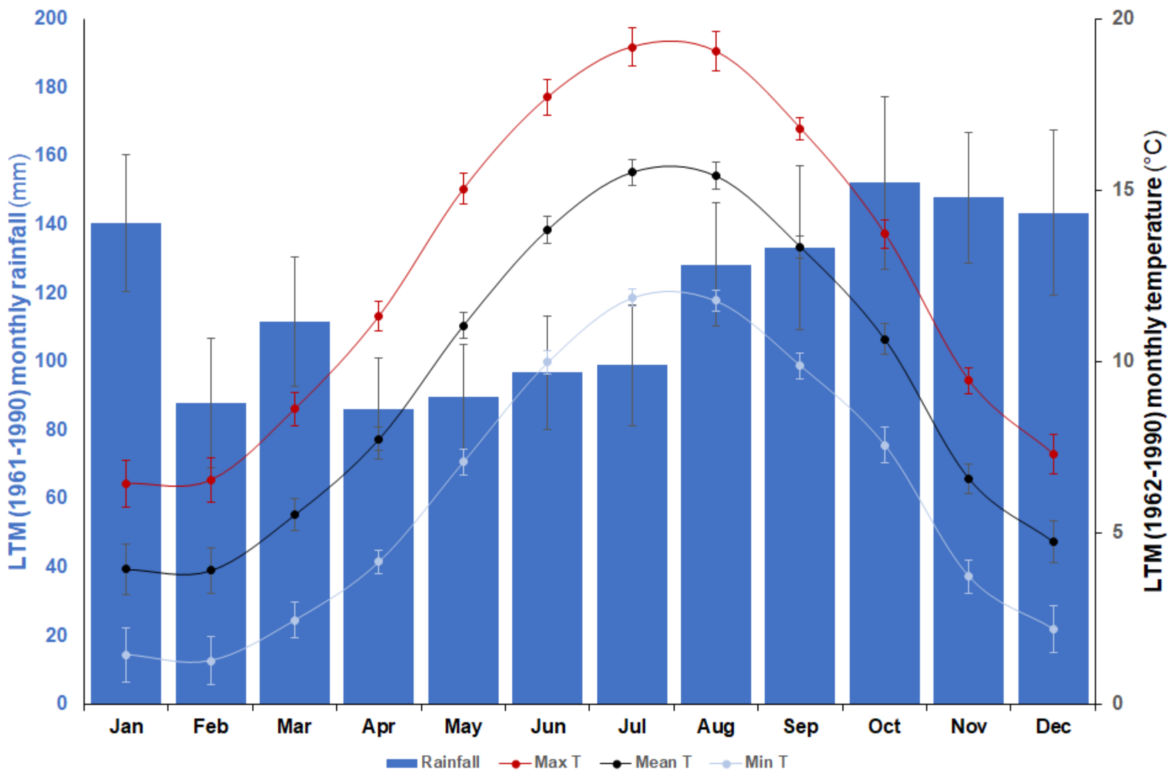


Figure 11. Long term mean (1961-1990) monthly rainfall recorded at Cranberry meteorological station and long term mean (1962-1990) monthly temperature recorded at Preston meteorological station (error bars show 1.96 * s.e.)

2.3 Humberhead Peatlands National Nature Reserve

Humberhead Peatlands NNR covers an area of 2,990 ha and is located in the north-east of England, approximately 10 km north-east of Doncaster (Figure 12). The NNR is comprised of Hatfield Moors, and Thorne, Goole and Crowle Moors, that together represent the largest complex of lowland raised bog in England (Natural England, 2015). As with all raised bogs in the UK, and many bogs across other parts of Europe, the geometric shape of the bog margins indicates that these are remnants of once-larger sites (Lindsay, 2021). The raised bogs here were also likely part of a much larger wetland system in the Humberhead Levels National Character Area (NCA: Figure 12). The NNR is part of the Hatfield, Thorne, Crowle and Goole SSSI, and is covered by European designation lying within Hatfield Moor SAC, Thorne Moor SAC and Thorne & Hatfield Moors SPA.

The areas of raised bog contained within the NNR were subject to commercial peat extraction and significant drainage from the 1870s to 2004 (Natural England, 2016). Partly as a result of peat removal, a Neolithic timber trackway and platform was discovered on Hatfield Moors in 2004 (Chapman & Gearey, 2013; Figure 13), and is the earliest identified example of corduroy trackway construction in Britain (dated to 2900-2500 BC; Historic England, 2017). A later trackway found on Thorne Moor (dated to 1450-990 BC; Chapman & Gearey, 2013), and a number of archaeological finds across both Hatfield and Thorne Moors (including bog bodies and Roman coins), indicate long-term use of the sites by humans. Across Hatfield Moors, where the fire examined in this study occurred, there is very little change in elevation (typically ranging between 0-2 m asl). This is indicative of a levelling of the bog surface as a result of peat extraction, and the raised, ombrotrophic component has been removed. Almost central to Hatfield Moors, but outside the extent of the NNR, is Lindholme Island where elevation reaches up to 5.5 m asl. This island is mapped as glaciofluvial sand and gravel deposits (Figure 14) and is not reported to have been covered by peat (Chapman & Gearey, 2013).

When commercial peat extraction ceased, the raised bog at Hatfield Moors was an exposed expanse of largely unvegetated milled peat (see Figure 13). Early phases of restoration began in 2005 and were enhanced by a larger phase in 2014 funded by EU LIFE+ funding (Restoring Humberhead Peatlands; Natural England, 2019). During this phase, water levels were managed by installing weirs on arterial drains, peat/plastic piling dams on compartments, and internal bunding on drained, but uncut areas of peatland. In addition, 254 ha of scrub was removed (Natural England, 2019). Pooling of water across Hatfield Moors is evident (Figure 13), and while mire vegetation communities including *Eriophorum* spp. and *Sphagnum* spp.. are re-establishing in these areas, the drier baulks are typically dominated by heath communities (T. Kohler, personal communication, 2022). Habitat mapping for Hatfield Moors is currently incomplete.

The only road into the NNR that is accessible to all vehicles (Lindholme Bank Road) leads to Lindholme Island (Figure 15). Parts of the NNR can only be accessed from Lindholme Island and the old peat works located on the north edge of the NNR. Access beyond these points is only possible by 4x4 vehicles.

The LTM annual rainfall (1961-1990) recorded at Crowle (located approximately between Hatfield Moors and Thorne Moors) is 564.4 mm, highlighting that this site receives the least rainfall of all sites examined. The data also indicate that the site receives fairly consistent rainfall through the year, with 10 months receiving 40-50 mm. Interestingly, August appears to be the wettest month receiving a mean of 57 mm of rainfall and February is driest receiving a mean of 37 mm of rainfall (Figure 16).

The LTM monthly mean temperatures (1961-1990) recorded at Cawood (located approximately 30 km north-west) range from 3.2°C in January to 18.0°C in July (Figure 16). The lowest LTM monthly minimum temperature is recorded for February (0.53°C) and the highest LTM monthly maximum temperature is recorded for July (20.2°C).

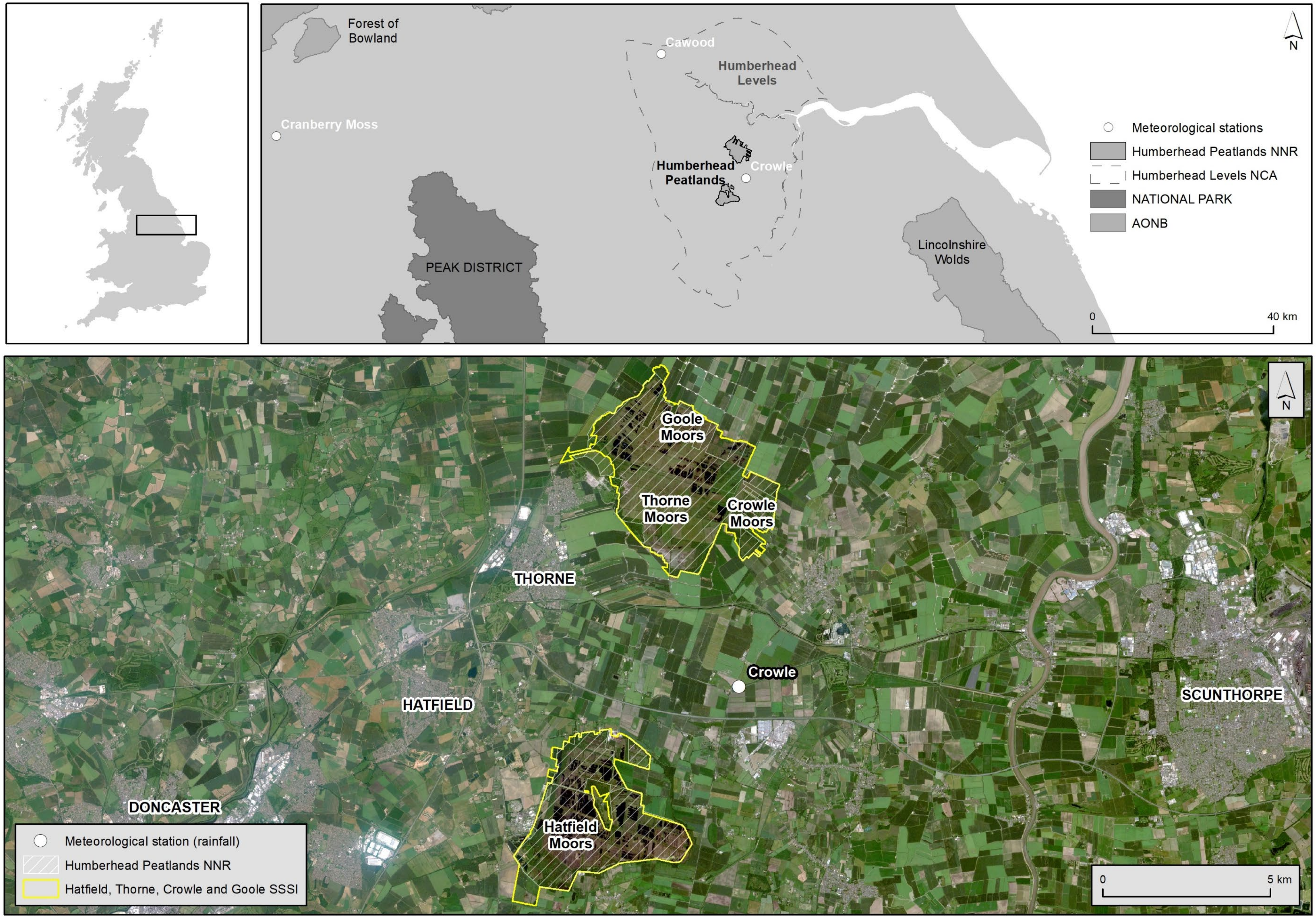


Figure 12. Location of Humberhead Peatlands NNR. Imagery: © Planet 18 June 2017

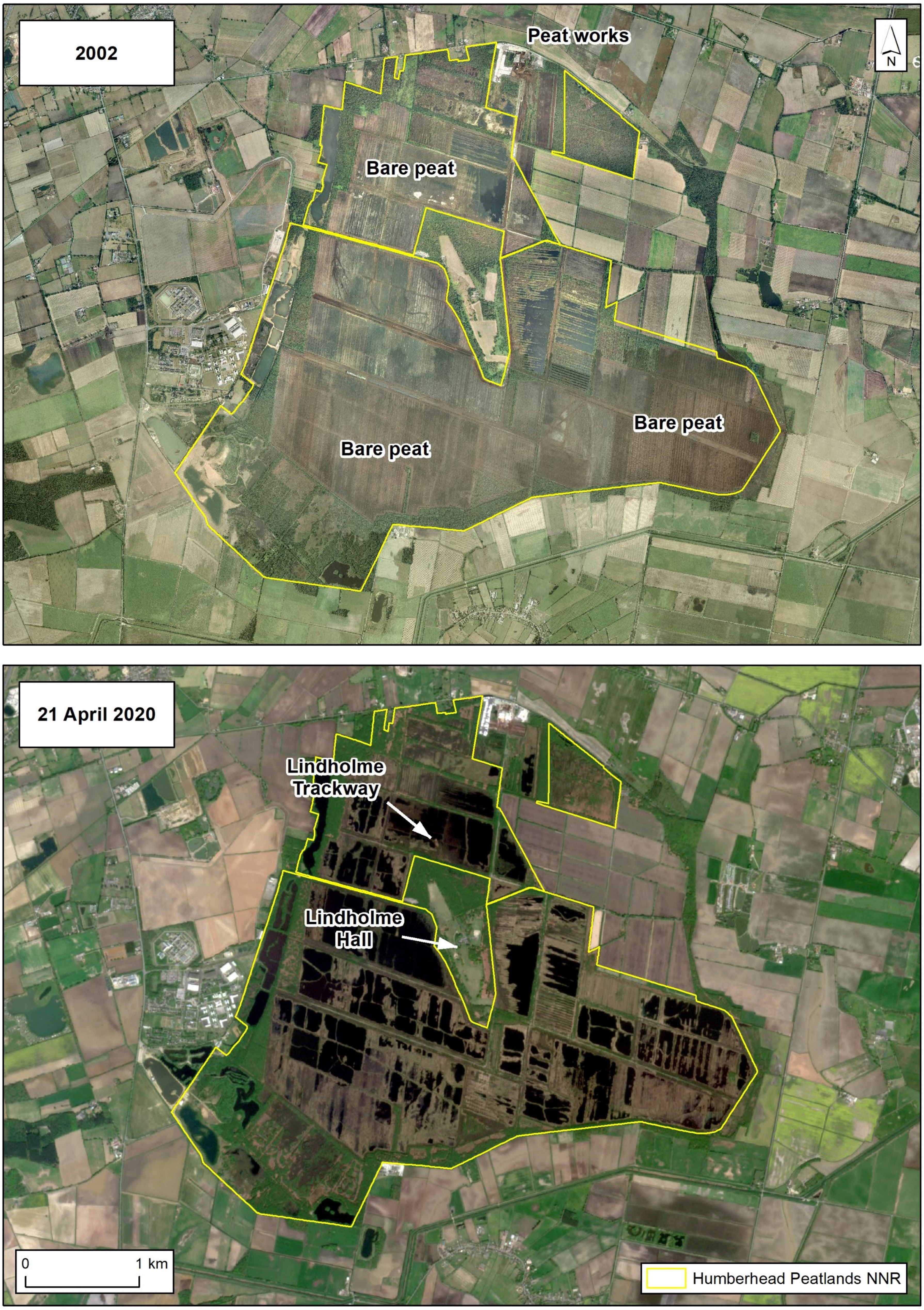


Figure 13. The area of Humberhead peatlands NNR covering Hatfield Moors showing the impacts of restoration activities on the milled peat surface and the location of Lindholme Hall and Neolithic timber trackway. Imagery: Top – Natural England (APGB), 2012; Bottom – © Planet 21 April 2020

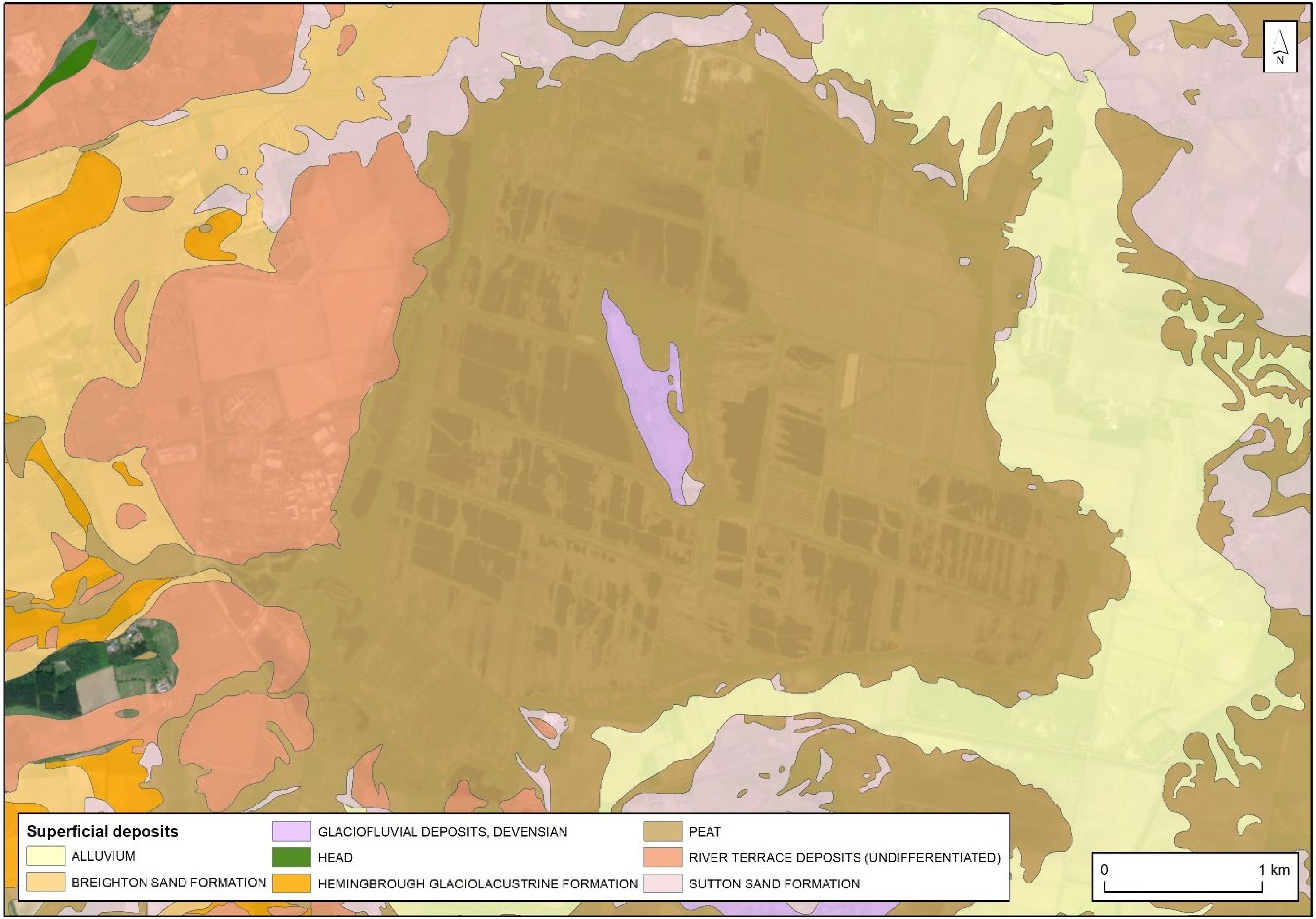


Figure 14. Superficial deposits across Hatfield Moors and surrounding area. Geological Map Data BGS © UKRI 2022

