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No. 687**

**Using Sentinel data to monitor change in habitats and historic landscape features
Technical Report for the Caroline Herschel Framework Partnership Agreement
for Copernicus User Uptake (Work Package Six)**

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Summary

Environmental policy delivery requires information on the extent, state and condition of habitats and historic landscape features, both within and outside protected area networks. Habitat mapping derived from Earth observation (EO) is becoming well established, but evidence on habitat condition and change over time is lacking. Satellite data can be analysed to detect gross landscape change as well as more subtle or gradual changes of habitat condition. The provision of analysis-ready Sentinel-1 and Sentinel-2 data in near real time offers unprecedented opportunities for landscape monitoring. To realise these opportunities, satellite-derived information must be presented to non-EO specialist users in a digestible and meaningful format.

Building on earlier proof-of-concept work, JNCC developed a web-delivered Landscape Monitoring app which provides automated analysis of satellite data, enabling users to track change over time at selected sites and highlight changed areas on a map. A five-year Sentinel-1 and Sentinel-2 time series was collated and used to generate indices for surface water and for vegetation productivity, structure and water content. These indices were combined with habitat maps to highlight land parcels whose index values deviate from average values for that habitat, potentially indicating a change in state or condition.

Working in partnership with Historic Environment Scotland (HES), Natural England (NE), Natural Resources Wales (NRW) and NatureScot (NS), the app was tested at eight pilot sites across the UK. Habitat and site specialists in each organisation evaluated the app and gave feedback on its usability and its effectiveness at detecting change. A number of improvements were made to the app interface in immediate response to users' comments. Enhancements which could not be delivered during the project were recorded as recommendations for future development. Feedback from this pilot informed subsequent projects to scale up the technical infrastructure to deliver this type of web-based app at a regional, and eventually national, scale. This includes recommendations for tackling challenges identified by this project such as gaps in the Sentinel-2 time series caused by cloud, or errors in underlying habitat maps leading to land parcels incorrectly highlighted as 'changed'.

This pilot study demonstrated the potential of giving non-EO specialists the ability to use the vast archive of Sentinel data to detect change in the landscape. Enabling site and habitat experts to interact with EO data provides new insight into management practices and their impact. Users agreed that this type of decision-support tool has potential to reduce costs and improve policy delivery through more effective targeting of survey and management resources. The ability to monitor landscape change on an almost daily basis could contribute significantly to multiple policy areas, including agri-environment scheme delivery, site management, natural capital assessment, biodiversity conservation and nature recovery networks.

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1 Introduction

Effective development, delivery and evaluation of environmental policy requires high quality evidence on biodiversity, ecosystems and natural capital assets. Information on the extent, state and condition of habitats and historic landscape features is needed to inform land management decisions within and outside protected areas networks. The [Copernicus](#) programme's Sentinel-1 (radar) and Sentinel-2 (multispectral) satellites provide high quality, high resolution imagery every few days, which is routinely processed to 'analysis-ready' format by the Defra Earth Observation Data Service and JNCC's [Simple ARD Service](#). These data are already used operationally to create regional or national scale habitat maps (Kilcoyne *et al.* 2017, 2020), and can also detect landscape features such as bare peat or moorland burns (Blake *et al.* 2021; Trippier *et al.* 2020). However, the most impactful opportunities lie in using these data for near real-time landscape monitoring, assessing habitat condition and analysing how this is changing over time.

JNCC developed a proof-of-concept app in 2019 which demonstrated the potential for site-level change detection using Sentinel-2 data. The app highlighted habitat parcels whose mean Normalised Difference Vegetation Index (NDVI) value increased or decreased by more than 10% from one month to the next. Although relatively simple, this app showed the benefit of making satellite-derived information easily accessible to ecologists and land managers with no previous experience of interpreting Earth observation (EO) data.