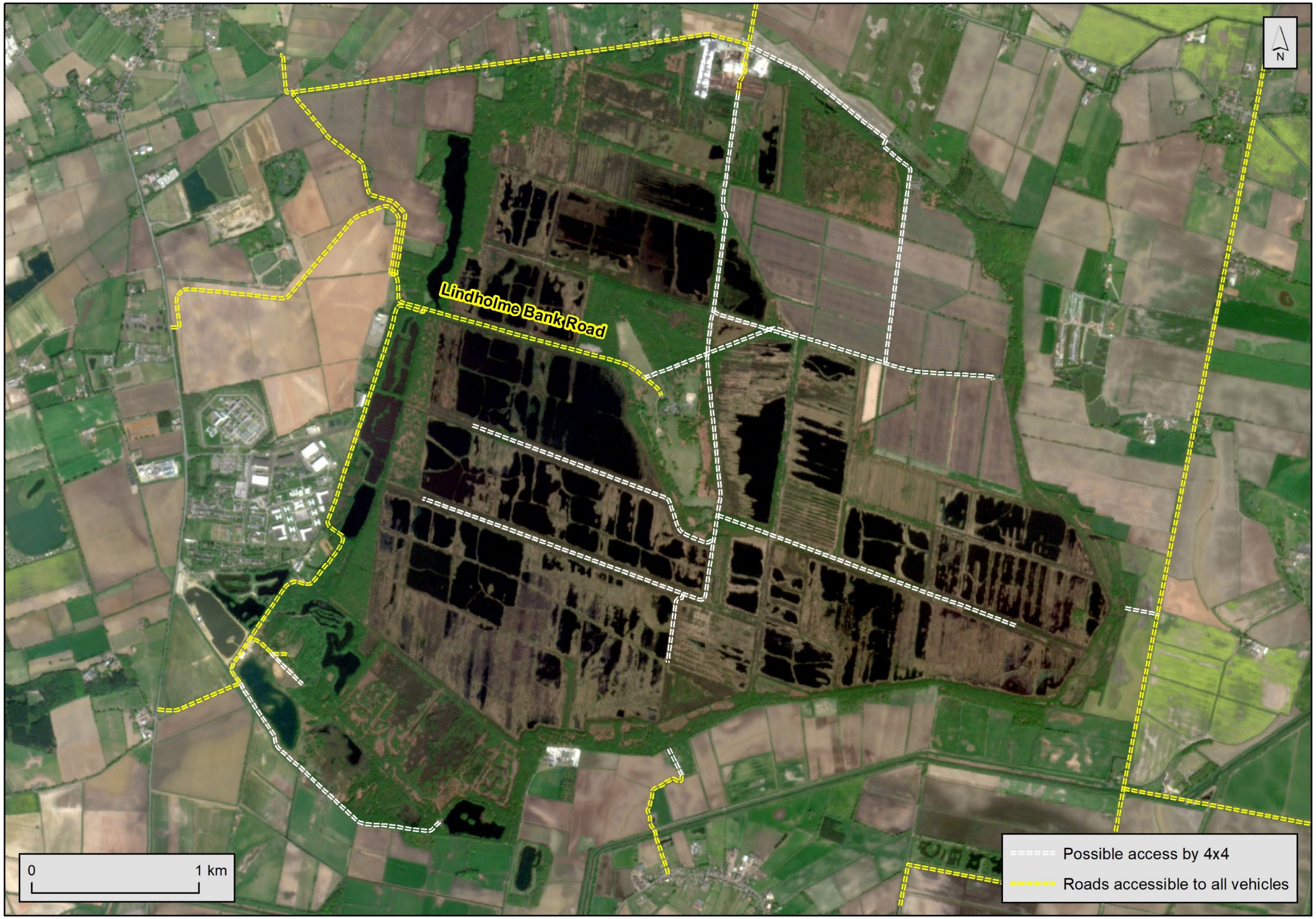


Figure 15. Access to and across Hatfield Moors. Imagery: © Planet 21 April 2020

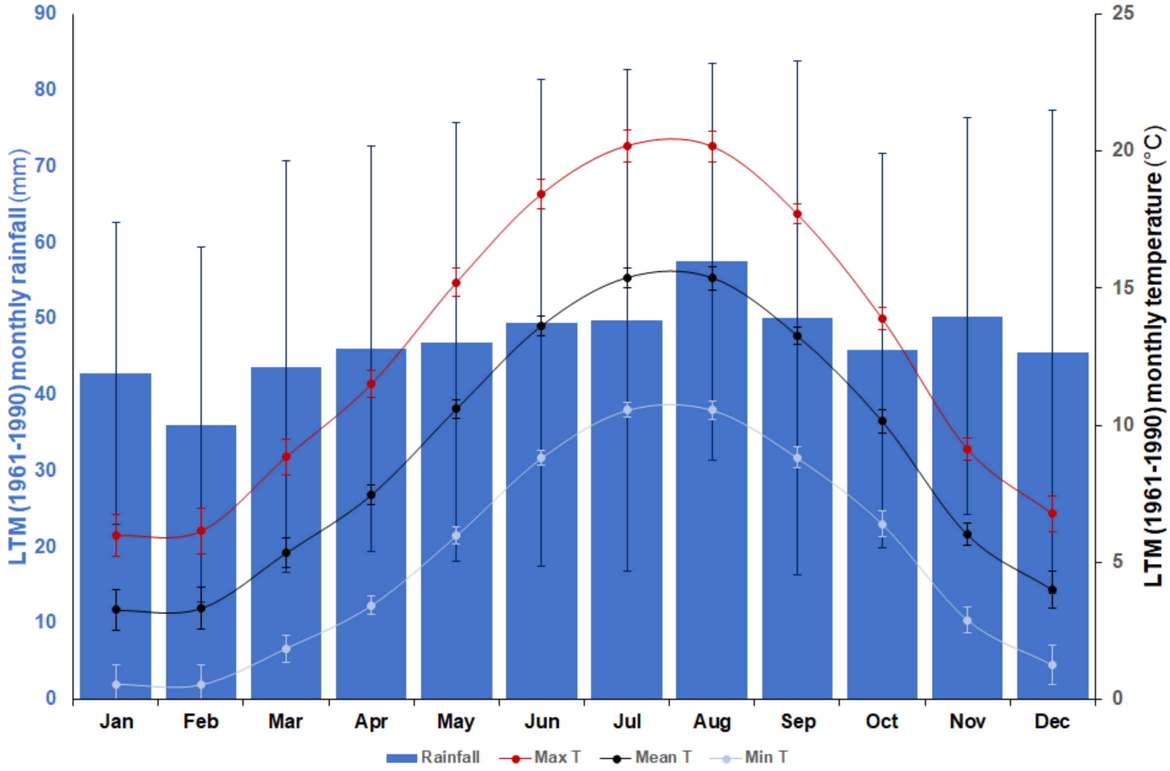


Figure 16. Long term mean (1961-1990) rainfall recorded at Crowle meteorological station and temperature recorded at Cawood meteorological station (error bars show 1.96 * s.e.)

3 Meteorological and environmental data

3.1 Meteorological data

Meteorological data for each site were sourced from the Centre for Environmental Data Analysis (CEDA; https://archive.ceda.ac.uk/). Data were obtained for the nearest meteorological monitoring stations operated by the UK Met Office that had the most complete records.

Daily rainfall and temperature measurements for Thursley NNR (1962-2022) were obtained for a monitoring station located 10 km to the west at Alice Holt Lodge (115 m.a.s.l.; Figure 1). Hourly wind measurements were obtained for a monitoring station located 13 km to the north in Farnborough.

For Winter Hill, monthly rainfall measurements (1961-2018) were obtained for a monitoring station located 6 km to the north-east on Cranberry Moss (301 m.a.s.l.; Figure 5) and supplemented with daily rainfall measurements (2019-2022) for the monitoring station located 4 km south-east at Bolton: Sweetloves water works (175 m.a.s.l.). Daily temperature measurements (1962-2020) were obtained for a monitoring station located 20 km to the north-west at an exposed site (Moor Park) in Preston (33 m.a.s.l.; Figure 5). Hourly wind measurements were obtained for a monitoring station located 30 km to the south-east at Rostherne (near Altrincham).

For Hatfield Moors, daily rainfall data (1961-2022) were obtained for a monitoring station located 5 km to the north-east at Crowle (3 m.a.s.l.; Figure 12), and daily temperature measurements (1961-2020) were obtained for a monitoring station located 32 km to the north-west at Cawood (6 m.a.s.l.; Figure 12). Hourly wind measurements were obtained for a monitoring station located 36 km to the south-east at RAF Scampton.

3.2 Environmental data

Estimations of daily fire danger (2013-2022) were obtained from the Copernicus Climate Data Store (CDS: https://cds.climate.copernicus.eu/). The Canadian Forest Service Fire Weather Index Rating System (FWI), which is used by the Met Office for deriving a fire severity index (Table 1; Perry et al., 2022), was used to provide information on environmental conditions. The FWI is created using three field moisture codes and three fire behaviour indices derived from temperature, relative humidity, wind speed and precipitation (Van Wagner, 1987).

Table 1. Relationship between Met Office FSI and FWI (adapted from Perry et al., 2022)

Met Office FSI	Level of fire danger	FWI
1	Low	< 4.54
2	Moderate	4.54 – 9.38
3	High	9.38 – 17.35
4	Very high	17.35 – 52.36
5	Exceptional	> 52.36

FWI data are a gridded dataset with a horizontal resolution of 0.25° in latitude-longitude (approximately 28 km by 15 km for England). Daily FWI values were extracted for the central coordinate of each site covering the five years preceding the fire event examined and up to 30 July 2022 (most recent data available at time of writing).

3.3 Data analysis

Monthly and annual rainfall totals for each monitoring station were calculated for each year of the record (Appendix A) and used to determine the long-term mean (LTM) monthly and annual rainfall (1961-1990). Variation in monthly rainfall from the LTM were determined for each site for the year of the fire event and for the preceding five years. Cumulative rainfall was also determined for each site from the start of the hydrological year (October) five years prior to the year of the fire. Soil moisture content is typically assumed to have returned to 'normal' at the beginning of the hydrological year, but there are potential issues recognised with this assumption (Weber & Stewart, 2014).

For each site, changes or trends in annual rainfall were determined using the Mann-Kendall test (MKT; Mann, 1945; Kendall, 1975) and trends in monthly and seasonal rainfall were determined using the seasonal Kendall test (SKT; Hirsch et al., 1982). Magnitudes of change were estimated from the Theil (MKT; Theil, 1950) and Sen (SKT; Sen, 1968) slopes, which provide median annual rates of change. This was undertaken from 1961 to the year of the fire for each site (1961-2020 for Thursley Common and Hatfield Moors; 1961-2018 for Winter Hill).

Monthly mean minima and maxima temperatures were calculated for each monitoring station, and subsequently used to derive monthly and annual mean values. Monthly mean temperature variation from the LTM (1961-1990) were determined for each site for the year of the fire event.

4 Fire events and interventions

Fires examined in this study occurred at Winter Hill in June 2018 and at both Hatfield Moors and Thursley NNR in May 2020. It is worth noting that the latter fires both occurred on a weekend. Cloud-free satellite imagery were obtained from Planet for all sites (Planet Team, 2017; Table 2) and used to map the full extent of the burn scar, and, as best possible, to map the initiation and progression of the fires. Satellite images were segmented using the tools in Definiens eCognition, and polygons representing areas of burn were manually selected and merged as required. The boundaries of the mapped fire footprints are therefore digitised at the resolution of the image pixel size retaining consistency of mapping between the sites.

For all three sites, 25 cm resolution colour (RGB) and colour infra-red (CIR) aerial photography dated pre- and post-fire were obtained through Natural England from the Aerial Photography of Great Britain (APGB) consortium.

Table 2. Cloud-free satellite data available for all sites (4-bands used: R, G, B & NIR). Some cells are blank

Site name	Date of fire initiation	Date fire extinguished	Date of cloud-free imagery	Satellite source	Ground resolution (m)
Winter Hill	25 June 2018	04 July 2018*	25 June 2018	Planetscope	3 m
	(Monday)		26 June 2018	Planetscope	3 m
			29 June 2018	Sentinel-2	10 m
			30 June 2018	Planetscope	3 m
			02 July 2018	Planetscope	3 m
			04 July 2018	Planetscope	3 m
Hatfield Moors	17 May 2020	26 May 2020	20 April 2020	Planetscope	3 m
	(Sunday)		21 May 2020	Planetscope	3 m
			25 May 2020	Planetscope	3 m
			25 June 2020	Planetscope	3 m

Site name	Date of fire initiation	Date fire extinguished	Date of cloud-free imagery	Satellite source	Ground resolution (m)
Thursley Common	30 May 2020	01 June 2020**	29 May 2020	Planetscope	3 m
	(Saturday)		31 May 2020	Planetscope	3 m
			02 June 2020	Planetscope	3 m

* No further spread of fire is evident in imagery dated post 04 July 2018, but FRS reported the ground (peat) was smouldering for 41 days;

** Best estimate - no cloud-free imagery are available for 01 June 2020.

4.1 Thursley NNR

A fire started on Thursley Common in the morning of Saturday 30 May 2020. The Reserve Manager for the NNR (Natural England) was informed by Surrey Fire and Rescue Services (SFRS) around 12:00 pm that a fire was in progress and being tackled (J. Giles, personal communication, 2022). No cloud-free satellite imagery are available for 30 May, but aerial footage captured by a small unmanned aerial vehicle (UAV) at some point on the 30 May indicates that the fire started in an area of pine trees approximately 100 m south of Pudmore Pond (https://www.youtube.com/watch?v=gE80JnMMQ7I; Figure 17). The source of the fire has not been confirmed but is considered to have been accidental, resulting from a disposable barbeque.

On 30 May, the direction of wind recorded at Farnborough ranged predominantly from 30-70° (i.e. from the NE). The aerial footage shows that the fire initially spread with the wind westwards towards The Moat. The boardwalk running between Pudmore Pond and The Moat (Figure 3) was destroyed in the fire but is not considered to have acted as a conduit (J. Giles, personal communication, 2022). Satellite imagery captured on 31 May at 08:13 shows that the fire had also spread eastwards against the wind, and in one day approximately 56 ha of the NNR had been burned (Figure 17). By 10:30 on the 31 May, a further 6 ha of the NNR had burned. The fire appears likely to have been extinguished on 01 June 2020, as there is no smoke visible in an image dated 02 June 2020. In total, 96 ha of the NNR burned. Although habitat mapping is relatively coarse (at SSSI unit level), the main habitats affected were dwarf shrub heath, the valley mire and several stands of trees central to the NNR and on the western fringe.

Fire barriers and interventions

With reference to Figure 18, some observations can be made about the course of the fire and the potential impact of 'natural' (pre-existing) fire breaks, and those created during the fire (digitised from aerial photography dated 21 October 2021). The fire is likely to have reached Point A on the 30 May, and the fire edge can be seen to run alongside, but not across, a public bridleway. At this location the bridleway is around 2 m wide and is comprised of a non-vegetated sandy substrate. It is possible that this feature provided a natural fire break, although it may also represent an area where access was sufficient for FRS vehicles to allow fire control. Points B and C tend to suggest that the latter may be the case, as at these locations the fire appears to have spread unhindered across the sandy bridleway. At point C the bridleway is around 4-5 m wide. It appears that sandy footpaths and bridleways do not slow or stop fire spreading with the prevailing wind. Locations D and E show a temporarily extinguished edge of the fire on 31 May 2020. This edge runs along a footpath, and although <0.5 m wide in places, may indicate that footpaths can act as fire breaks against the direction of wind (on 31 May, the origin of the wind again ranged from 30-70°).

Location E shows a fire break visible in imagery on 02 June that is not visible in imagery at 10:30 on 31 May. Here vegetation was mown or flailed in a strip 3-5 m wide, possibly at some point on 31 May. This appears to have been successful in containing re-igniting sections of the fire, as at point D, where no mowing was undertaken, the fire spread further. However, it is possible that the easterly spread at point D on 01 June may have been assisted by a change in direction of the wind, which on 01 June was recorded to come from a direction ranging from 320-360° (i.e. NNW). This would explain the southerly spread of the fire at several locations on 01 June and may also indicate that footpaths present less of a barrier to fire if oriented perpendicular to the direction of wind. Three mown breaks visible at location F further highlight the effectiveness of this approach to preventing spread of fire, even with the wind for one example.

During the fire, The Moat was used as the primary water source. Local farmers employed slurry spreaders towed by tractors to spray the fire, and SFRS deployed a high-volume pump (HVP) and 3 km of 150 mm hose (S. Nicholls, personal communication, 2022). Although the bridleways enabled FRS vehicles to access several parts of the NNR (Figure 3), it is notable that no fire breaks were created in the centre of the burn scar. This area is coincident with the valley mire, and there were several reports of FRS vehicles becoming trapped in the peat (J. Giles, personal communication, 2022); numerous vehicle tracks running across the valley mire are visible in aerial imagery captured in 2021.

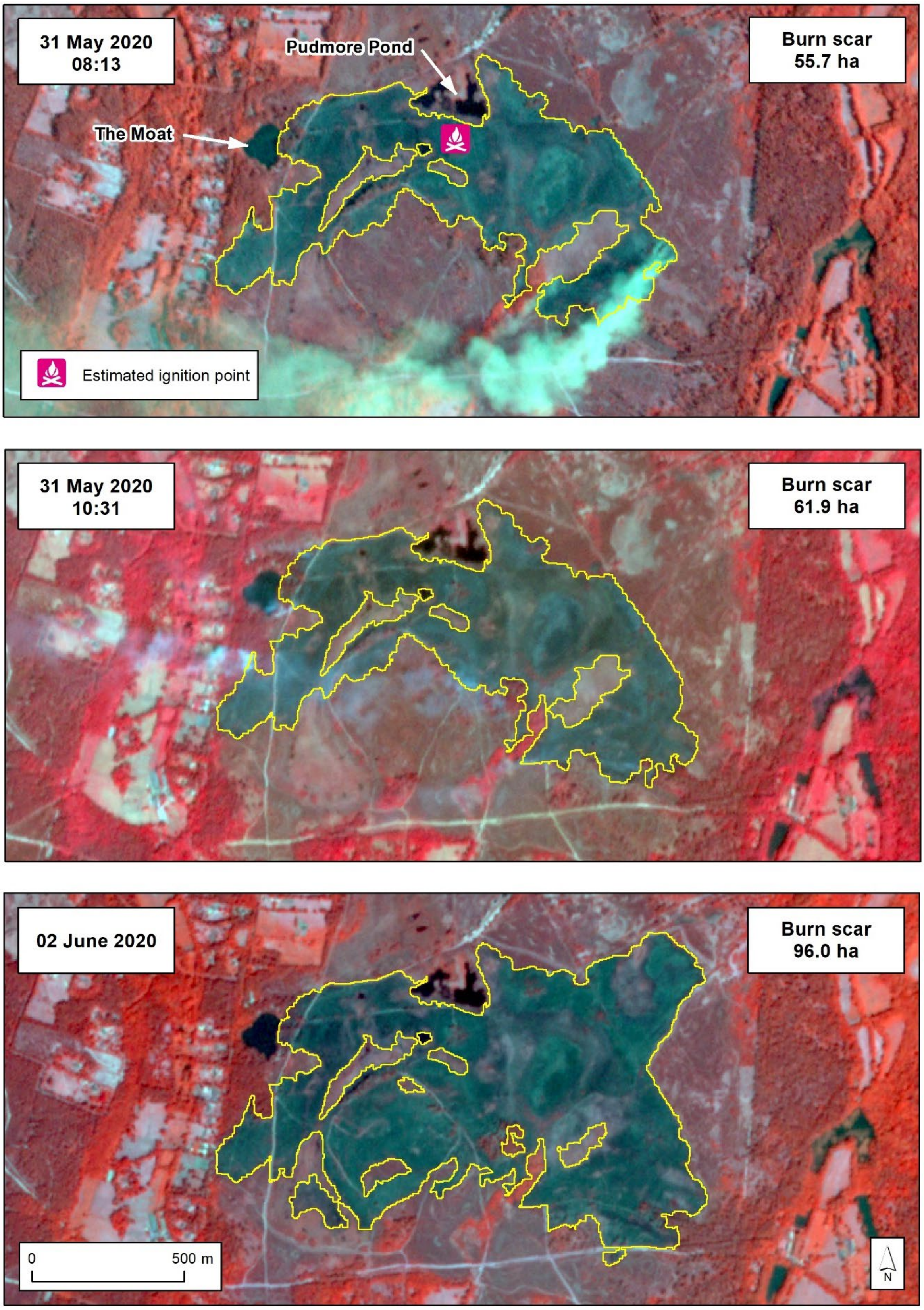


Figure 17. Progression of wildfire event at Thursley NNR, May 2020. Imagery: © Planet

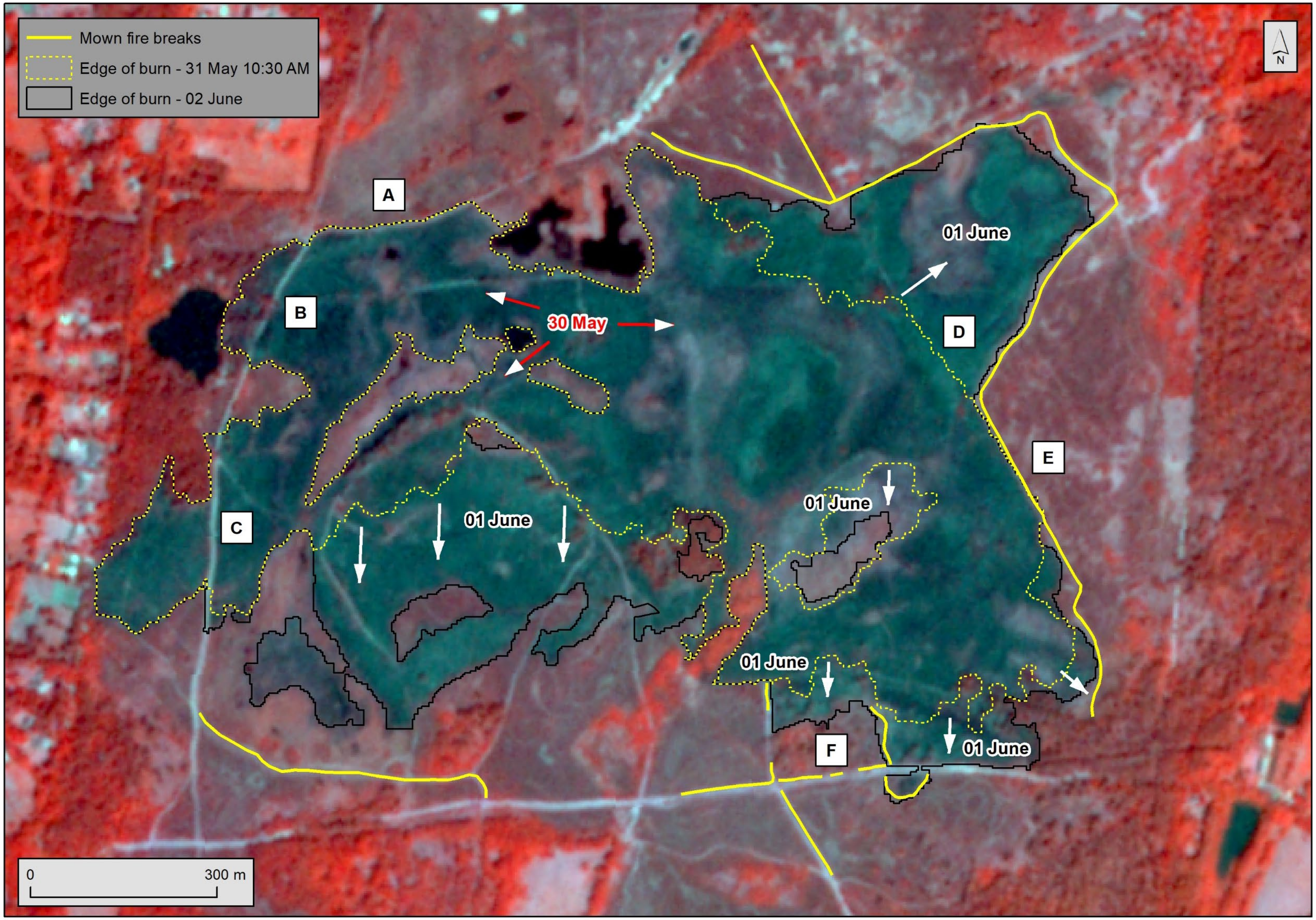


Figure 18. Progression of wildfire event and interventions at Thursley NNR (May 2020). Imagery: © Planet

4.2 Winter Hill

The fire event at Winter Hill in 2018 was unusual in that there were three separate ignition points. At some point on the 25 June 2018, a fire started on the northwest corner of Rivington Moor. The direction of wind recorded at Rostherne between 08:00-22:00 ranged from 280° - 350° (WNW-NNW). Aerial imagery available on Google Earth (dated 28 June 2018) suggest that the fire started in an area of young woodland located within 100 m of a car park (Figure 19) and spread uphill with the wind (slope approximately 14°; see Figure 6). The fire was contained and extinguished by Lancashire Fire and Rescue Services (LFRS) on the 25 June; no smoke is visible in satellite imagery captured on 26 June (Figure 20). A disposable barbeque was subsequently found in the area of woodland (K. Rogers, personal communication, 2022), suggesting that the incident was accidental. This event burned an area of 12.2 ha classified under NVC in approximate equal parts as acid grassland and upland fens, flushes and swamps (data provided by Penny Anderson Associates).