The current project aimed to build on that proof-of-concept work to evaluate the use of Sentinel-1 and Sentinel-2 for monitoring the condition of habitats and historic landscape features. Working in partnership with Historic Environment Scotland, Natural England, Natural Resources Wales and NatureScot, the project's specific objectives were to:

- Improve the proof-of-concept app with new data and functionality
- Test the app at eight pilot sites across the UK
- Gain feedback from habitat and site specialists on the app's usability and effectiveness

The three statutory nature conservation bodies were interested in detecting change in the condition of protected sites and habitats as an aid to management. This includes detection of gross change as an 'early warning system' to trigger a site visit, as well as monitoring condition change in response to management activities such as grazing, scrub clearance or peat re-wetting. NatureScot were particularly interested in detecting change in inaccessible upland sites. Historic Environment Scotland were interested in monitoring the impacts of land-use change on the historic environment. Changes likely to impact archaeological sites and other historic landscape features include afforestation, erosion, bracken encroachment and conversion of grassland to arable.

This project was delivered as part of JNCC's [Copernicus Project](#), which was launched in 2020 to increase uptake of Copernicus data and services across the UK via capacity building and cross-border collaboration. Through a set of work packages including training sessions, thematic workshops, and development of practical applications, the project aimed to facilitate the use of EO data to deliver public environmental functions more efficiently or effectively across multiple policy areas.

JNCC's Copernicus Project is funded by the European Commission under the [Caroline Herschel Framework Partnership Agreement on Copernicus User Uptake](#) (FPCUP), which was established in 2018 to increase the use of Copernicus data, products and services.

This report outlines the data analysis methodology, introduces the technical infrastructure used for the app, and presents the findings and recommendations arising from user testing.

2 Scientific context

Terrestrial landscapes are naturally dynamic, subject to seasonal change and longer-term cyclical succession. In addition to natural influences, landscapes change in response to human activities such as land use, management practices, introduction of non-native species and the impacts of climate change. Some landscape changes such as habitat loss and fragmentation can have devastating impacts on biodiversity and ecosystem services. The extent, distribution and condition of habitats needs to be monitored to assess natural capital and inform environmental policy.

EO data can provide insight into change on a range of temporal and spatial scales. Changes of state may occur abruptly, for example in response to flooding, landslide or fire, requiring regular data over a period of a few days or weeks. In contrast, more subtle changes to ecosystem services and health, or habitat conversions and fragmentations can be detected only over longer monitoring periods of several months or years. The detection of abrupt, short-term changes at a practicable spatial scale has recently become possible with the enhanced revisit times of the Copernicus Programme's Sentinel satellites.

Demonstrated applications of Copernicus data in detecting abrupt and short-term changes in the landscape such as those expected from natural hazards and events include the detection of wildfires via Sentinel-2 imagery (Filipponi 2019), or the mapping of flooding extents with a combination of Sentinel-2 and Sentinel-1 data which was updated with sub-weekly temporal resolution (Planque *et al.* 2020). Similarly, Sentinel-1 coherence products were used in Cyprus for the detection of landslides after heavy rains with the aim to provide risk maps for raising awareness in remote areas (Tzouvaras *et al.* 2020). Importantly, change detection has also been deployed successfully for compliance monitoring in agricultural and environmental policy. This was demonstrated for example by Page *et al.* (2020), who used a combination of Sentinel-1 and Sentinel-2 data to map illegal tyre and plastic waste sites in Scotland, and by Kanjir *et al.* (2018) who monitored compliance with the European Union's Common Agricultural Policy (CAP) in Slovenia using Sentinel-2 time series data.

There are also examples of long-term monitoring and detection of more subtle changes over time, such as tracking of vegetation biomass presented by Fabre *et al.* (2020), who used a four-year time series of Sentinel-2 data to assess the recovery of soil and vegetation health in a former mining site in France. Other long-term monitoring approaches include the use of Sentinel-2 data to detect the conversion of permanent grassland into arable fields in the Czech Republic (Šandera & Štych 2020), or to estimate the development of grassland biomass under different grazing rotation schemes in Brazil (Guerini Filho *et al.* 2020).