On 28 June 2018, a second fire started near the summit of Winter Hill and a third fire started on Horrocks Moor 4 km to the south-east, approximately 100 m from the disused Horrocks Fold Quarries (see Figures 10 and 20). The direction of wind recorded at Rostherne on 28 June ranged from 70° - 100° (E), and the fire at the summit spread downslope in a south-westerly direction across Rivington Moor towards Rivington Pike (Figures 20 and 21). The fire on Horrocks Moor spread uphill in a north-westerly direction. Satellite imagery dated 29 June indicate that both fires had been extinguished (Figure 20). The fire on Rivington Moor burned an area of 146.7 ha predominantly classified as blanket bog. The fire on Horrocks Moor burned an area of 3.7 ha that was predominantly classified as upland heathland. Despite the apparent lack of smoke visible in satellite imagery, the fires had burned into the peat and were still smouldering (A. Ryding, personal communication, 2022).

At some point on either the 29 or 30 June 2018, smouldering peat re-ignited. The direction of wind recorded at Rostherne ranged from 70° - 110° (E), and the re-ignited peat on Rivington Moor spread against the wind in a south-easterly direction towards Wilder's Moor (Figures 20 and 21). The re-ignited peat on Horrocks Moor spread west with the wind across Winter Hill towards the summit and masts. On 30 June LFRS declared the fire as a major incident and began undertaking tactical defensive burns around the masts to protect the infrastructure (Gibson, 2019).

Over the course of 01 and 02 July the fires continued to spread and merged leaving a burned area covering almost 700 ha. Data recorded at Rostherne show that the direction of wind remained predominantly from the east over this time (70° - 100°), with the exception of the hours between 03:00-05:00 on 01 July when the wind was recorded to come from the north (320° - 360°). Satellite imagery captured on 02 July show significant smouldering of peat across the burn and a further 7 ha due east of Wilder's Moor burned between 02 July and 04 July as peat re-ignited (Figure 21). Although the fire did not spread beyond the footprint mapped on 04 July (706.1 ha), smouldering peat continued to re-ignite, and the fire was not fully extinguished until 08 August 2018, 41 days after the event started (Gibson, 2019).

The two later fires started at locations that were 4 km distant and were separate acts of arson. An individual was arrested for the fire at the summit, but no charges were brought (A. Ryding, personal communication, 2022).

Fire barriers and interventions

During the course of the incident, over 950 FRS appliances were mobilised from 20 FRS across the UK (Gibson, 2019). 35 km of hose was run out for ground-based intervention, supplemented by helicopters dropping an estimated 400 tonnes of reservoir water (Gibson, 2019). In addition, 9.9 km of fire breaks (digitised from aerial photography dated 23 May 2019) were created (Figure 21), initially by a local contractor with an excavator, and subsequently with a low ground pressure bulldozer (K. Rogers, personal communication, 2022). Several observations can be made about the course of the fires and the potential impact of 'natural' (pre-existing) fire breaks, and those created during the event.

The easterly edge of the first burn (occurring on 25 June) runs alongside the unsurfaced Belmont Road (Figure 19), Staff at United Utilities monitored the fire from Belmont Road, and it did not cross onto Winter Hill (A. Ryding, personal communication, 2022), despite the fire front travelling uphill and with the wind. It can also be seen at location A (Figure 21) that a second fire on 28 June did not cross Belmont Road, again despite travelling with the wind. Similarly at location B, on the north side of Winter Hill (Figure 21), the edge of the burn that spread on 01 and 02 July runs alongside the disused, unsurfaced Miners' track running north-east from the masts (see Figure 10). At this location the fire front was travelling perpendicular to the wind. From these observations, it would seem reasonable to conclude that roads and tracks offer an effective barrier to the spread of wildfire and may not require intervention.

At location C, the southerly edge of the burn spreading across Rivington Moor on 28 June is coincident with the footpath that runs from Rivington Pike to the TV mast (see Figure 10). Aerial imagery captured prior to the fire (30 October 2016) shows that the footpath was characterised by bare peat with little vegetation and this may therefore have acted as a barrier to the spread of fire against the wind. However, on 29-30 June, when smouldering peat re-ignited, the fire spread against the wind across the footpath towards Wilder's Moor (Figure 21). It is not clear if defensive burns undertaken by FRS near the masts extended to upper sections of the footpath. At location D, the fire can be seen to have spread across the footpath that follows the route of Coal Pit Road (see Figure 10). It is clear from these observations that footpaths should not be assumed to provide a barrier to the spread of fire, unless there is preventive maintenance.

Several fire breaks created by bulldozers during the incident appear to have been effective at stopping the spread of fire, but it must be noted that areas of blanket bog suffered significant damage from this intervention strategy. At location A (Figures 19 and 21), a trench was dug, and vegetation scraped back by 3-4 m (A. Ryding, personal communication, 2022). The area was kept wet, and this presented an effective barrier. Similar observations can be made at locations E, G, I and H. At the latter location, this intervention was undertaken to protect areas of woodland. Locations F, J and K highlight that these types of fire break are not always entirely effective. At location F, when peat re-ignited after 30 June, the fire spread across the initial break created, and an additional section of fire break was added. The break created at location K did not appear to stop the initial fire that started on 28 June, as the fire crossed the break. There also seem to have been multiple attempts to contain the spread at location J.

It should also be noted that the fire breaks created are all periphery to Winter Hill. Access for FRS vehicles is only possible via the road leading to the masts. Access to the remainder of Winter Hill is lacking.

Figure 19. Burn scar of wildfire on Rivington Moor (28 June 2018)

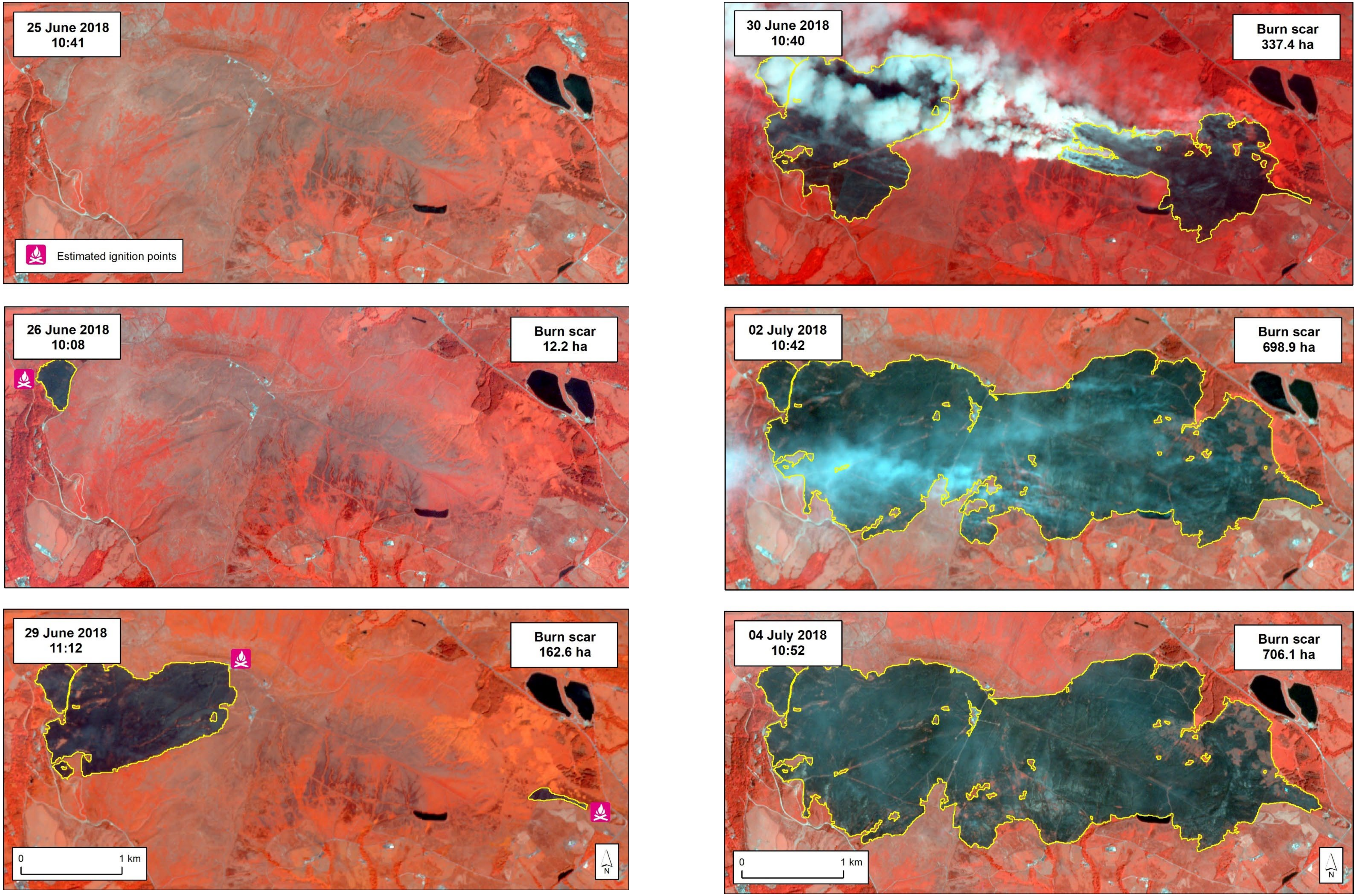


Figure 20. Progression of wildfire event at Winter Hill. Imagery: © Planet

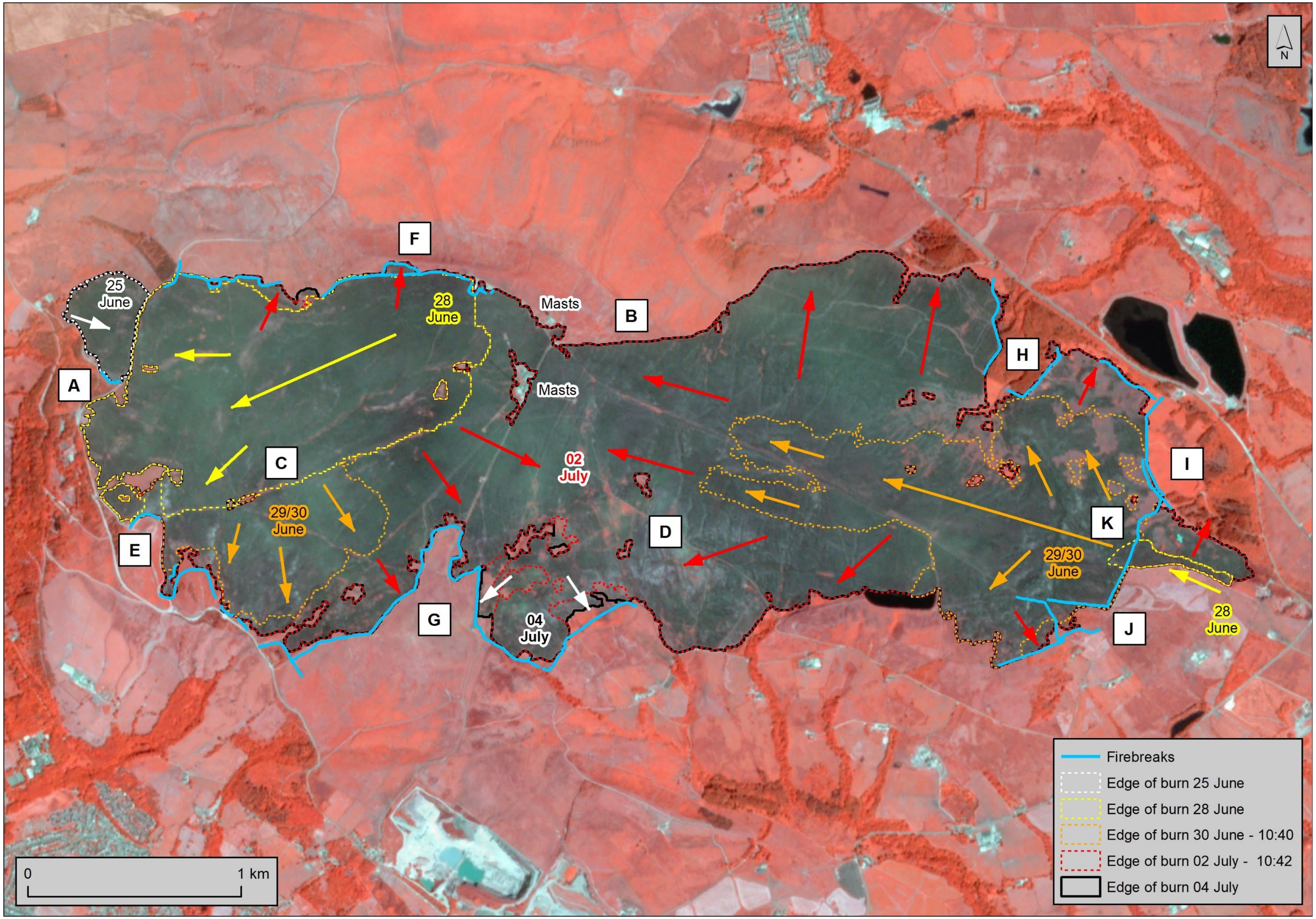


Figure 21. Progression of wildfire event and interventions at Winter Hill (June 2018). Imagery: © Planet

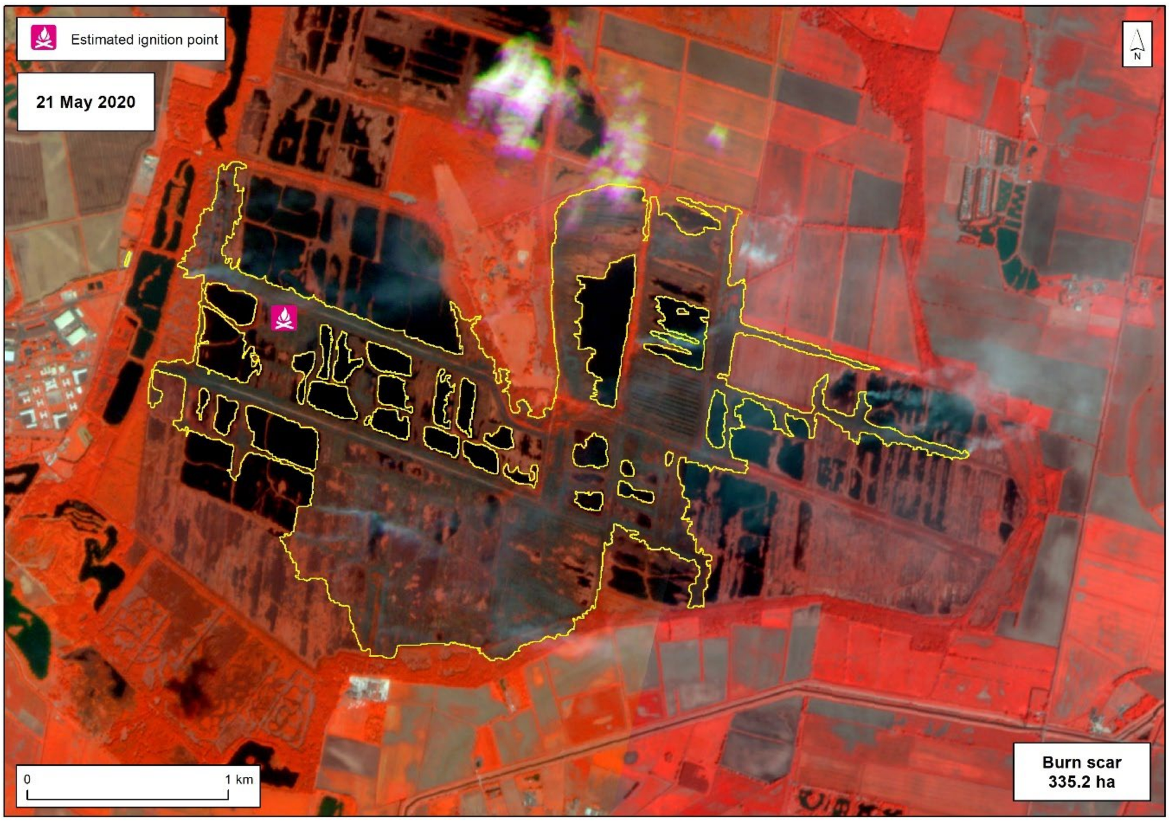
4.3 Hatfield Moors

A fire started on Hatfield Moors on Sunday 17 May 2020. Although the time of ignition is not known, South Yorkshire Fire and Rescue Services (SYFRS) were alerted to the incident at 17:35 (SYFRS, 2020). No cloud-free satellite imagery are available for the 17 May 2020, and the earliest image available was captured on 21 May 2020. By this time, the fire had spread across an area covering 335.2 ha (Figure 22). A second image captured on 25 May 2020 shows the fire spread a further 96.1 ha (Figure 22). Although there was no wider spread of fire beyond the extent mapped on 25 May, the fire was only reported to be under control on 02 June 2020 (SYFRS, 2020). The site continued to be dampened down for several months, and one patch of peat was still smouldering in October 2020 (T. Kohler, personal communication, 2022).

Mapping the initial spread of the fire was not possible, but the ignition point was estimated by Reserve staff (Figures 22 and 23). The source of the fire has not been confirmed but is considered to have been accidental, resulting from a disposable barbeque. Although restoration activities have created pools of water across the site, the dividing bunds, baulks and trams had established heather, and at the time of the fire these were noted to be extremely dry (T. Kohler, personal communication, 2022). The fire was observed by Reserve staff to spread rapidly along the heather dominated bunds and baulks, which acted as conduits allowing the fire to spread between the system of pools (Figure 23). A specialist helicopter was drafted in on 21 May to drop water on the fire from nearby lakes (SYFRS, 2020). Lindholme trackway (see Figure 13) was not damaged by the fire.

Fire barriers and interventions

During the course of the incident, a bulldozer was used to create fire breaks. Three fire breaks are visible in satellite imagery on the periphery of the burn scar. A fire break created on the east side of Lindholme island (location A; Figure 23) appears have been effective at preventing the fire spreading on to the Island. The fire break constructed adjacent to Lindholme bank Road appears to have prevented the fire spreading at one point (location B). It is not possible to comment on the effectiveness of the fire break at location C as the fire did not reach this structure.



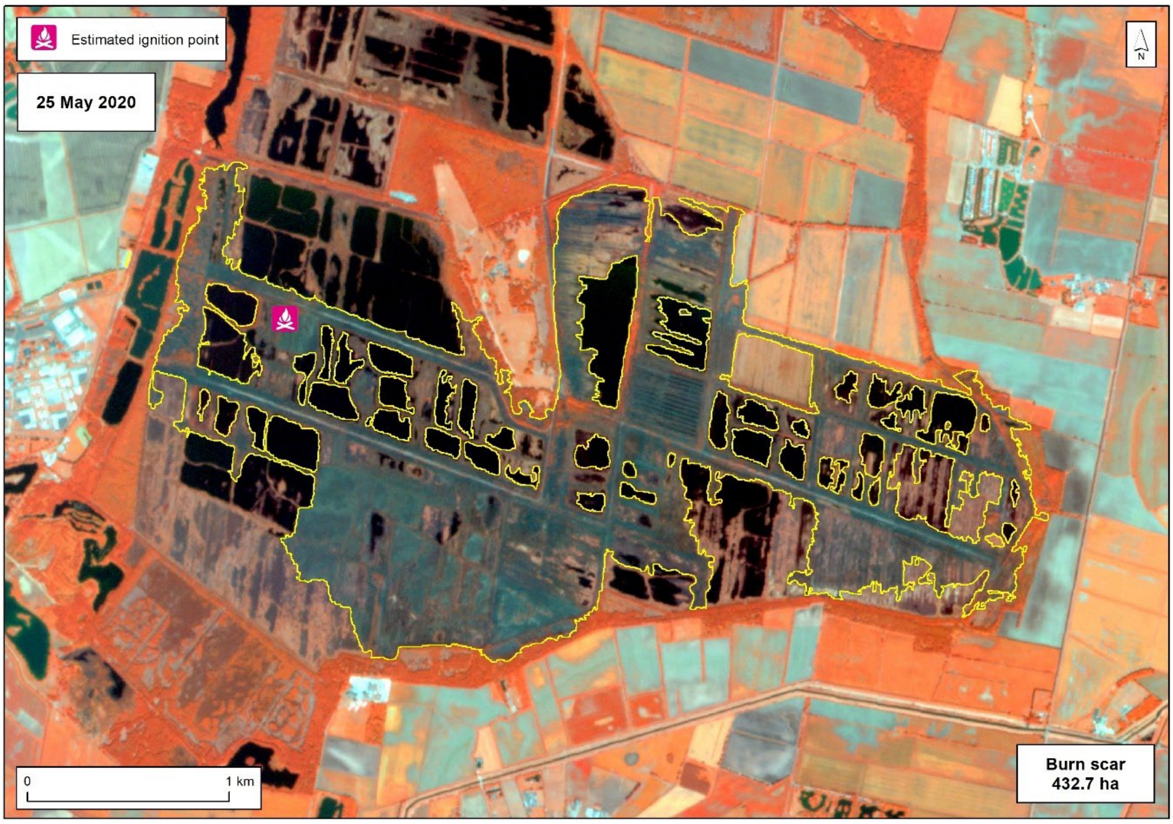


Figure 22. Progression of wildfire event at Hatfield Moors (May 2020). Imagery: © Planet

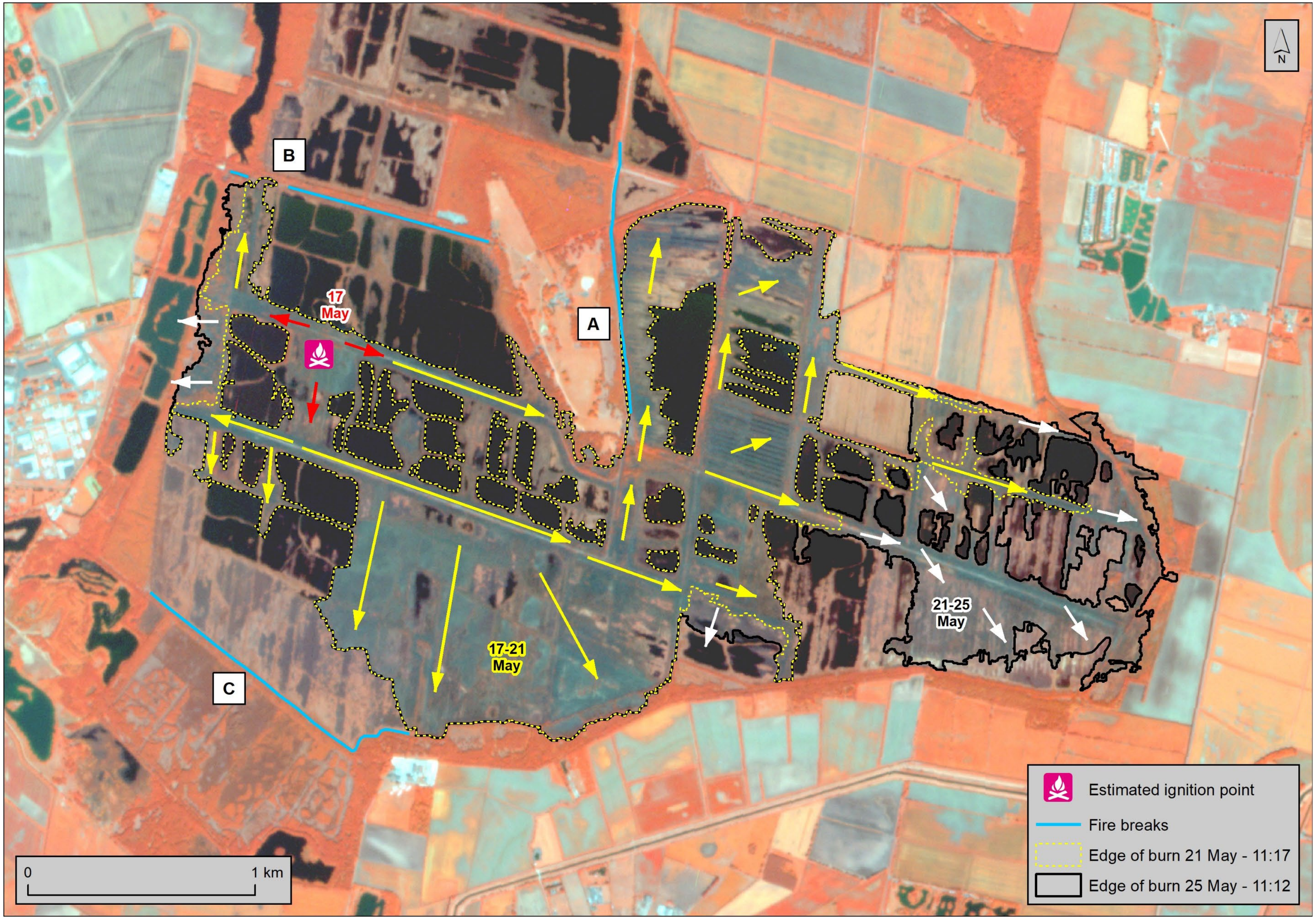


Figure 23. Progression of wildfire event and interventions at Hatfield Moors (May 2020). Imagery: © Planet

5 Synthesis

5.1 Meteorological and environmental conditions

5.1.1 Thursley NNR

The rainfall data recorded at Alice Holt Lodge indicate that in the month the fire occurred (May 2020), Thursley NNR received 1.8 mm of rainfall (2.9% of the LTM monthly rainfall; Figure 24), a deficit of 59.4 mm (Figure 25). Proportionally, May 2020 was the second driest month in the period 2015-2020, behind June 2018, where only 0.6 mm of rainfall was recorded (1.1% of the LTM monthly rainfall; a deficit of 52.6 mm). It is perhaps worth noting that a previous fire, albeit far smaller (3.5 ha), occurred on 17 June 2018 (a Sunday; J. Giles, personal communication, 2022). It is also worth noting that the very low rainfall recorded in May 2020 was not part of a longer-term trend. The preceding Autumn and Winter periods were wetter than average, particularly February 2020 where 128 mm of rainfall was recorded (235% of the LTM; an excess of 73.7 mm; Figures 24 and 25). In addition, 80-100% of the LTM rainfall was received in March and April 2020 (Figure 24).

The wetter period from September 2019 to April 2020 is evident in the cumulative rainfall plot (Figure 26), as the actual cumulative rainfall fell below the cumulative LTM (expected) from November 2016 to February 2020 (over 3 years). From February 2020 to April 2020 LTM actual and cumulative values achieved parity.

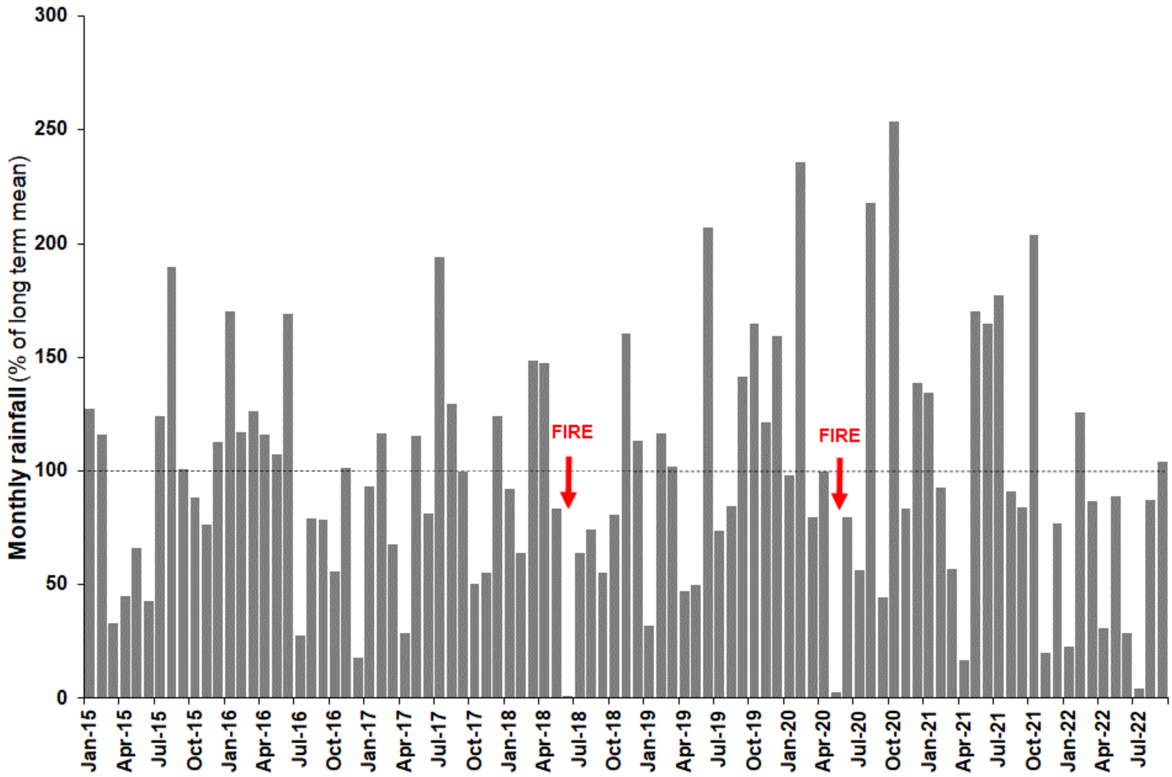


Figure 24. Total monthly rainfall as a proportion of 1962-1990 monthly mean recorded at Alice Holt Lodge meteorological station (dashed line indicates the LTM)

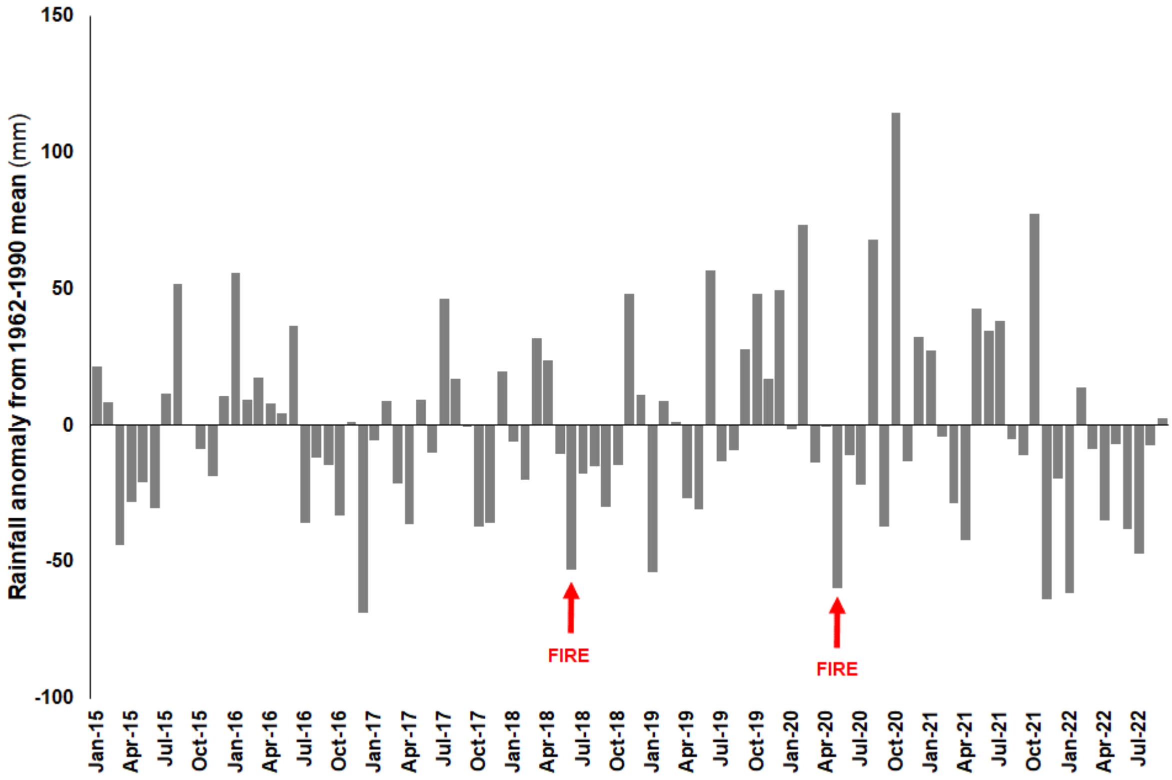


Figure 25. Monthly rainfall anomaly from 1962-1990 monthly mean recorded at Alice Holt Lodge meteorological station

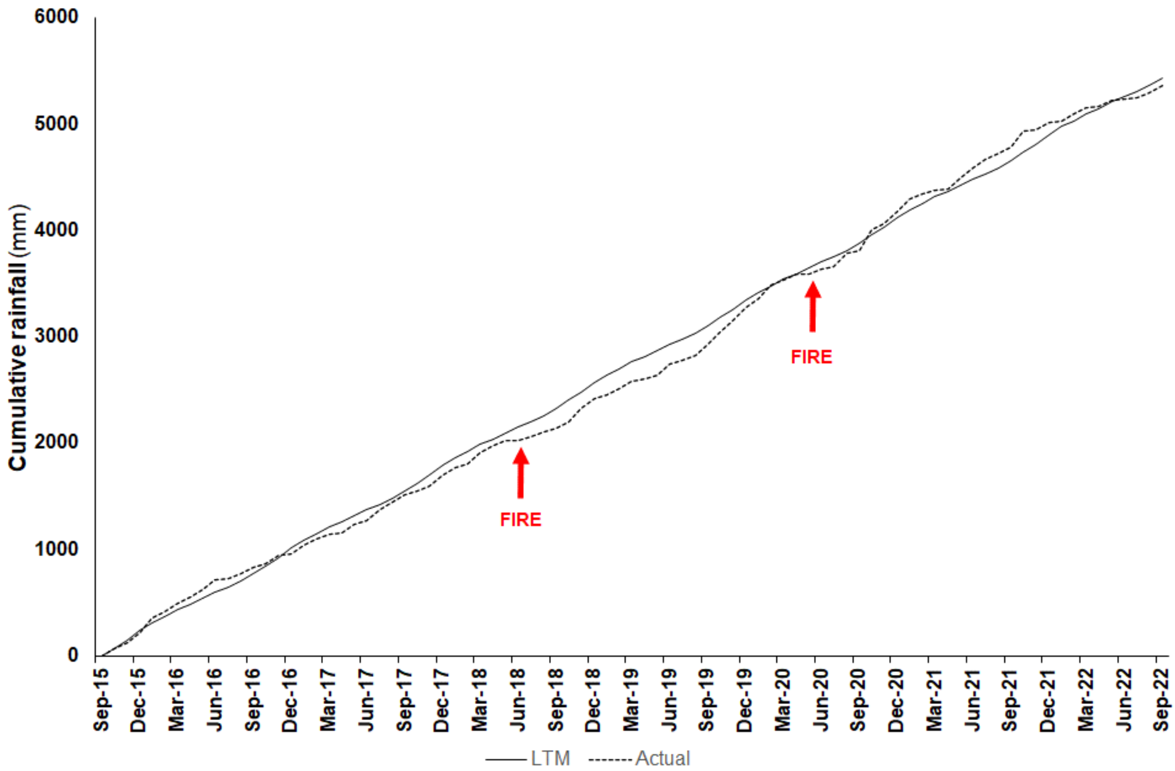


Figure 26. Cumulative monthly rainfall from 01 October 2015 to 31 December 2020 recorded at Alice Holt Lodge meteorological station

Mean monthly air temperatures for January 2020 to May 2020 recorded at Alice Holt Lodge were above the LTM monthly temperature (by 3°C in January, February and April, 0.9°C in March and 1.8°C in May; Figure 27). Air temperature at the time of ignition is not known, but the maximum air temperature recorded on 29 and 30 May 2020 was 23.8°C and 24.1°C.

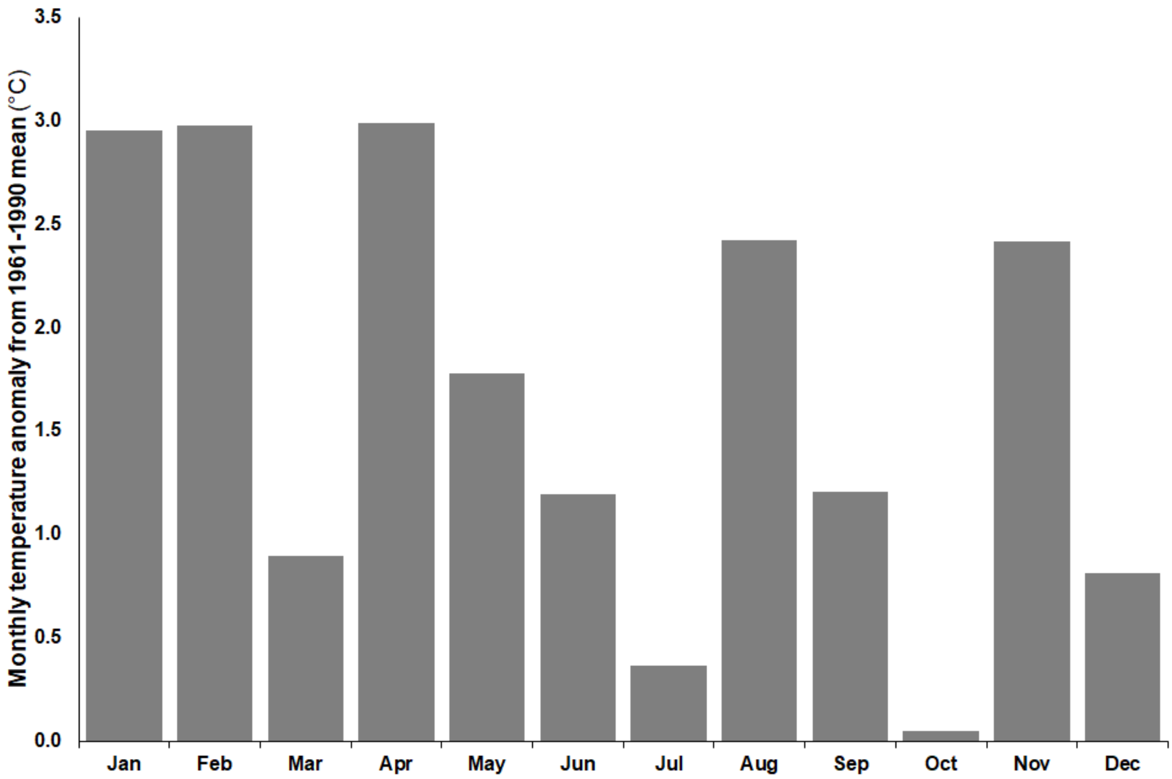


Figure 27. Mean monthly temperature variation from 1961-1990 monthly mean recorded at Alice Holt Lodge meteorological station in 2020

Although meteorological data highlight that the fire in May 2020 occurred after a very short period of extremely low rainfall, FWI data indicate how quickly fire danger conditions developed (Figure 28). Mean (±SD) FWI in April 2020 was moderate (8.2±5.5) peaking at 22.2 on 13 April. The mean and peak values in May were very high (17.5±10.2) and 38.8 on 23 May). During the course of the fire (30 May to 01 June) the FWI values were 31.0, 37.2 and 35.7.

Other notable peaks in FWI over the period 2015-2022 occurred in 2018 and 2022. Interestingly, the fire in June 2018 occurred on day where the FWI was 12.4 (high) and two weeks before a very high peak FWI of 47.3 was estimated on 03 July. The highest FWI value (49.1) was estimated on 18 July 2022.

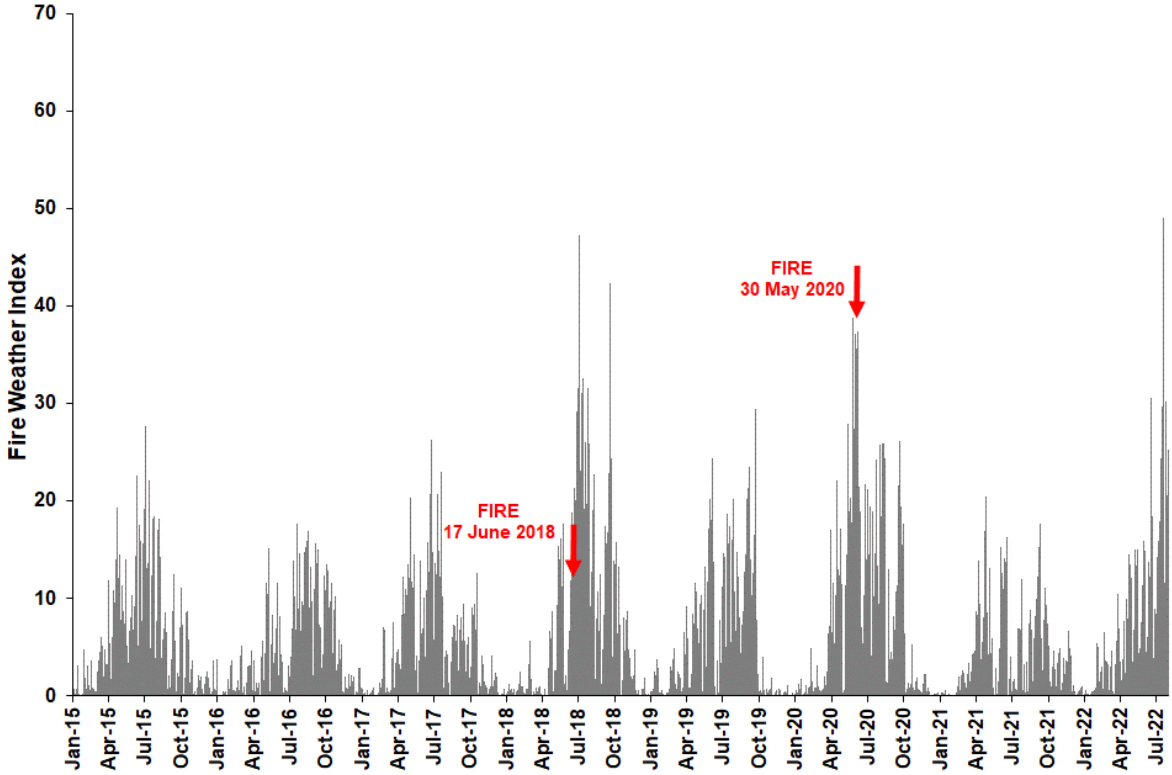


Figure 28. FWI values estimated for Thursley NNR from 2015-2022 (a maximum value of 70 is shown for comparison with Winter Hill and Hatfield Moors)

5.1.2 Winter Hill

The rainfall data recorded at Cranberry Moss indicate that in the month the fire occurred (June 2018), Winter Hill received 30 mm of rainfall (30.9% of the LTM monthly rainfall value; Figure 29), a deficit of 66.9 mm (Figure 30). May 2018 was also drier than average, where 36 mm of rainfall was recorded (40.1% of the LTM monthly rainfall value; Figure 29); a deficit of 53.8 mm (Figure 30). However, the rainfall received in April was equal to the LTM monthly value, and the preceding Autumn and Winter months, and March 2018, all received higher than average rainfall (Figures 29 and 30).

Interestingly, the cumulative rainfall plot indicates that for the period from November 2015 to May 2018, Winter Hill had received higher than average rainfall overall (Figure 31), as the actual cumulative rainfall plots above the expected cumulative LTM.

Two further wildfires occurred on Winter Hill Flats, to the north of Winter Hill summit (Figure 10), on 23 March 2019 (a Saturday) and 27 March 2020 (a Friday). Both events were reported to have started from deliberate ignitions and burned areas of 6.2 ha and 98.5 ha respectively. It is notable that March 2019 was wetter than average where 200% of the LTM rainfall was received (112.3 mm), and in March 2020, 100% of the LTM rainfall was received. March 2020 also followed a very wet February where over 300% of the LTM rainfall was received (188.6 mm; Figures 29 and 30).