There are two approaches to detecting landscape change using EO data. The simplest and most widely used approach is bi-temporal comparison, i.e., comparing imagery acquired on two different dates. This could involve looking at imagery from the same date in consecutive years, or imagery immediately before and after an event such as a wildfire, or comparison of all pairs of consecutive images in a time-series. Change in land use or land cover identified through bi-temporal comparison is often defined using a directional (from-to) classification (e.g., 'from grassland to scrub'). Using the bi-temporal approach, change may be identified based on user-defined thresholds of band values or derived values such as vegetation or water indices. However, the thresholding approach is often subjective, does not generalise well and has therefore only limited transferability to other studies (Wieland & Martinis 2020).

The second approach can overcome this problem by using all data in a time-series, rather than just data from two dates. In this method, statistical regression is used to highlight deviation from the typical annual pattern. This approach is more robust and repeatable, and

enables analysis of intra- and inter-annual changes if the time-series is split into a seasonal change component and a long-term trend component (Abbes *et al.* 2018).

The methods which are used to detect, and monitor changes depend on the time period that is analysed. Typically, changes in land use and land cover are assessed using a directional (from-to), post-classification evaluation which is based on multi-seasonal imagery. Abrupt changes are commonly detected via direct comparison of two consecutive images which includes for example the manual thresholding of band values or derived vegetation indices such as the NDVI. One method which can overcome these problems exploits time series data of band values and vegetation indices. By using statistical regression approaches it is possible to highlight changes that deviate from the stable state of the time series which makes these approaches more robust and transferrable. In addition, the analysis of subtle intra- and inter-annual changes in condition becomes possible with this method if the time series is decomposed into a seasonal change component (such as growth stages and solar elevation), noise and a long-term trend.

Landscape change can be detected from EO data on the single pixel level or via object-based analysis. Pixel-based approaches have traditionally been applied for the direct, bi-temporal comparison of images but the detected changes have high variability and are often noisy. This is particularly problematic for the high-resolution data and impedes the correlation of observed changes with on the ground activity. The combination pixel-derived change with ancillary data and the creation of rules for change determination can improve this problem, but these methods require manual input which may make them less repeatable. In addition, the varying pixel sizes of different sensors complicate the interoperability of data acquired from different satellite missions. However, especially for the detection of long-term trends and developments it is useful to combine data from newer sensors with historic recordings, for example from the Landsat archive which dates to the 1970s (Awty-Carroll *et al.* 2019). Therefore, object-based methods have been developed which use image segmentation to aggregate pixels that represent meaningful features on the ground (Chen *et al.* 2012). These approaches improve on some of the difficulties of pixel-based analysis but have their own limitations, for example in the repeatability of multi-temporal data. For this reason, hybrid approaches of pixel-level change detection and object level recognition (Xiao *et al.* 2016) and data mining methods (Hussain *et al.* 2013) are increasingly being explored to enhance repeatability and assist with the interpretation of observed change patterns.

This project used object-based analysis to generate EO-derived statistics for individual habitat parcels. A five-year time-series was collated to enable users to investigate bi-temporal change on a monthly or seasonal basis, while also providing the opportunity to detect deviation from annual trends. The methodology is described in detail in the following section. The project brought together EO specialists, data analysts, ecologists and land managers in a collaborative approach defined by Willis (2015) as crucial for relating EO-derived variations to changes in ground conditions such as vegetation management and health.

3 Methodology

The project methodology is outlined below and described in detail in the following sections.

Outline of methodology

- **Site selection**
Project partners chose eight pilot sites with known management regimes and expectations of habitat / condition change within the past five years. Habitat maps were supplied for each site by the partners.
- **Collation of Sentinel-1 and Sentinel-2 time series**
A time series of Sentinel-1 and Sentinel-2 Analysis-Ready Data (ARD) from 2015-2020 was collated for each site.
- **Generation of indices and zonal statistics**
Indices for surface water, vegetation productivity and vegetation water content were derived from Sentinel-2 after the application of cloud and shadow masks. Vegetation structure indices were derived from Sentinel-1. Zonal statistics were calculated for the polygons in the habitat maps for each site.
- **Creation of Landscape Monitoring app**
The Landscape Monitoring app was created in RShiny. This provides a user-friendly interface with the following components:
 - Filters to select parameters (e.g., site, index, habitat).
 - Calendar showing dates of imagery in the time series.
 - Graphs of index values for a selected habitat and polygon.
 - Gallery of thumbnails for the site or a selected polygon.
 - Interactive map enabling polygon selection. **Polygons are highlighted if their mean index value deviates from the mean index value of all polygons of that habitat at that site by more than 1 standard deviation.**
 - Data download functionality.