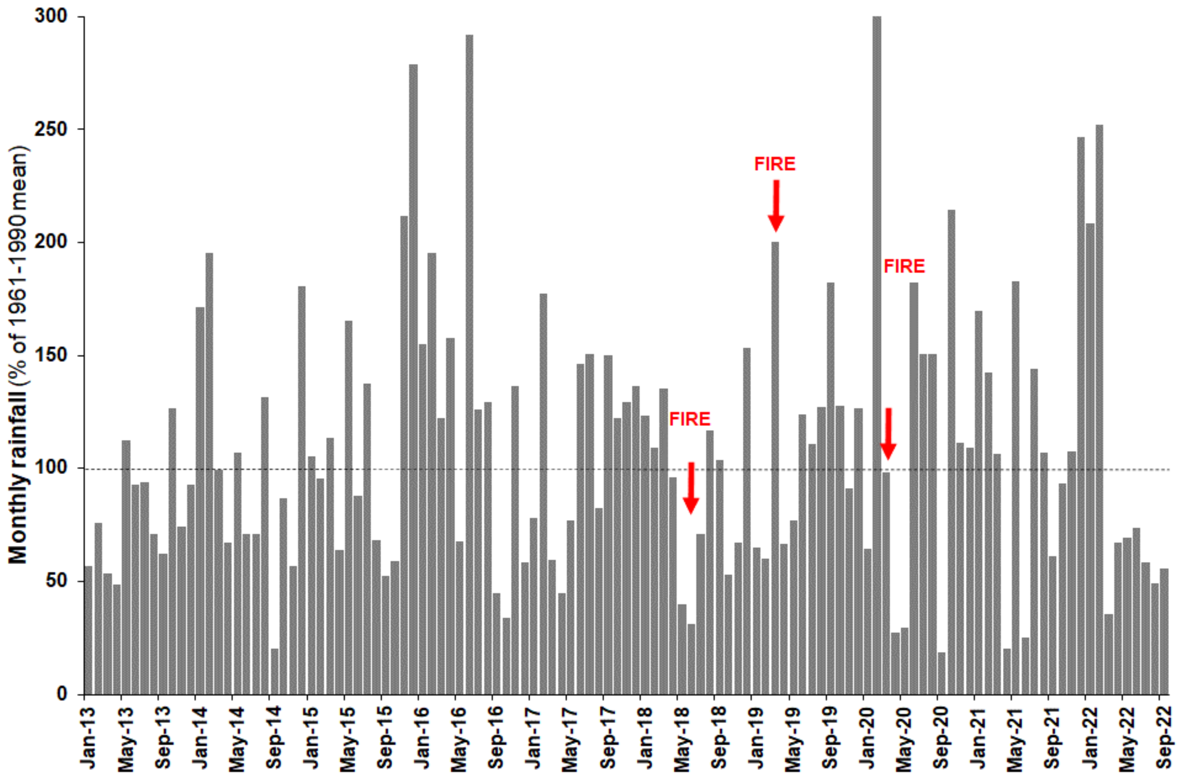


Figure 29. Total monthly rainfall as a proportion of 1961-1990 monthly mean recorded at Cranberry Moss meteorological station

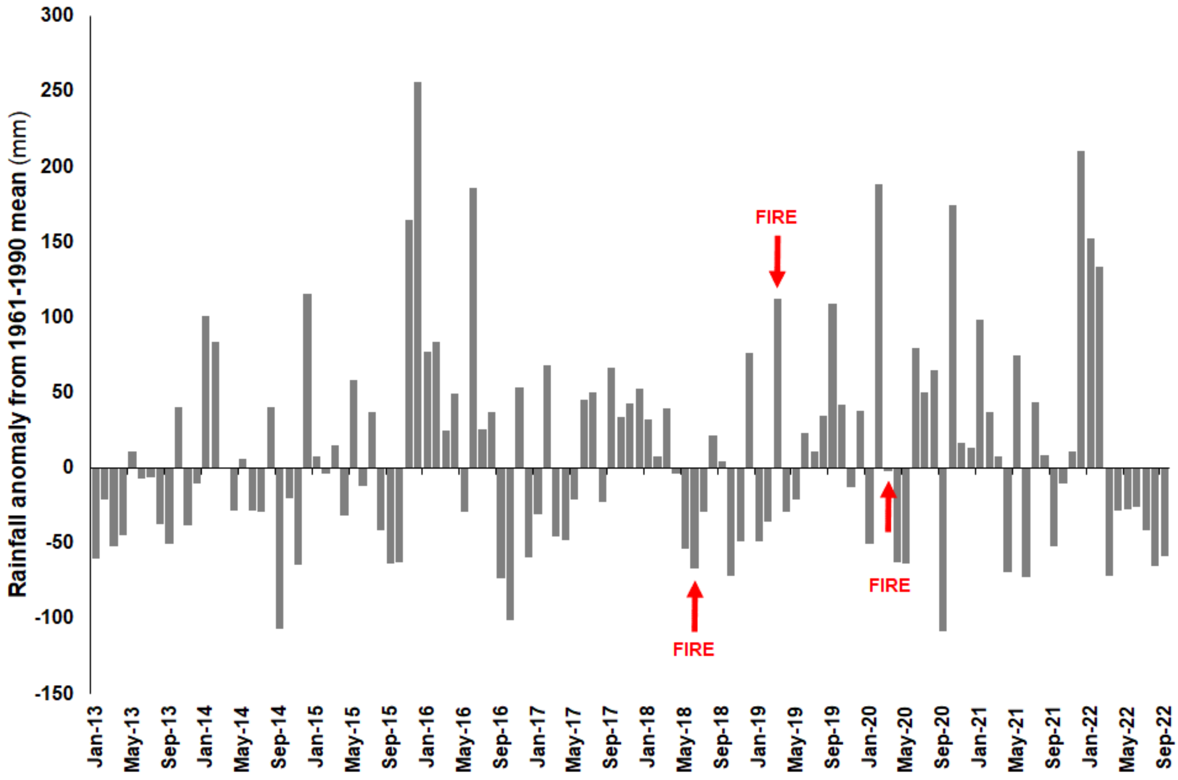


Figure 30. Monthly rainfall variation from 1961-1900 monthly mean recorded at Cranberry Moss meteorological station

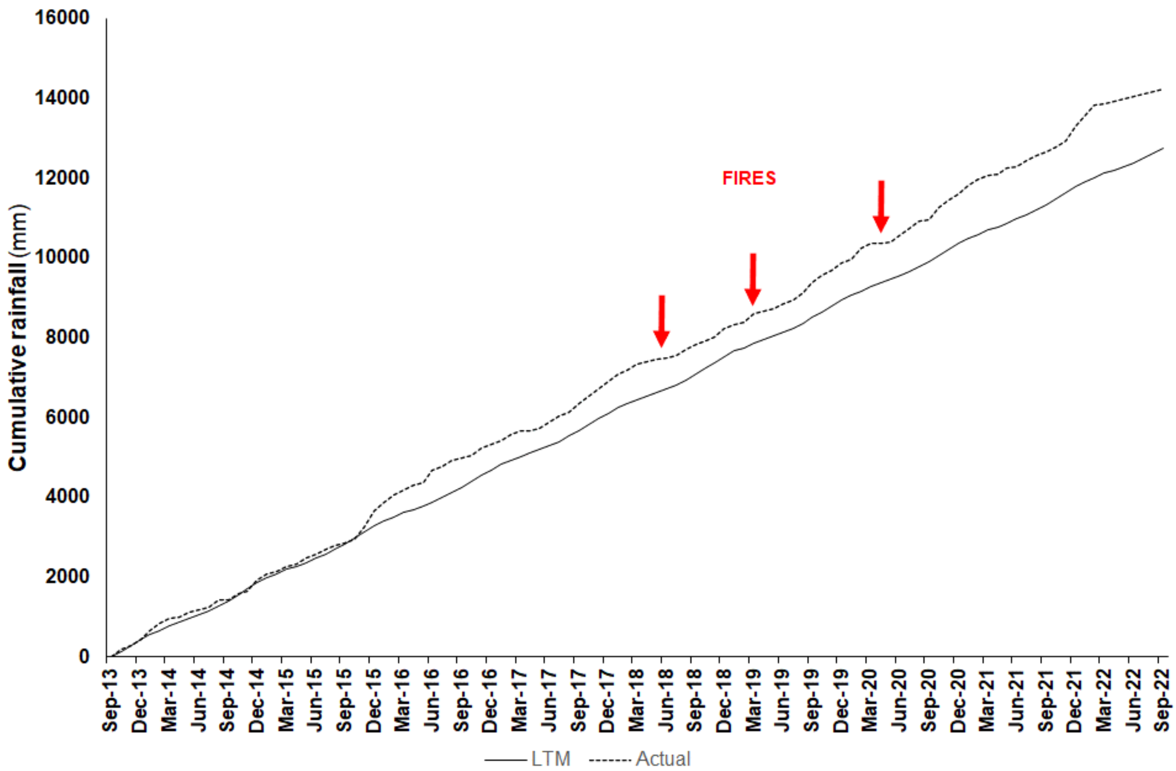


Figure 31. Cumulative monthly rainfall from 01 October 2013 to 31 December 2018 recorded at Cranberry Moss meteorological station

Mean monthly temperatures for April 2018 to June 2018 recorded at Preston were above the LTM monthly temperature (by 1.5°C in April and 2.5°C in May and June; Figure 32). Maximum daily air temperature recorded for the period of fire mapping (25 June – 04 July 2018) ranged from 25°C to 29.8°C, up to 10°C higher than the LTM maximum monthly temperatures for June and July (17.7°C and 19.2°C respectively; Figure 11).

Values of FWI estimated for Winter Hill (Figure 33) are notably lower than FWI values estimated for Thursley NNR (typically by around 50%). In the month prior to the fire (May 2018), the mean FWI for Winter Hill was low/moderate (4.7 ±3.8). On the day the first ignition occurred (25 June), FWI rose to high (10.7), increasing to very high on 01 July (25.5) and peaking at 30.7 on 02 July.

It is particularly noteworthy that the fires in March 2019 and March 2020 both occurred on days where the FWI was low (0.4 and 4.3 respectively).

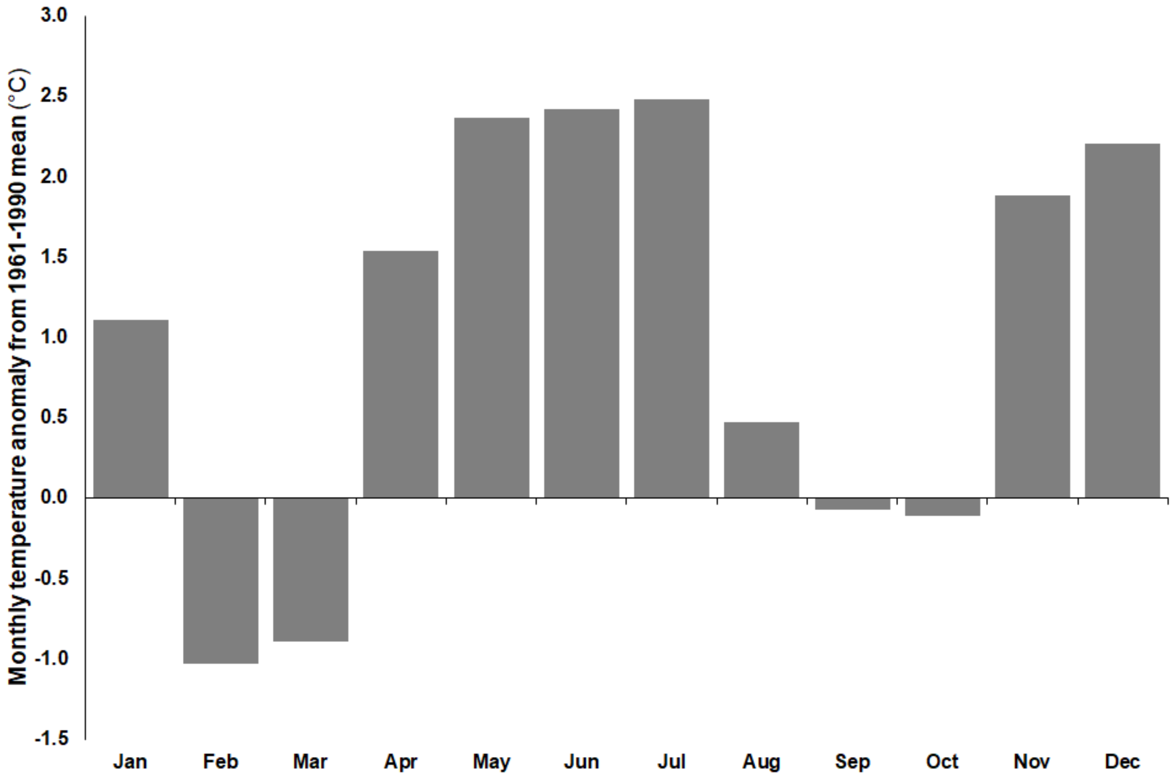


Figure 32. Monthly temperature anomaly from 1961-1900 monthly mean recorded at Preston meteorological station in 2018

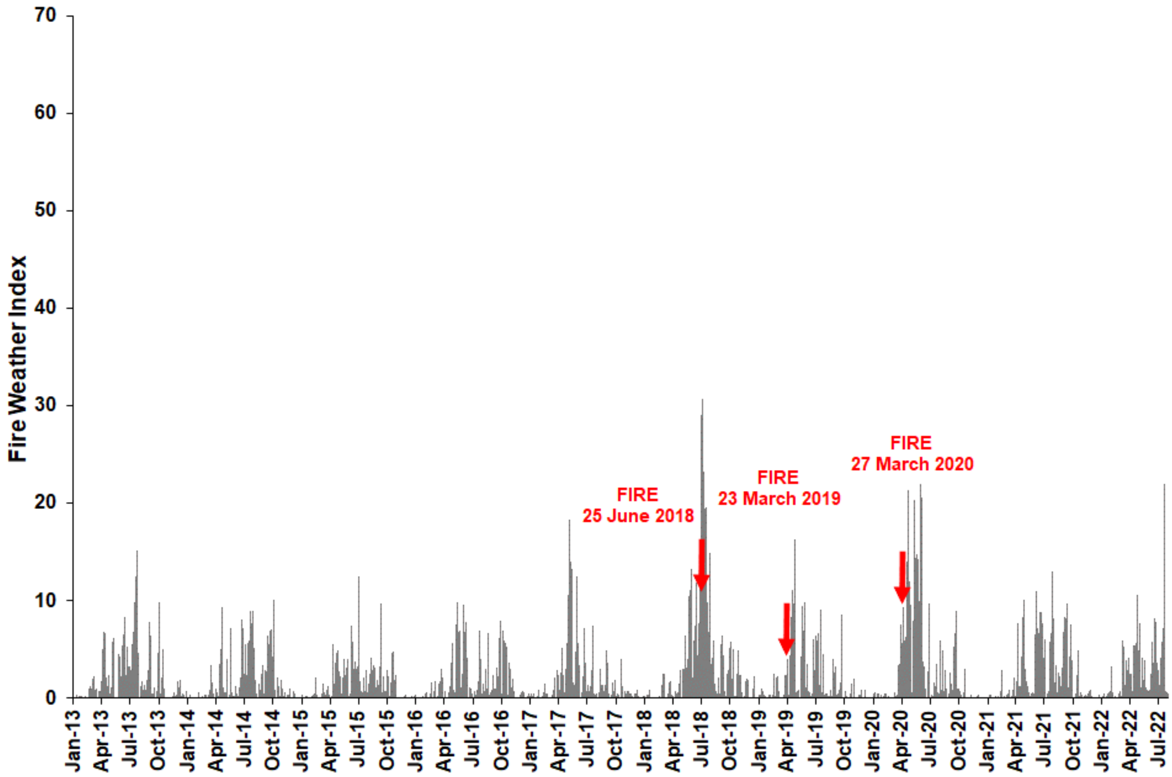


Figure 33. FWI values estimated for Winter Hill from 2013-2022 (a maximum value of 70 is shown for comparison with Thursley NNR and Hatfield Moors)

5.1.3 Hatfield Moors

The rainfall data recorded at Crowle indicate that in the month the fire occurred (May 2020), Hatfield Moors received 11.6 mm of rainfall (24.7% of the LTM monthly rainfall value; Figure 34), a deficit of 35.3 mm (Figure 35). In the preceding two months (March and April) 15.5 mm and 8.1 mm of rainfall were recorded (35.5% and 17.6% of the LTM respectively; Figure 34; deficits of 28.2 mm and 38.0 mm; Figure 35). Similarly low amounts of rainfall were received in April 2015 and April 2017, but at the time of the fire occurring, Hatfield Moors had experienced a greater deficit of 101.5 mm over a prolonged period of low rainfall.

Interestingly, this deficit is less evident in the cumulative rainfall plot owing to wetter than average preceding Summer, Autumn and Winter months (Figure 36).

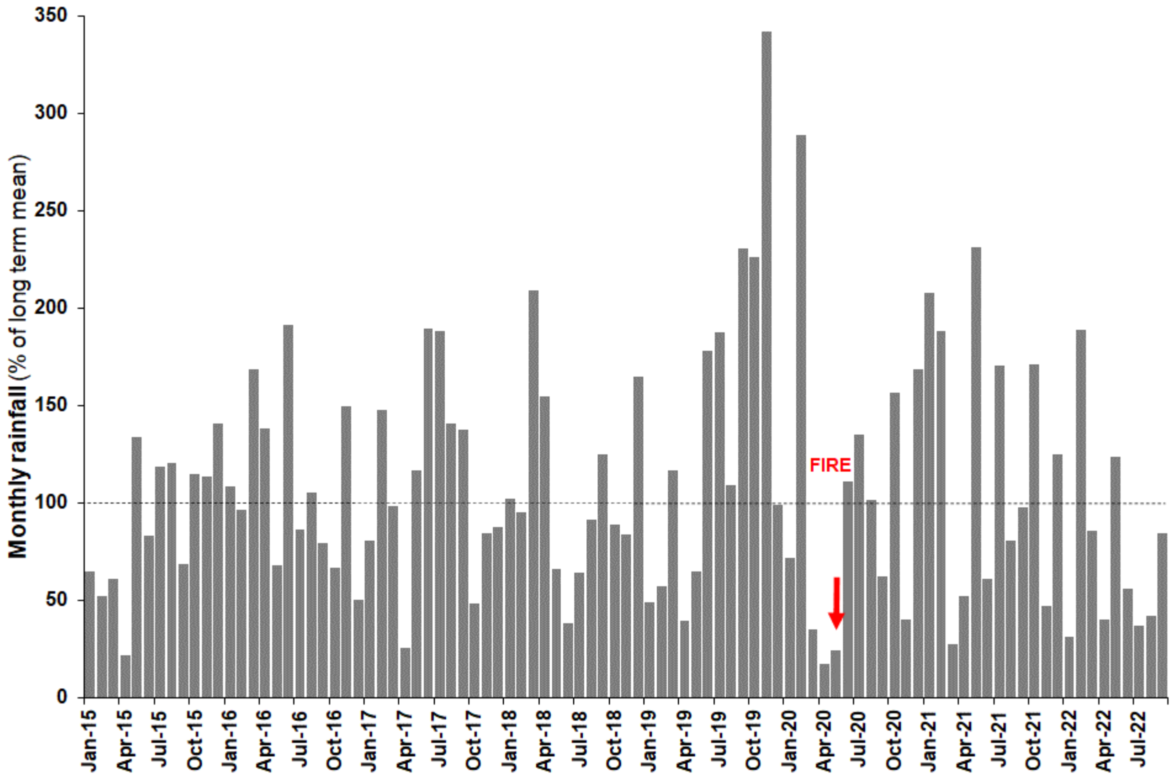


Figure 34. Total monthly rainfall as a proportion of 1961-1990 mean recorded at Crowle meteorological station

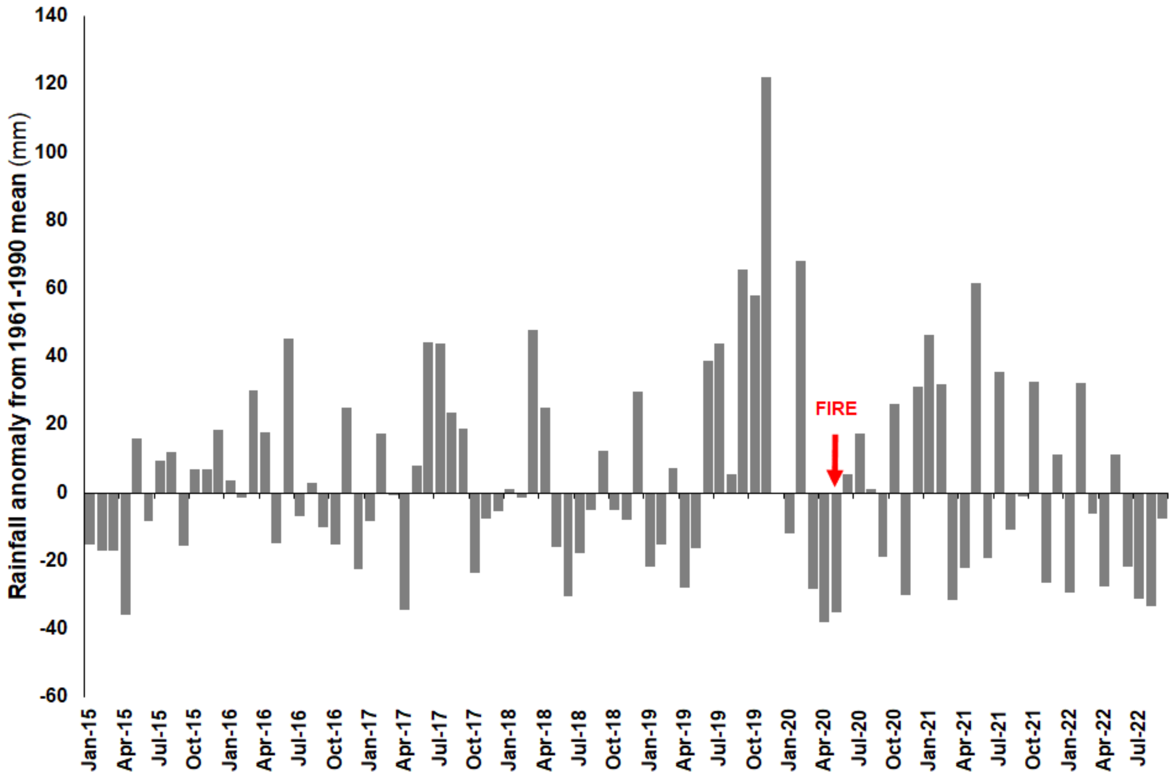


Figure 35. Monthly rainfall anomaly from 1961-1900 mean recorded at Crowle meteorological station

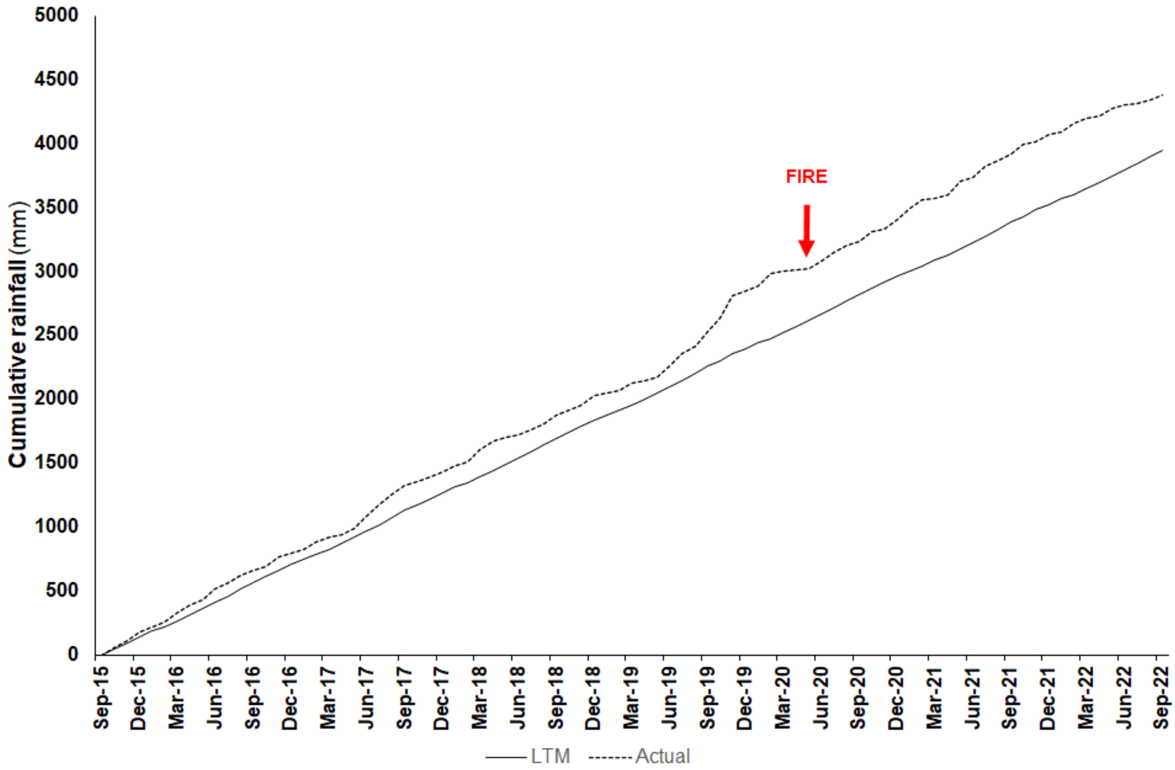


Figure 36. Cumulative monthly rainfall from 01 October 2015 to 31 December 2020 recorded at Crowle meteorological station

Mean monthly temperatures for January 2020 to May 2020 recorded at Cawood were above the LTM monthly temperature (by 2.7-2.9°C in January, February and April, 1.1°C in March and 1.6°C in May; Figure 37). Maximum air temperature recorded on the day of ignition (17 May 2020) was 18.1°C, approximately 3°C higher than the LTM monthly maximum for May (15.2°C; Figure 16).

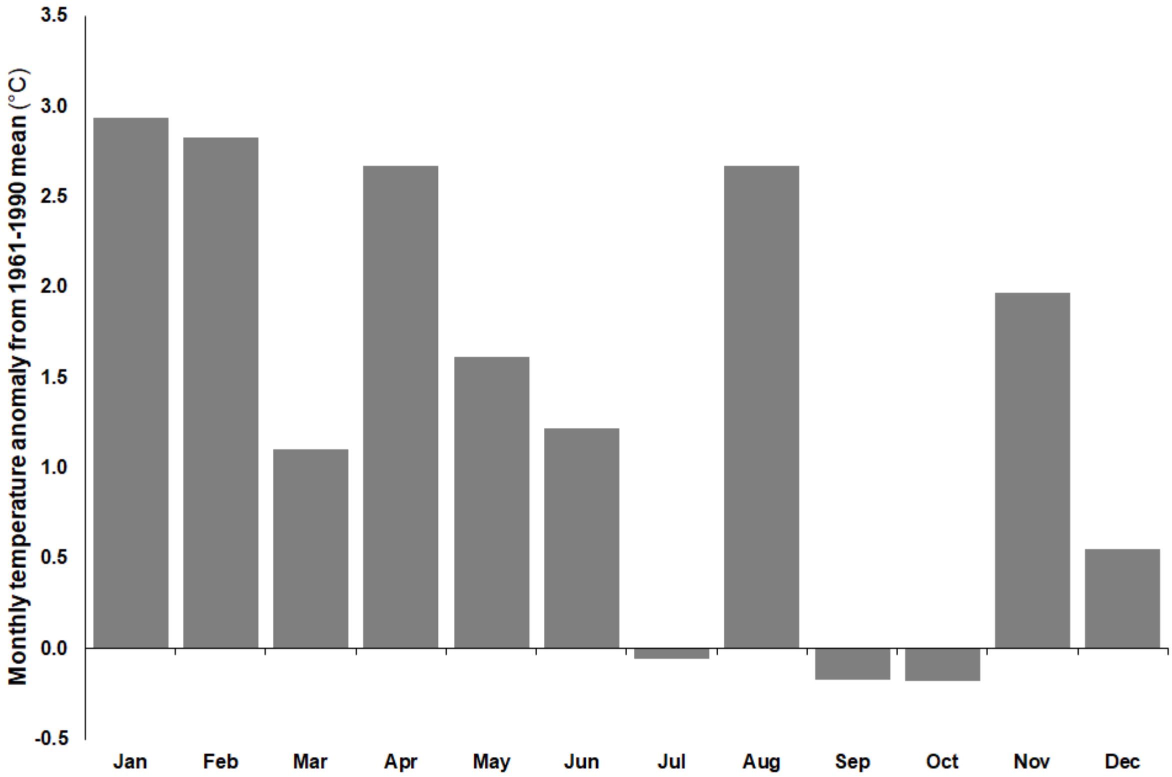


Figure 37. Monthly temperature variation from 1961-1900 monthly mean recorded at Cawood meteorological station in 2020

FWI values over the three months with lower-than-average rainfall in 2020 increased from low (2.9 ±2.7) in March, to high in April and May (9.9 ±6.0 and 16.7 ±11.7 respectively). A peak value of 24.0 (very high) was recorded in April (on the 24). On the day the fire started (17 May) the FWI value was 21.0 (very high) and increased to a peak of 49.0 on 23 May.

Other notable peaks in FWI over the period 2015-2022 occurred in 2018 and 2022. The mean FWI in May 2018 (6.1 ±4.8; moderate) was notably lower than the value in May 2020, but the summer values in 2018 were notably higher. Interestingly, the peak FWI value in 2018 (51.1; very high) was recorded in September. Hatfield Moors was the only site where an exceptional FWI value (65) was recorded over the period examined (on 18 July 2022).

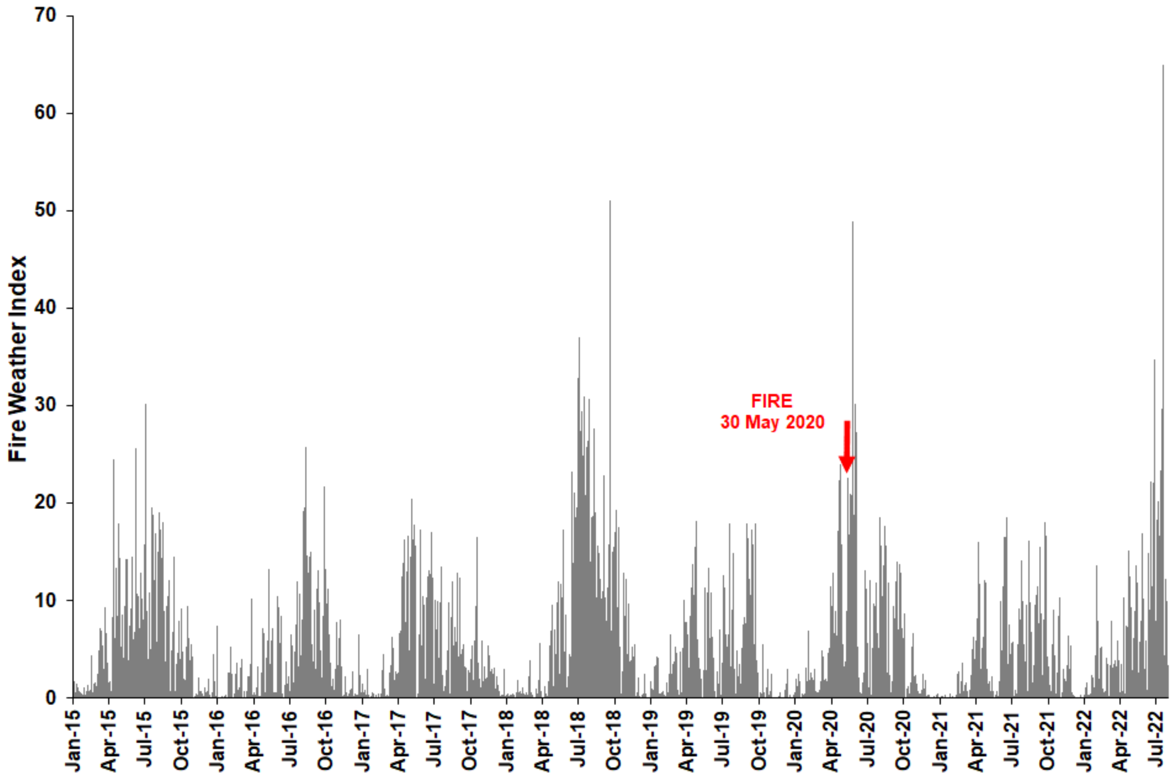


Figure 38. FWI values estimated for Hatfield Moors from 2015-2022

5.1.4 Trends in rainfall

No significant changes or trends in total annual rainfall were identified for any of the sites over the period examined (1961-2020). In contrast, changes in monthly and seasonal rainfall amounts were identified, notably that lower rainfall is being received in spring months and greater rainfall is received in winter months (Figures 39-44). This is consistent across all sites, but for Thursley NNR there is indication that Autumn months are wetter and that at Hatfield Moors summer months are wetter.

However, it must be noted that the only changes identified as being significant were the increasing trend in winter rainfall for Thursley NNR (Z=1.89; p=0.029) and Winter Hill (Z=2.67; p=0.004). At Thursley NNR, increased rainfall in February (Z=1.82; p=0.034) and October (Z=2.08; p=0.019) were both identified as being significant. At Winter Hill increased rainfall in December was identified as being significant (Z=2.19; p=0.014).

Given that the accidental fires at Thursley NNR and Hatfield Moors occurred in spring (May), the trend of drier spring months may suggest that the risk of fires occurring in spring becoming uncontrolled is increasing.

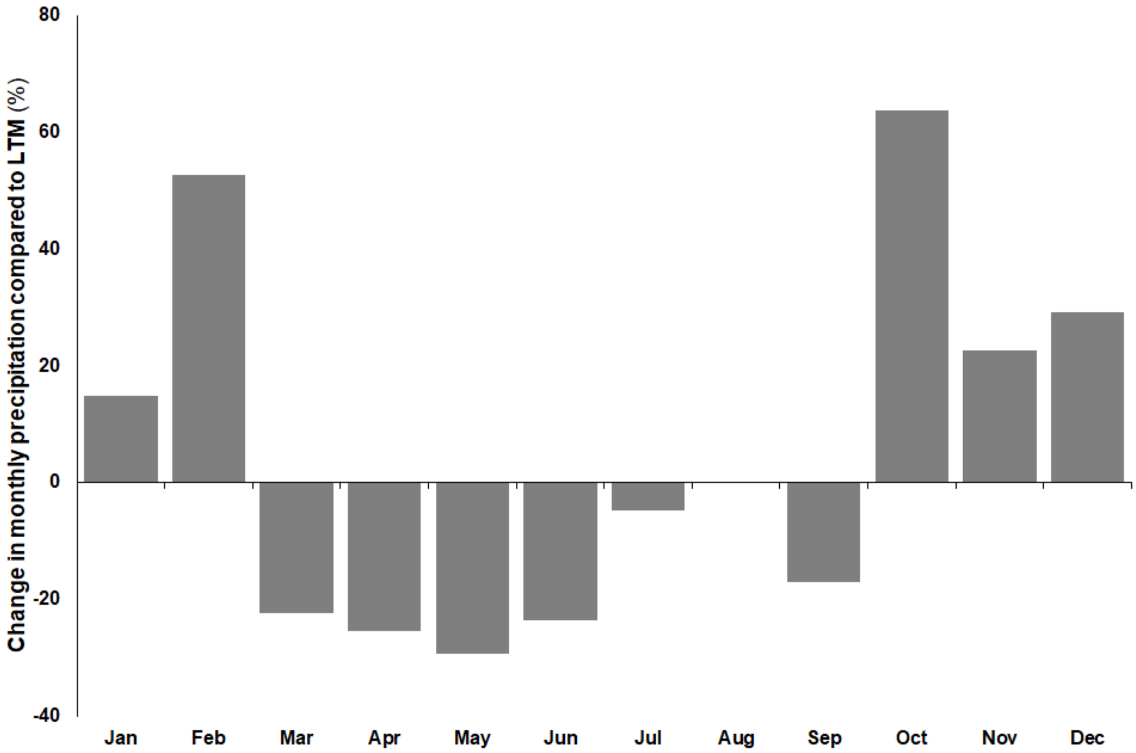


Figure 39. Change in total monthly rainfall from 1961-2020 compared to long term mean rainfall recorded at Alice Holt Lodge meteorological station

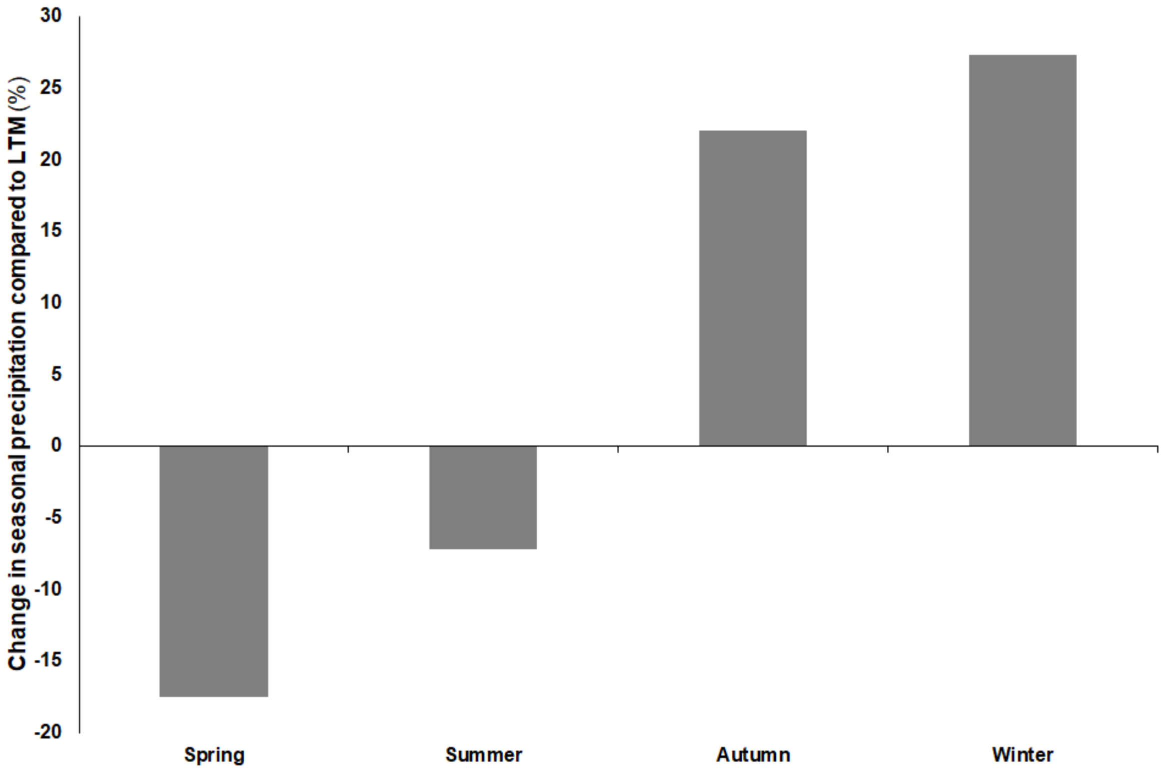


Figure 40. Change in total seasonal rainfall from 1961-2020 compared to long term mean rainfall recorded at Alice Holt Lodge meteorological station

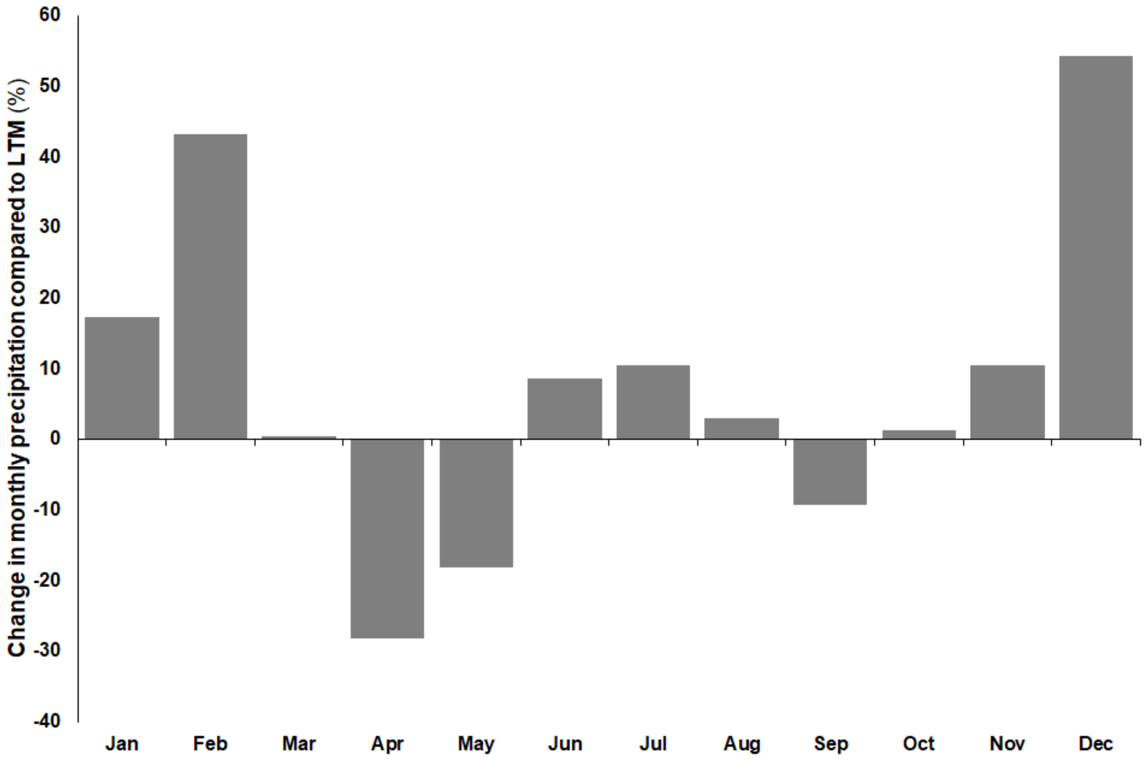


Figure 41. Change in total monthly rainfall from 1961-2018 compared to long term mean rainfall recorded at Cranberry meteorological station

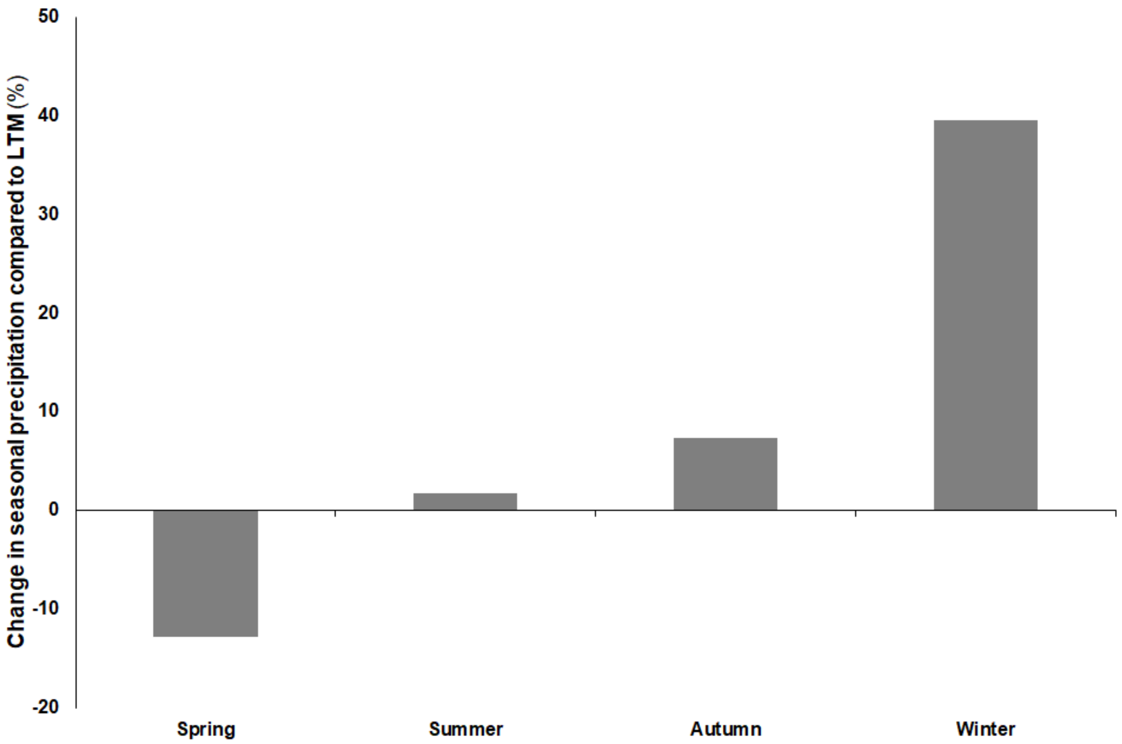


Figure 42. Change in total seasonal rainfall from 1961-2018 compared to long term mean rainfall recorded at Cranberry meteorological station