3.1 Site selection

Eight pilot areas were selected by the project partners, of which four were in Scotland, two in England and two in Wales. The following criteria were considered in site selection:

- Site area: the recommended area was around 10km x 10km
- Extent and condition of target habitat(s) or feature(s)
- Management regime
- Knowledge/expectation of change, including cause(s) of change and rate of change
- Availability of field survey data on habitat type and condition
- Potential for user engagement
- Variety of habitat conditions and management approaches within the site

The locations of the pilot areas are shown in Figure 1 and further information about each site is provided in Table 1.

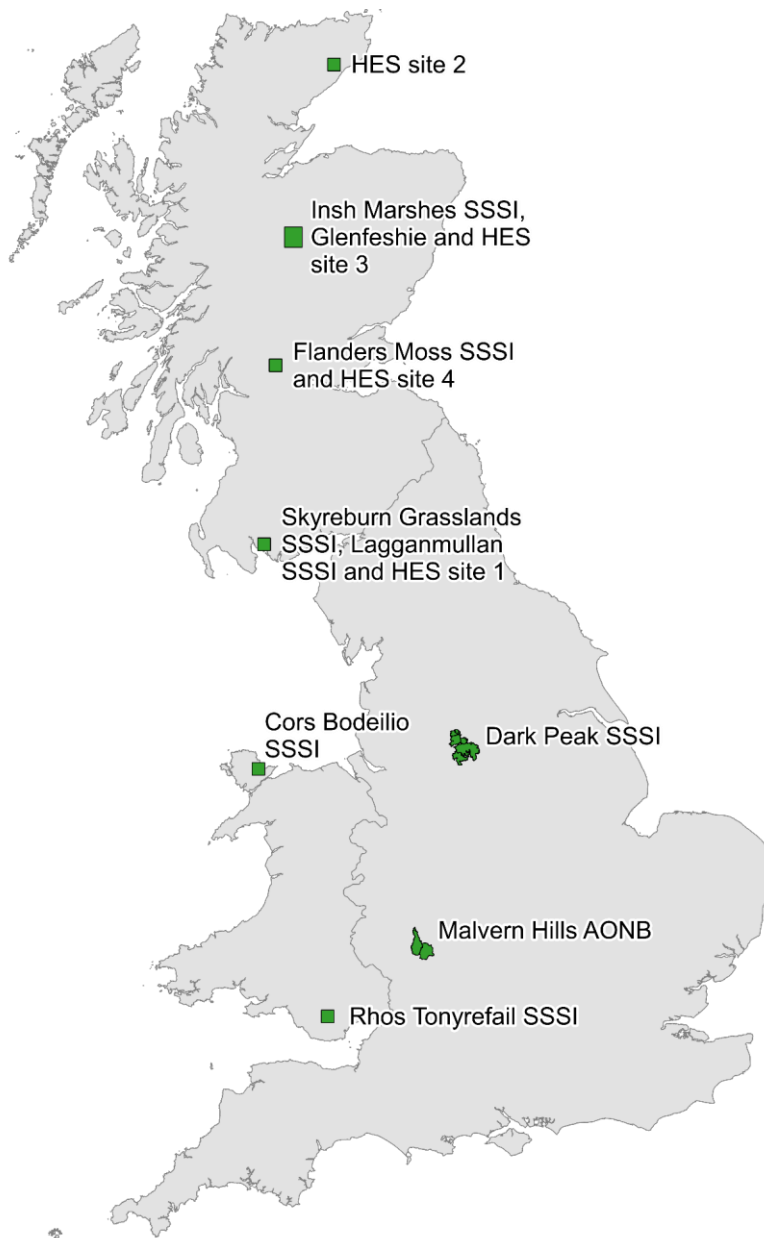


Figure 1. Map showing the locations of the eight pilot sites in England, Scotland and Wales.