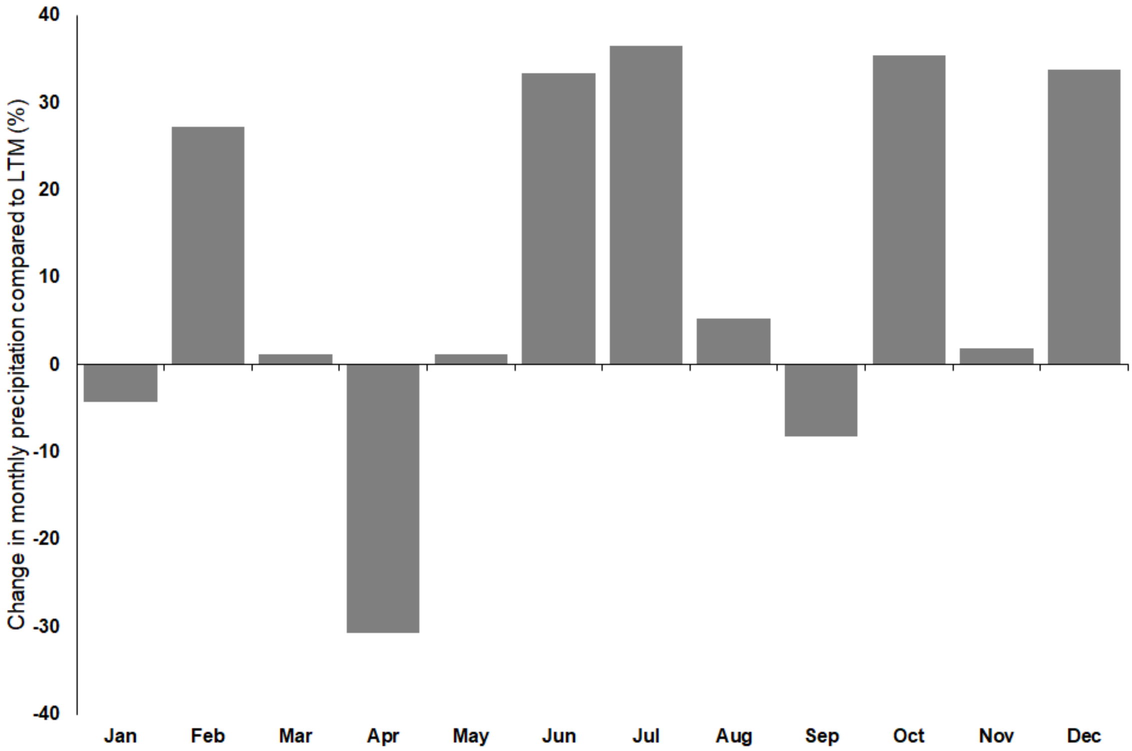


Figure 43. Change in total monthly rainfall from 1961-2020 compared to long term mean rainfall recorded at Crowle meteorological station

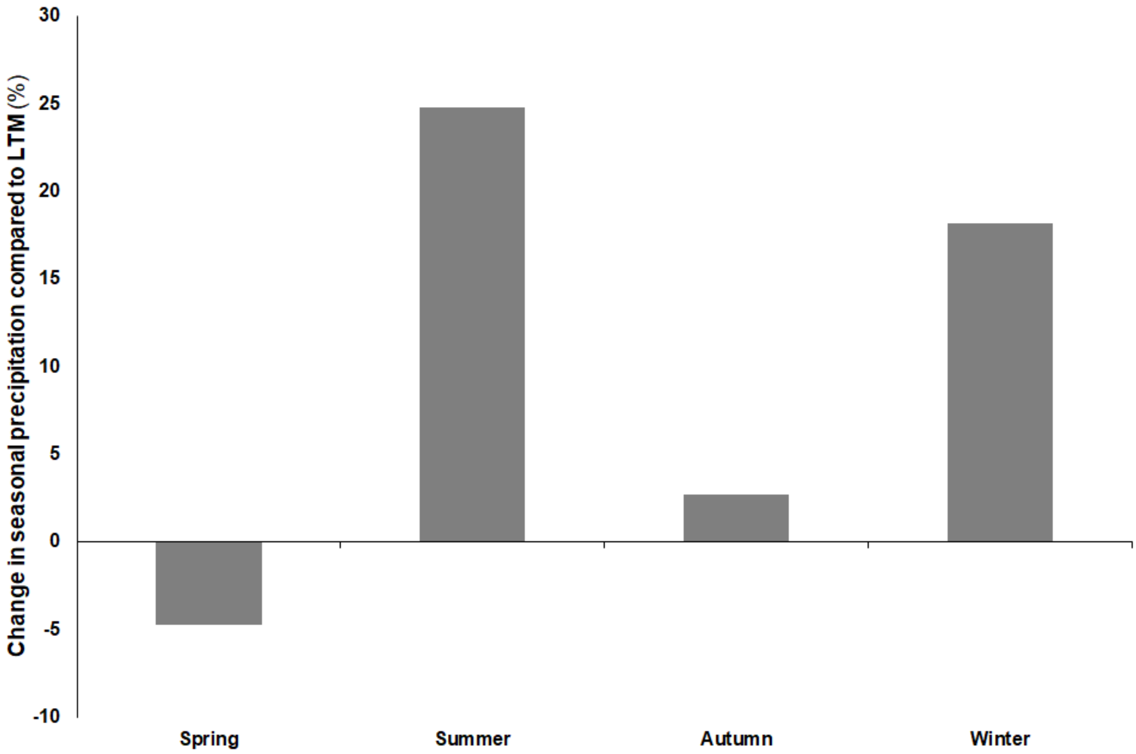


Figure 44. Change in total seasonal rainfall from 1961-2020 compared to long term mean rainfall recorded at Crowle meteorological station

5.2 Pre-fire measures

5.2.1 Thursley NNR

The Thursley National Nature Reserve Management Plan (Giles et al., 2012) recognises the vulnerability of heathland habitat to wildfire events. The Plan presents a series of measures to reduce the likelihood of uncontrolled fires:

- Extension of the areas grazed by cattle;
- Regular cutting or controlled burns of mature areas of heath, particularly in areas with
  high visitor numbers;
- Removal of cut material following scrub management;
- Effective bracken control to minimise build up of dense leaf litter;
- Rotational management of gorse;
- Use of scrapes, wide rides and mown areas to provide fire breaks;
- Maintenance of high water levels in the mires;
- Retention of trees in selected areas to provide shade;
- Awareness raising amongst visitors;
- Regular removal of litter;
- High profile wardening during periods of high risk;
- Encouragement of volunteer involvement in patrolling during high risk periods.

These measures are typically undertaken routinely, and prior to the fire in May 2020, there have been no significant uncontrolled heath fires since July 2006 (the fire in June 2018 burned an area of approximately 3 ha). However, owing to resource cuts in 2020, Reserve staff confirm that some of the measures, such as mowing either side of footpaths to create fire breaks, was not undertaken in the months preceding the fire in May 2020.

5.2.2 Winter Hill

Prior to June 2018, the last significant fire in the area occurred on Anglezarke Moor in April 2011, burning an area of 1,017 ha (Kitchen, 2012). As part of routine management, United Utilities had cut some fire breaks on the top of Winter Hill in 2018 before the fire. However, pre-fire management activity was largely focussed on Anglezarke Moor (4 km to the north; Figure 5) owing to the greater number of fires occurring there historically (A. Ryding, personal communication, 2022). Improvements to access tracks, such as the Miners' track running northeast from the summit of Winter Hill (Figure 10), had been discussed, but actions were not undertaken before June 2018 due to cost.

5.2.3 Hatfield Moors

A few fires occurred on Hatfield Moors in the 15 years between cessation of peat extraction in 2005, and the fire that occurred in May 2020, but these were small and extinguished by Reserve staff (J. Small, personal communication, 2023). As a result, Reserve staff admit that the threat of wildfire was not a key consideration and there were no measures in place to mitigate the risk and severity of wildfire events.

5.3 Fire barriers and interventions

5.3.1 Thursley NNR

The bridleways and footpaths that dissect parts of Thursley, Elstead and Ockley Commons are characterised by an unvegetated, sandy substrate. If left unmanaged, these routes appear to provide some form of barrier to the spread of fire, but only when the fire front is travelling against the wind. In instances where the fire front is with the wind, fire appears to spread across these features unhindered. Fire breaks that were created during the fire by mowing or flailing vegetation were largely successful, and if the vegetation on either side of footpaths and bridleways are cut, as the Management Plan advises (Giles et al., 2012), an effective network of fire barriers could be maintained.

The fact that footpaths and bridleways offer some resistance to fire against the wind indicates that if future fire events occur, the creation of additional fire breaks, if required, should be prioritised in relation to the direction of wind. Efforts should focus first on fire fronts spreading with the wind.

5.3.2 Winter Hill

The unsurfaced Belmont Road running NE-SW on the west side of Winter Hill acted as an effective barrier to the spread of fire on several occasions, even when the fire front was spreading with the wind. The unsurfaced Miners' track running NE from the masts on the summit of Winter Hill was also effective at stopping the spread of fire, although the fire front is likely to have been spreading perpendicular to the wind at this feature. These observations indicate that roads and tracks offer some form of barrier to the spread of fire. Cutting vegetation either side of roads and tracks would likely enhance the protection that these features offer, but in future events, roads and tracks should be monitored, but interventions can be prioritised elsewhere first.

Footpaths running across the blanket bog on Winter Hill may offer slight resistance to the spread of fire when the fire front is travelling against the wind. However, their function as a barrier to fire can not be assumed. If vegetation is managed, perhaps mown, on either side of footpaths this could provide additional fire control features.

Fire breaks created using a bulldozer during the fire were effective at stopping the spread of fire at several locations. However, this approach caused significant damage to areas of peat highlighted by the slow recovery of vegetation on these features (K. Rogers, personal communication, 2022). In contrast, dislodged sections of peat resulting from fire breaks created using an excavator appear to be easier to reinstate and vegetation on these features is recovering more quickly (K. Rogers, personal communication, 2022).

During the fire, United Utilities worked with local farmers to develop a system to assist FRS with the provision of water. The approach, referred to as an ‘umbilical system’ (A. Ryding, personal communication, 2022), comprises a series of water containers (2000 litre capacity) located in a relay system to sequentially pump water up from reservoirs towards a fire event. The contribution of this approach to tackling the fire on Winter Hill is not clear, but it was effective when used on a subsequent fire on Darwen Moor (Figure 5) in 2020. The fire on Darwen Moor was smaller, but had similar characteristics to the fire on Winter Hill as the fire had burned into the peat and areas continued to re-ignite.

5.3.3 Hatfield Moors

Although Lindholme Bank Road that runs to Lindholme Island may function as an effective fire break, the fire only reached the road at one location. The fire did not cross the road, but a fire break had been created adjacent, so it is not possible to determine the level of protection that the road provides without additional intervention. The fire break created on the east side of Lindholme Island, adjacent to an access track, appears to have functioned well. It should be noted that creation of the fire breaks left numerous large piles of brash/scrub. These were cleared after the fire as they presented a future fire risk.

5.3.4 All sites

A common observation for all three sites examined is that access for FRS vehicles is constrained and for some parts of each site, impossible. At Thursley NNR, FRS vehicles gained access to more central areas of the site but got stuck in wetter areas of the mire. Improving accessibility would enable better management of fire events, but at all sites it is unlikely that this would be possible without damaging the habitats.

Key mitigation and control of fires where access is limited, particularly in designated sites, requires a faster, near real-time fire alert system and more rapid deployment of helicopters to extinguish fires.

6 Lessons learned and recommendations

Ignition source, environmental conditions and education

The three fires examined in this study all occurred in months with below average rainfall, above average temperatures and where the level of fire danger (FWI value) was very high. The fires at Thursley NNR and Hatfield Moors were accidental and occurred in late spring (May), but the preceding autumn and winter months were wetter than average. The fire at Winter Hill (comprising one accidental and two deliberate incidents) occurred in early summer (June), following wetter than average autumn, winter and spring months. It is therefore clear how quickly fire danger conditions can develop. Albertson et al. (2010) also highlighted that wetter winters did not reduce the likelihood of spring wildfires in the Peak District National Park. A trend of increasingly drier spring months identified for all sites (albeit not statistically significant) may suggest that the risk of fires occurring in spring/early summer and becoming uncontrolled is increasing.

However, two additional deliberate fires at Winter Hill occurred in months with above average (March 2019) or average (March 2020) monthly rainfall, and the FWI values were low (0.4 and 4.3 respectively). Moderate fire danger levels start at a FWI value of 4.54. It is also noteworthy that no fires occurred at any of these sites in 2022. Thursley NNR and Hatfield Moors received below average rainfall in November 2021 and in January, April, June and July 2022 (Figures 24 and 34). Winter Hill experienced eight continuous months from February to September 2022 with below average rainfall (Figure 29). At each site there was no ignition source during these periods. An exceptional FWI value of 65 was recorded at Hatfield Moors on 18 July 2022 (the highest value recorded at any site over the period examined).

Measures have been taken at all three sites to reduce the severity and spread of fires should they occur in the future. However, a further key area that requires immediate action is to increase awareness of the risk of fires, and how they can occur, to all users of these and other designated sites.

The use of disposable barbeques and campfires should be banned from all designated sites. It is concerning that the convenience store in Elstead, located less than 2 km from Thursley NNR (Figure 1), sells a large number of disposable barbeques and fuel. The sale of barbeque equipment near NNRs may be adding additional risk as this may facilitate impromptu barbeques where participants are not aware of local environmental or fire conditions. Site managers may want to explore options for providing safe and controlled fixed barbeque or cooking facilities.

NNR resources

Reduced resource significantly impacts the ability of Estate staff to manage vegetation across NNRs. Under these circumstances, if there is an ignition source, the risk of a fire becoming uncontrollable is markedly increased. This was the case at Thursley NNR in 2020. It is therefore imperative that NNRs are fully resourced to enable Estate staff to create and maintain fire control measures. Sufficient resources should also be provided for all designated sites to allow appropriate management to be maintained elsewhere.

Restoration projects

For any restoration project, a fire management plan must be designed and put in place at the onset. Since the fire at Hatfield Moors in May 2020, a wildfire management plan has been created for Humberhead Peatlands NNR and covers both Thorne and Hatfield Moors. The plan addresses actions to:

- Reduce the risk of ignition;
- Reduce the severity of wildfire (spread);
- Reduce the risk of damage to neighbours, the areas of highest environmental value and to NNR infrastructure.

The plan is in a rolling programme of review and actions have already been taken. A network of fire control lines has been designed and includes some of the fire breaks created during the fire in May 2020. These consist of 2 m wide strips of mowing either side of trams or tracks, and 6 m wide strips of mown vegetation if distant from trams or tracks (Small, 2021). In addition, greater presence of fire wardens and visitor management is being undertaken and may be more effective as this proactive strategy reduces the chance of fires starting (J. Small, personal communication, 2023).

The measures adopted here should be undertaken at other sites.

Site access, fire detection and control

Access for FRS vehicles is constrained at all sites and reduces the ability for fires to be damped down with water or controlled with the creation of fire breaks. Improving accessibility is unlikely to be possible at any of the sites examined here, or at other designated sites, without damaging the habitats. It is clear that pre-emptive measures need to be in place.

Existing roads and tracks appear to provide an effective fire break, but footpaths may only offer some resistance if the fire front is spreading against the direction of wind. It is suggested that vegetation is managed either side of any of these types of access routes by mowing or cutting to enhance the potential of providing a fire barrier. Continued management in this way may maintain a series of fire defences.

Additional fire breaks can be created and maintained in areas that are difficult to access. It is not recommended that hard fire breaks are dug or bulldozed, rather that vegetation is mown or cut. The dimensions outlined for Humberhead Peatlands NNR (6 m wide strips) are recommended as a minimum. Actions undertaken at Humberhead peatlands by cutting vegetation back has also improved access for FRS vehicles and allows High Volume Pumps to utilise additional water sources (J. Small, personal communication, 2023).

The fire break used to control the accidental fire at Winter Hill by scraping vegetation away was kept wet, and this additional intervention may have enhanced the effectiveness of the defence. A similar approach of wetting was applied to a fire break created next to a track at a fire on Darwen Moor in 2020, and the fire did not cross the break (K. Rogers, personal communication, 2023). It is therefore suggested that fire breaks should be kept wet during fire events.

To facilitate fires being tackled before they get out of control, a faster, near real-time alert system should be explored. The National Trust are currently assessing a range of novel detection and monitoring approaches at Marsden Moor (West Yorkshire).

For any degraded peatland, restoration interventions should focus in part on rewetting the peat body, for example by blocking drainage structures and building surface structures such as bunds (Convention on wetlands, 2021). If higher water tables are restored this can reduce the severity of wildfires (Grau, 2016; Aylen et al., 2007), but hydrological recovery is slow, so other fire control measures such as fire breaks still need to be employed until water tables are restored.

At Winter Hill, a series of water containers were used to create a relay system pumping water from reservoirs up to the fire event. The contribution of this approach to tackling the fire on Winter Hill is not clear, but it was effective when used on a subsequent fire on Darwen Moor in 2020. It is suggested that similar systems are considered at all designated sites, particularly any that have a history of wildfires. Containers could be mounted on trailers to allow relocation during fire events if required.

For NNRs and designated sites, it is also recommended that fire control using water dropped from helicopters is deployed rapidly and at the onset. Although there is a greater cost associated with this approach compared to ground-based suppression methods, it is likely to reduce damage inflicted on sensitive habitats and costs of post fire restoration activities. However, for these and ground-based suppression approaches, consideration must be given to the source of water collected. During breeding seasons, significant disturbance, or reduction in available water, could negatively impact other habitats and sensitive species present. Guidance on water sources should be provided in fire management plans for all sites.

Other recommendations

This study has examined a very low number of wildfire events. The ignition sources were either accidental (most likely from a disposable barbeque) or deliberate acts of arson. Other sources of ignition can relate to surrounding land use or management activities (e.g. Holland et al., 2022), and it would be a valuable exercise to examine a wider number of fire events to better relate sources of ignition with the number and severity of wildfires. These could include events such as that on Saddleworth Moor/Stalybridge in June 2018 (starting on the same day as the fire at Winter Hill), and numerous fires that have occurred on Marsden Moor over the past few decades.

The impact of the fires, and water supplies used to suppress the fires, on water quality has not been examined for any site in this study. Nottingham Trent University initiated a water quality monitoring programme at Thursley Common with NNR Estate staff in August 2022. The aim is to provide information on the spatial and temporal variation of water quality in the valley mire, but it will also serve as baseline data with which changes can be assessed. It is recommended that routine water quality monitoring is undertaken at all designated sites to enable the impacts of future fires, or other events, to be quantified. There may be a greater impact on ombrotrophic ecosystems, such as blanket and raised bogs, if external nutrient-rich water is used to suppress fires.

Habitat and vegetation mapping is inconsistent between the sites examined: for Winter Hill, detailed NVC mapping was undertaken by Penny Anderson Associates; for Thursley NNR, SSSI units have been broadly mapped using NVC; for Hatfield Moors, current habitat mapping is incomplete. It is suggested that a consistent approach to mapping is employed on these and other sites to better understand habitats impacted by future fire events.

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Appendix

Historical rainfall data for study sites from 1961 to 2022.