The project partners provided a habitat map for each site in ESRI shapefile format. The habitat maps provided for the Welsh sites were outputs from the [Terrestrial Phase 1 Habitat Survey of Wales](#). The Scottish sites used the [Habitat Map of Scotland EUNIS Land Cover Scotland](#) (HabMoS ELCS), a broad scale EUNIS map providing seamless coverage of the whole country. Additionally, a grid of 1 ha squares was generated for each Scottish site, each square attributed with the EUNIS class which occupied the majority of the square's area. The habitat maps used for the English sites consisted of polygons created by segmenting Sentinel-1 and Sentinel-2 imagery using the Living Maps Method (Kilcoyne *et al.* 2017), attributed with habitat classes from the [Priority Habitat Inventory](#). Habitat maps were processed to remove polygons smaller than 100m² and to remove land-use classifications that were not of interest for monitoring, such as buildings, caravan sites and rubbish dumps.

Table 1. Pilot sites used in this project.

Site name	Total area (km ²)	Number of habitat polygons	Description
HES Site 2	99.83	386	Peat and moorland habitats at risk from change due to forestry, erosion and drainage.
Insh Marshes Site of Special Scientific Interest (SSSI), Glenfeshie and HES Site 3	218.45	4,716	Insh Marshes – floodplain wetlands undergoing management, including grazing. Glenfeshie – woodland habitats in a restoration scheme.
Flanders Moss SSSI and HES Site 4	95.83	1,975	Lowland raised bog surrounded by fen. Peatland system restored after decades of active management. Surrounding area consists of arable, recreation and woodland.
Skyreburn Grasslands SSSI, Lagganmullan SSSI and HES Site 1	90.55	2,245	Fen meadow and lowland neutral grassland, partly under an agreed grazing regime. The wider area is undergoing rapid change, with grassland habitats at risk from forestry, development and lack of management.
Dark Peak SSSI	318.09	4,312	Blanket bog in a range of condition states. Heavily degraded in the past but has undergone intensive restoration. Other habitats include acid flushes and dwarf shrub.
Cors Bodeilio SSSI	82.54	2,292	Fen habitats which have recently undergone significant restoration work.
Malvern Hills Area of Outstanding Natural Beauty	206.09	5,327	Lowland dry acid grassland, lowland meadows, good quality semi-improved grassland and small areas of calcareous grassland, intermixed with deciduous woodland. Grazing and other management practices.
Rhos Tonyrefail SSSI	94.48	3,112	Marshy and neutral grassland, subject to regular habitat assessment for Marsh Fritillary.

3.2 Collation of Sentinel-1 and Sentinel-2 time series

Sentinel-1 and Sentinel-2 analysis-ready data was provided by the Defra Earth Observation Data Service for England and Wales, and by JNCC's Simple ARD Service for Scotland. Details of the Sentinel-1 and Sentinel-2 analysis-ready data processing workflows and a table of Sentinel-2 band values are provided in Appendix 1.

The Sentinel-1 time series consisted of one scene captured from the same satellite and orbit every 12 days between October 2016 and June 2020. The start and end dates and number of images in the Sentinel-2 time series varied due to differences in the availability of cloud-free imagery at each location. The number of suitable images ranged from 35 to 83 per site. Details of the Sentinel-1 and Sentinel-2 time series are shown in Table 2.