Table A1. Total monthly rainfall recorded at Alice Holt lodge meteorological station (1962-2022)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1962	130.7	12.3	35.4	49.1	60.6	7.4	33.5	86.9	112	41	76.2	70.4	**715.5**
1963	20.9	19.2	116.2	92.3	34.2	44.9	45.7	108.1	63.6	55.8	153.2	21.4	**775.5**
1964	18.3	25.7	107.2	71.2	102.9	99.9	33.7	40.1	15.7	46.1	51.3	76.8	**688.9**
1965	77.8	10	69.9	52.3	44.5	66.1	74.5	58.6	111.1	12.8	92	133.3	**802.9**
1966	50.8	137.5	13.8	98.7	70.2	62.1	66.5	66	32.8	111.9	53.6	91.4	**855.3**
1967	83.2	91.1	70.6	46.5	143.5	39.5	25.8	61.9	75.1	165.6	50.5	69.9	**923.2**
1968	55.6	42	27.3	68.9	83.9	80.7	100.3	58.5	192.7	93.7	63.6	99.4	**966.6**
1969	120.3	50.4	67.2	15.7	86.5	27.7	52.9	90.6	18	3.2	119.8	74.3	**726.6**
1970	107.9	65.8	42	66.5	29.7	31.1	51.2	56.8	63.3	14.8	208.7	41.5	**779.3**
1971	115.2	22.8	64.6	69	42.1	135.3	17.1	81.6	11.4	57.9	67.4	23.8	**708.2**
1972	89.3	79.4	76.3	57.6	78.6	36.1	37.2	19.3	25.3	26.6	77.7	141.2	**744.6**
1973	26.5	19	16.9	56.6	65.9	52.1	95.9	49	83.8	25	29.2	67.4	**587.3**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1974	131.1	114.7	32.2	11.9	37	76.5	62.1	89.8	162	79.6	193.3	66.1	**1056.3**
1975	136.5	27.1	90	53.5	47.3	8.6	37.2	29.5	150.6	26.3	71.2	33.3	**711.1**
1976	17.2	33.1	15.7	15.9	19.1	15.6	31.7	14.3	140.7	182.2	124	82.8	**692.3**
1977	93.3	97.1	94.9	28.1	56.9	61.7	20.9	99.9	20.1	47.7	89.9	102.7	**813.2**
1978	113.7	73.1	79.8	47.4	68.5	45.3	65.2	58.5	13.8	8	19.9	184.4	**777.6**
1979	67.7	61.3	123.7	62.3	113.5	46.9	30.8	52.7	15.1	83.5	56.6	118.9	**833**
1980	41.4	59.2	69.8	18.2	15.5	90.6	71.9	54.5	79.1	118.3	47.1	43.8	**709.4**
1981	37.3	22.3	138.4	37.9	98.2	43.3	60	28.1	143.9	99	42.5	94	**844.9**
1982	40.4	37	81.1	16.2	46.5	91.2	24.6	33.7	67.1	152.9	113.6	94.8	**799.1**
1983	75.2	34.2	35.8	102.2	79.4	52.3	25.1	21.2	68	54	42.4	85.8	**675.6**
1984	129.7	48.8	88.6	2.9	109.8	16.5	35	50.2	84.1	90.6	112.9	91.5	**860.6**
1985	67.1	39.7	52.6	46.6	60.4	85.6	54	97.7	12.6	28.6	61	134.6	**740.5**
1986	132.7	23.3	50	69	64	23.5	46	104.2	25.2	87.4	118.2	101.8	**845.3**
1987	19.3	31.9	81.8	63.9	47.7	77.2	74.9	41.2	46.6	225.1	68.7	28.5	**806.8**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1988	142.4	43.2	71.9	48.2	37.2	21.6	111.9	67.2	41.9	64.3	22.9	17.8	**690.5**
1989	32.4	80.7	84.9	65.9	7.5	53.1	32.2	33.1	30.4	87.5	35.3	166.5	**709.5**
1990	130.1	173.2	4	26.8	24.1	51.6	11.4	27.9	38.4	77.7	41.7	70.7	**677.6**
1991	106.2	46.3	61.6	64.5	12.5	87.4	82.5	15.7	47.6	45.7	65.5	14.6	**650.1**
1992	20.3	33.5	58.9	80.5	30.2	31.8	61.3	116.1	75.5	72.9	139.8	88.4	**809.2**
1993	100.6	4.4	36.1	91.1	44.7	68.7	49.1	36.6	110.9	169.6	45.5	121.3	**878.6**
1994	125.7	73.8	54.8	68.1	78	34	11.2	39.7	68.3	108.1	70	118.1	**849.8**
1995	146.2	103.6	50.8	15.8	25.3	12	42.3	4.9	106.8	46	53.9	98.8	**706.4**
1996	69.7	76.6	40.6	34.7	47.3	10.5	42.4	72.9	32.8	59.4	166.1	22.9	**675.9**
1997	15.9	94.9	18.5	7	33.8	80.1	34.7	76.6	16.5	67.9	103.2	87.1	**636.2**
1998	110.2	7.7	69.9	106.8	23.5	97.2	37	30.2	91	152.7	69.1	88.7	**884**
1999	138.6	35.6	40.7	50.1	73.9	69.8	6.8	83.5	112.7	76.9	36	130.6	**855.2**
2000	25	84.5	23.8	154.5	94.3	19	60.8	38.4	109.1	198.1	185.5	145.9	**1138.9**
2001	82.5	112.6	136.6	90	34.1	19.5	56.3	88	81.3	146.5	37.2	21.7	**906.3**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2002	98.4	114.2	47.4	45	95.3	58.4	75	29.5	22.6	108	190.8	162.4	**1047**
2003	91	35.7	24.2	39.6	50	43.4	44.1	18.1	8	44.1	187.2	83.5	**668.9**
2004	112.6	36.2	44.4	83.4	43.3	21.4	47.9	70.1	41.3	141.2	39.6	53	**734.4**
2005	41.3	19.1	36.9	36.1	26.7	24.8	64	48.1	41.7	111.4	53.6	86.2	**589.9**
2006	26.9	52.6	67.5	30.1	96.5	26.8	28	70	65.7	138.8	125.5	130.3	**858.7**
2007	202.7	96.1	71.2	0.8	207.1	234.2	269.1	106.4	59.9	106.7	178.1	141.8	**1674.1**
2008	112.3	22.7	95.9	93.8	74.7	33.5	76.9	61.6	73.9	65.9	89.4	52.6	**853.2**
2009	98.4	61.4	47.7	36.2	38.9	15.6	94	34.6	44	46.2	200.4	96.4	**813.8**
2010	73.2	102.2	68.4	22.4	17.4	24.2	30.2	114.2	66.8	103.2	86.8	38	**747**
2011	104.4	59.6	13.8	0.4	29.6	73.2	56.4	67.2	36.6	32.4	76.2	77.6	**627.4**
2012	52.2	19.2	20.2	146.8	44.6	98.4	98.4	37	55.6	108.6	115	132.2	**928.2**
2013	73.4	39.4	76	30	71.4	17.6	11.8	28.6	67.2	127.6	58.4	186	**787.4**
2014	228.4	170.8	49.6	114.6	56.8	21.8	4.2	57.6	7.8	121.4	168.8	58.2	**1060**
2015	101	63	21.6	22.6	40.6	22.8	61.2	110	67.6	66.2	60.8	94.4	**731.8**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2016	135.4	63.6	83	58.4	65.8	90	13.6	46	52.6	41.8	80.6	15	**745.8**
2017	74.2	63.2	44.4	14.4	70.6	43.4	95.6	75.2	66.8	37.6	44	103.8	**733.2**
2018	73.4	34.6	97.6	74.2	51	0.6	31.6	43	37.2	60.2	127.6	95	**726**
2019	25.6	63.4	66.8	23.8	30.4	110.2	36.2	49	94.8	123.2	96.6	133.4	**853.4**
2020	78	128	52.2	50.2	1.8	42.4	27.8	126.2	29.8	189.4	66.2	116.2	**908.2**
2021	107	50.2	37.2	8.4	104.2	87.8	87.4	52.8	56.4	152.2	15.8	64.4	**823.8**
2022	18.2	68.2	57	15.6	54.4	15.4	2.2	50.6	69.8				

Table A2. Total monthly rainfall recorded at Cranberry Moss meteorological station (1961-2018)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1961	177.8	112.5	55.4	155.2	92.7	79	151.6	187.7	123.2	188.2	123.7	105.4	**1552.4**
1962	172.7	103.4	56.6	139.2	116.1	33.8	92.5	222.8	151.1	69.9	71.4	120.7	**1350.2**
1963	10.2	9.9	131.8	114.3	78.7	125.7	41.1	168.9	157.5	136.7	173.2	58.4	**1206.4**
1964	60.5	44.5	100.3	90.2	121.9	81.5	200.7	105.2	80.3	107.4	117.6	192.3	**1302.4**
1965	157.5	10.7	50	99.3	112.8	78.2	124.5	103.9	177.8	77.5	113.3	331.2	**1436.7**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1966	69.3	193.8	101.1	99.6	146.8	130.6	133.6	109.2	103.6	140	110.5	199.4	**1537.5**
1967	101.9	126.2	63.5	55.1	169.2	112	107.4	182.9	195.6	273.6	134.6	105.4	**1627.4**
1968	186.7	53.3	126.5	78.7	118.1	133.4	100.3	69.9	342.9	229.9	99.1	52.8	**1591.6**
1969	125.7	73.7	85.1	91.7	132.1	105.9	46	90.2	65.8	48.3	205.7	135.9	**1206.1**
1970	126.2	116.1	102.9	156	12.7	67.6	101.9	114.3	106.2	180.3	250.2	74.9	**1409.3**
1971	95.3	97.5	84.6	83.3	82.3	99.6	42.2	176	41.9	135.1	128.3	42.2	**1108.3**
1972	158.8	84.1	121.9	134.6	126	127.5	130.8	55.9	53.6	65.5	232.7	118.4	**1409.8**
1973	93.5	83.6	64.8	102.6	80.3	54.4	145.5	130	116.1	101.1	137.2	162.1	**1271.2**
1974	161.3	144.3	80	6.9	78.2	96.8	172.7	123.2	243.1	136.9	148.3	155.7	**1547.4**
1975	196.9	49	75.7	112.5	21.3	27.9	138.4	107.7	176.3	62.7	134.6	129	**1232**
1976	188.7	63	92.7	52.1	133.1	19.8	49.3	21.6	160.5	200.7	98	87.9	**1167.4**
1977	95.2	190.5	88	111	45.8	163	47	88	104	138.5	206	115	**1392**
1978	161	69	128	39	31.5	102	117	85	136	74	118	165	**1225.5**
1979	115	20	166	87.5	160	55.5	58.5	184	91.5	90.5	182	222	**1432.5**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1980	155.5	166	118.5	2	24.5	229	101.5	196	116	340	171	177	**1797**
1981	174	79	291	50	124	84.5	68	111.5	182	242	185	63.5	**1654.5**
1982	107	71	174.5	49	80.5	138	23.5	195	110	104	206	176.5	**1435**
1983	209	59	152.5	115	130.4	75	36	62	186	203	85.5	233	**1546.4**
1984	238	97	51	13.5	40.5	99	32.5	77	233	180.5	272.5	104	**1438.5**
1985	116	14	117	130.3	84.5	82.3	116.5	195	117	87	110	188	**1357.6**
1986	175.2	2.3	153	114.5	108	52.4	84.9	137.6	32	195.8	202.5	296.4	**1554.6**
1987	61.6	103.2	129.8	75.2	85.4	174.7	135.3	140	116	206.8	140.6	109.8	**1478.4**
1988	215.6	100.6	198	40.9	69	39.6	203.4	182.4	148	137.4	79.2	137	**1551.1**
1989	78	164.9	146	97	42	98.2	94	120.5	30.5	190	118	107.4	**1286.5**
1990	227.7	136.8	44.5	92.9	45	141.5	72.3	108.7	103.5	224.2	83.2	138.5	**1418.8**
1991	88.5	98.5	107	79	15.9	128.5	76	74	74.5	126.5	185.5	128.5	**1182.4**
1992	91.2	90.5	182.2	117.5	54.2	42	82	161.2	121.5	165	202.5	150.5	**1460.3**
1993	164.5	18.6	28.3	148	107.5	57	153.5	86	88.5	57	64	295	**1267.9**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1994	217	85	174.3	118	29	84.2	75.5	70.4	134.6	205.4	151.5	224.3	**1569.2**
1995	269.9	181	104.5	35	64.5	40	67	17	141	56	72	46.5	**1094.4**
1996	48.5	133	50	73.5	66	79	71	128.1	74.4	152	219.5	62.5	**1157.5**
1997	9.6	209.5	83.9	50	151	99	113.3	64	85	90.4	123.2	199.3	**1278.2**
1998	163	64.9	202.6	104	61	180	129	147.7	109.3	301.6	155.5	102.6	**1721.2**
1999	162.1	154.5	106.5	98	99	109.4	39.8	89.5	141.2	150	78	312	**1540**
2000	141	191	122	104	97.5	138	73	110	162.3	307	272	172	**1889.8**
2001	111.3	151.5	77.5	163	69.5	81.5	47.5	161.5	147.5	208	124.5	116.5	**1459.8**
2002	126	313.5	57	106.9	192	138	123	104	50	174.5	195	168.5	**1748.4**
2003	105	69.5	74	84.5	177.5	83.8	94.1	32.5	76.5	85	139.5	171	**1192.9**
2004	202	102	51.5	136	53	142	87.5	312.9	170	189	121.9	181	**1748.8**
2005	101.8	99	57	137.5	121	49.5	65	126	*109*	123	175	96	**1150.8**
2006	90	97.5	205	86.5	165	42	50.7	220	76	165	156.3	202	**1556**
2007	217	71.5	*65*	38	128	208	218	105	153.7	88.5	133	204.5	**1565.2**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2008	294	80	145	102	26	118	192.5	192	201	187	94	129.1	**1760.6**
2009	139	33	73	54	112.5	61.5	180	129	89	105	311	117	**1404**
2010	97	87	87	30	21	31	151	109	217	139	174	66	**1209**
2011	122	191	34	23	129	92	136	149	187	164	86	287	**1600**
2012	147	87	34	153	87	283	138	182	245	170	196	296	**2018**
2013	80	67	60	42	101	90	92.7	91	83.4	193	110	133.4	**1050.8**
2014	241	172	111	58	96	69	70	169	27	132	83.7	259	**1487.7**
2015	148	84	127	55	148.6	85	136	87.4	70	90	313	400	**1744**
2016	218	172	*136.6*	136	61	283	*124.9*	166	60	*51.5*	201.7	84	**1660.7**
2017	110	156	66.5	*39*	*69*	142	149	106	200	186	191	196	**1586.5**
2018	173	96	151	83	36	30	70	150	138	81	99.1	220	**1327.1**

* Note measurements for September 2005, March 2007, July 2013, March, July & October 2016, and April & May 2017 were taken from Bolton: Sweetloves.

Table A3. Total monthly rainfall recorded at Bolton: Sweetloves water works meteorological station (2019-2022)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2019	91.4	52.8	224	57.6	69	120.2	109.6	163.4	242.8	194.6	135	181.9	**1642.3**
2020	90.5	276.6	110	23.4	26.6	176.9	148.9	193.4	24.8	326.7	165	157	**1719.8**
2021	238.6	125.4	119.2	17.4	164.2	24.2	142.8	137.2	81.6	142.4	159	354	**1706**
2022	292.6	221.6	39.8	58.2	62.4	71.5	58	63	74.6				

Table A4. Total monthly rainfall recorded at Crowle meteorological station (1960-2022). Some cells are blank

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1960	106.2	36.4	28.4	18.1	16.4	11.9	83	56.7	49.3	120.2	87.1	53.2	**666.9**
1961	79.1	28.4	8.9	62.5	34.8	30.2	54.2	75.5	36.6	60.7	27.4	56	**554.3**
1962	42.8	19.6	17.8	35.9	53.7	8.7	35.2	86.4	69.1	12.3	36	32.4	**449.9**
1963	26.7	18.6	40.1	41.6	17.7	65	37	78.3	51.2	32.5	88.6	12.2	**509.5**
1964	15.8	17.4	81.4	44.5	18.2	51.2	39.7	34.1	21.3	33	20	20.9	**397.5**
1965	39	15.6	36	53.6	44.2	47.3	66.6	69.2	134.8	16	76.9	97.4	**696.6**
1966	29.8	94.4	15.1	73.8	38.1	61.4	73.1	101.2	38.9	68.6	40.6	41.2	**676.2**
1967	22.2	40.5	22.8	24.3	112.1	32.8	28.2	65.2	52.4	70.8	68.5	39.4	**579.2**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1968	32.2	21.2	21.3	80.7	41.1	46.9	124.4	45.9	94.8	44	83.3	31.2	**667**
1969	44.6	48	74	88.6	79	48.4	78.5	38.6	32.9	22.6	123.9	61.5	**740.6**
1970	62.8	38.1	30.3	75.3	9.7	24.8	43	66.9	22.9	24.5	87.3	24.7	**510.3**
1971	41.7	8.7	34.7	43.7	46.7	52.2	31.5	76.9	21	46.3	40.9	17	**461.3**
1972	39.8	21.1	58.1	14.9	31.3	47.4	46.8	15.7	28.4	8.5	45.8	30.9	**388.7**
1973	20.1	17.5	5.8	53.8	51.7	63.7	142.6	46.8	46.7	41.6	19.4	30.9	**540.6**
1974	39.6	37.8	32.3	15.6	29.1	38.7	90.4	67.2	62	92.3	49.3	33.3	**587.6**
1975													
1976	28.4	18.1	21.2	13.8	85.1	4.2	22.2	18.3	138.5	97.5	26.9	49.4	**523.6**
1977	58	97.2	35.3	26.2	36.3	77.3	9.7	40.3	24.3	30.4	47.5	47.6	**530.1**
1978	55.9	56.9	45.5	35.7	36.8	38.1	89.9	45.3	36.2	6.1	23	150.9	**620.3**
1979	40.6	47.6	67.1	39.1	110	14.8	23.2	95.4	15.9	44.7	42	100.6	**641**
1980	80.6	82.8	75.5	8.5	34.3	114.3	22.5	87.6	31	87.4	65.9	15.8	**706.2**
1981	27.3	45.7	126	79.9	69.6	25.2	28.8	72.3	85.5	60.2	37	41.3	**698.8**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1982	34.1	14.2	60.1	10.2	12.5	144.5	23.6	81.7	46.1	41.3	60.1	42.3	**570.7**
1983	45.1	30.8	53.4	79.1	93.4	12.8	30.5	14.4	78.9	28.1	33	76	**575.5**
1984	75	34.1	48.7	13.7	60.7	27.7	13.4	54.5	88.1	40.8	82.6	32.3	**571.6**
1985													
1986	54.5	22.8	37.1	93.9	74.3	35.9	21.5	93.6	11.5	50.6	58	66.2	**619.9**
1987	24.4	24.7	66.3	57.4	33.7	108.7	69.2	45.5	62.6	99	50.5	31.5	**673.5**
1988	83.3	31.1	60.9	40.5	30.1	39.2	71.6	50.1	29.3	42.9	29.5	18.3	**526.8**
1989	9.4	24.4	42.9	69	17.2	60.1	51.4	19.8	19.6	47.1	27	2.3	**390.2**
1990	45.7	53.8	5.5	14.2	11.9	65.2	26.6	23	22.7	34.3	19	74.3	**396.2**
1991	39.3	46.9	30.4	35.8	11.5	32.9	30	6.6	52.6	32.4	24.8	21.8	**365**
1992	33	16.8	53.5	37.1	41.2	59.5	85	72.3	80.8	50.5	63.2	39.7	**632.6**
1993	40.7	8.6	7.1	71	39.9	53.8	53.4	31.1	106.6	64.1	65.8	68	**610.1**
1994	63.5	38.1	29.3	35.3	49.5	13.1	56.5	37.3	113.3	59.5	59.7	65	**620.1**
1995	88.7	49.5	33.6	14	26.4	17	17.2	7.9	74.2	10.9	45.5	47.2	**432.1**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1996	33	36.7	16	27.8	19.8	22.3	66.8	59.8	19.1	44.9	72.5	68.8	**487.5**
1997	10.7	47.6	12.8	19.6	54.6	127	70.2	63.1	14.2	48.9	59.4	46.6	**574.7**
1998	62.4	6.1	58.8	83.6	30.1	96.8	54	32.3	35.1	101.2	36.6	44.9	**641.9**
1999	53.2	22.8	72.4	69.3	25.3	74.9	22.1	61.9	71	50.7	37.3	58	**618.9**
2000	18.4	43.4	10.7	124.1	50.2	28.5	43.2	40.3	96.6	82	110.9	64.8	**713.1**
2001	28.3	69.9	44.4	76.5	30.7	27.9	37.3	87.9	68.8	85.5	32.8	19.6	**609.6**
2002	25.8	46.4	29.1	25.5	50	35.2	90.5	83.8	15.8	85.1	94.1	102.2	**683.5**
2003	48.9	23.8	16.2	33.2	37.6	86.8	51.2	7.8	28.6	25	33.9	54.3	**447.3**
2004	63.5	32.3	24.9	101.6	26.9	43	75.7	195.7	26.6	75.7	27.7	13.7	**707.3**
2005													
2006	14.6	42.4	43	29	65.5	6.4	29.4	113	57.8	65.4	46.6	57.8	**570.9**
2007	46.2	55.2	22.4	10	76.5	194.2	90.6	27.8	32.8	29.4	39.4	45	**669.5**
2008	120.2	18	52.8	61.5	27.8	57.7	88.3	82.9	68.2	52.3	45.3	42.4	**717.4**
2009	44.5	40.9	24.7	16.2	57.5	43.4	144.9	81.7	19.6	40	84.8	67.1	**665.3**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2010	53.5	62.8	34.9	22.1	14.8	42.2	29.7	52.3	72.1	52	56.3	23.8	**516.5**
2011	30.9	59.7	7.4	2.9	31.7	41	36.7	63.3	23.6	41.8	27.1	58.2	**424.3**
2012	32.4	12.2	25.9	156.7	43.1	97.8	101.9	58.1	67.1	66.2	93.6	99.3	**854.3**
2013	34	25.5	55.6	12.8	58.1	32.2	42.4	43.8	20.4	81.3	35.9	27.1	**469.1**
2014	82.3	42.2	27.2	34.6	112.3	40.1	82.5	104.9	15	48.1	75.5	43.7	**708.4**
2015	27.7	19	26.8	10.2	62.7	41.2	59.3	69.3	34.4	52.7	57.3	64.3	**524.9**
2016	46.5	34.8	73.9	63.9	32	95	43.1	60.5	39.9	30.6	75.5	23.1	**618.8**
2017	34.5	53.5	43.1	11.8	54.8	93.8	93.8	80.9	69	22.4	42.6	40.1	**640.3**
2018	43.8	34.5	91.4	71.2	31.1	19.1	32.2	52.6	62.6	40.8	42.3	75.2	**596.8**
2019	21	20.8	51.1	18.3	30.5	88.4	93.7	62.9	115.7	103.9	172.4	45.2	**823.9**
2020	30.8	104.4	15.5	8.1	11.6	55.1	67.3	58.6	31.2	71.8	20.3	76.9	**551.6**
2021	89.1	68	12.2	24.1	108.6	30.2	85.2	46.6	49	78.6	23.8	57	**672**
2022	13.4	68.2	37.6	18.6	58.2	27.8	18.6	24.2	42.4	94.2	106.6		

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