Table 2. Sentinel-1 and Sentinel-2 data collated and processed for each site

Site name	Sentinel-1	Sentinel-2
HES Site 2	S1B orbit 132 ascending <i>104 scenes</i> 09/10/2016 – 14/06/2020	Tile 30VVK orbits 80 and 123 <i>51 granules</i> 17/08/2015 – 30/05/2020
Insh Marshes SSSI, Glenfeshie and HES Site 3	S1B orbit 30 ascending <i>106 scenes</i> 02/10/2016 – 19/06/2020	Tile 30VVJ orbits 80 and 123 <i>47 granules</i> 17/08/2015 – 14/06/2020
Flanders Moss SSSI and HES Site 4	S1B orbit 30 ascending <i>107 scenes</i> 02/10/2016 – 19/06/2020	Tile 30VVH orbits 80 and 123 <i>41 granules</i> 07/03/2016 – 01/06/2020
Skyreburn Grasslands SSSI, Lagganmullan SSSI and HES Site 1	S1B orbit 30 ascending <i>107 scenes</i> 02/10/2016 – 19/06/2020	Tile 30UVF orbits 77 and 80 <i>35 granules</i> 28/06/2015 – 01/06/2020
Dark Peak SSSI	S1B orbit 30 ascending <i>106 scenes</i> 02/10/2016 – 19/06/2020	Tile 30UWE orbits 37 and 137 <i>53 granules</i> 29/12/2015 – 25/06/2020
Cors Bodeilio SSSI	S1B orbit 30 ascending <i>106 scenes</i> 02/10/2016 – 19/06/2020	Tile 30UVE orbits 37, 77, 80 <i>78 granules</i> 28/06/2015 – 16/06/2020
Malvern Hills AONB	S1B orbit 30 ascending <i>107 scenes</i> 02/10/2016 – 19/06/2020	Tile 30UWC orbits 37 and 137 <i>83 granules</i> 10/09/2015 – 25/06/2020
Rhos Tonyrefail SSSI	S1B orbit 30 ascending <i>107 scenes</i> 02/10/2016 – 19/06/2020	Tile 30UVC orbit 37 <i>40 granules</i> 22/11/2015 - 23/06/2020

3.3 Generation of indices and zonal statistics

A square bounding box was created around each site to designate the area of interest (AOI). The habitat maps and Sentinel-1 and Sentinel-2 time series were cropped to the AOI. Indices for surface water, vegetation productivity and vegetation water content were derived from Sentinel-2 after the application of cloud and shadow masks. Vegetation structure indices were derived from Sentinel-1. Thumbnail images of the AOI were generated in .png format for each Sentinel-1 and Sentinel-2 image and each index in the time series. Details of the five indices generated are provided in Table 3.

Table 3. Indices generated from Sentinel-1 and Sentinel-2 time series.

Index	Formula	Reference
Normalised Difference Moisture Index (NDMI)	$(\text{band 8} - \text{band 9}) / (\text{band 8} + \text{band 9})$	https://custom-scripts.sentinel-hub.com/custom-scripts/sentinel-2/ndmi/
Normalised Difference Vegetation Index (NDVI)	$(\text{band 8} - \text{band 3}) / (\text{band 8} + \text{band 3})$	https://custom-scripts.sentinel-hub.com/custom-scripts/sentinel-2/ndvi/
Normalised Difference Water Index (NDWI)	$(\text{band 2} - \text{band 8}) / (\text{band 2} + \text{band 8})$	https://custom-scripts.sentinel-hub.com/custom-scripts/sentinel-2/ndwi/
Radar Vegetation Index (RVI)	$\text{dop} = (VV / (VV + VH))$ $(\text{Math.sqrt}(\text{dop})) * ((4 * (VH)) / (VV + VH))$ <p><i>dop = degree of polarisation</i> <i>VV = band 1, VH = band 2</i></p>	https://custom-scripts.sentinel-hub.com/custom-scripts/sentinel-1/radar_vegetation_index/
Radar Vegetation Index 'v' (RVIV)	$(4 * VH) / (VV + VH)$	https://custom-scripts.sentinel-hub.com/custom-scripts/sentinel-1/radar_vegetation_index_code_dual-polarimetric/supplementary_material.pdf

Zonal statistics consisting of mean, median, first quartile and third quartile were generated for each index and each polygon. Zonal statistics for each polygon were aggregated to find the mean, maximum and standard deviation of each index per month and per season.

Seasons were defined as follows:

Spring: March, April, May
 Summer: June, July, August
 Autumn: September, October, November
 Winter: December, January, February

The seasonal and monthly statistics were exported in .txt file format for use in the landscape monitoring app. The complete data processing workflow is shown in Figure 2.

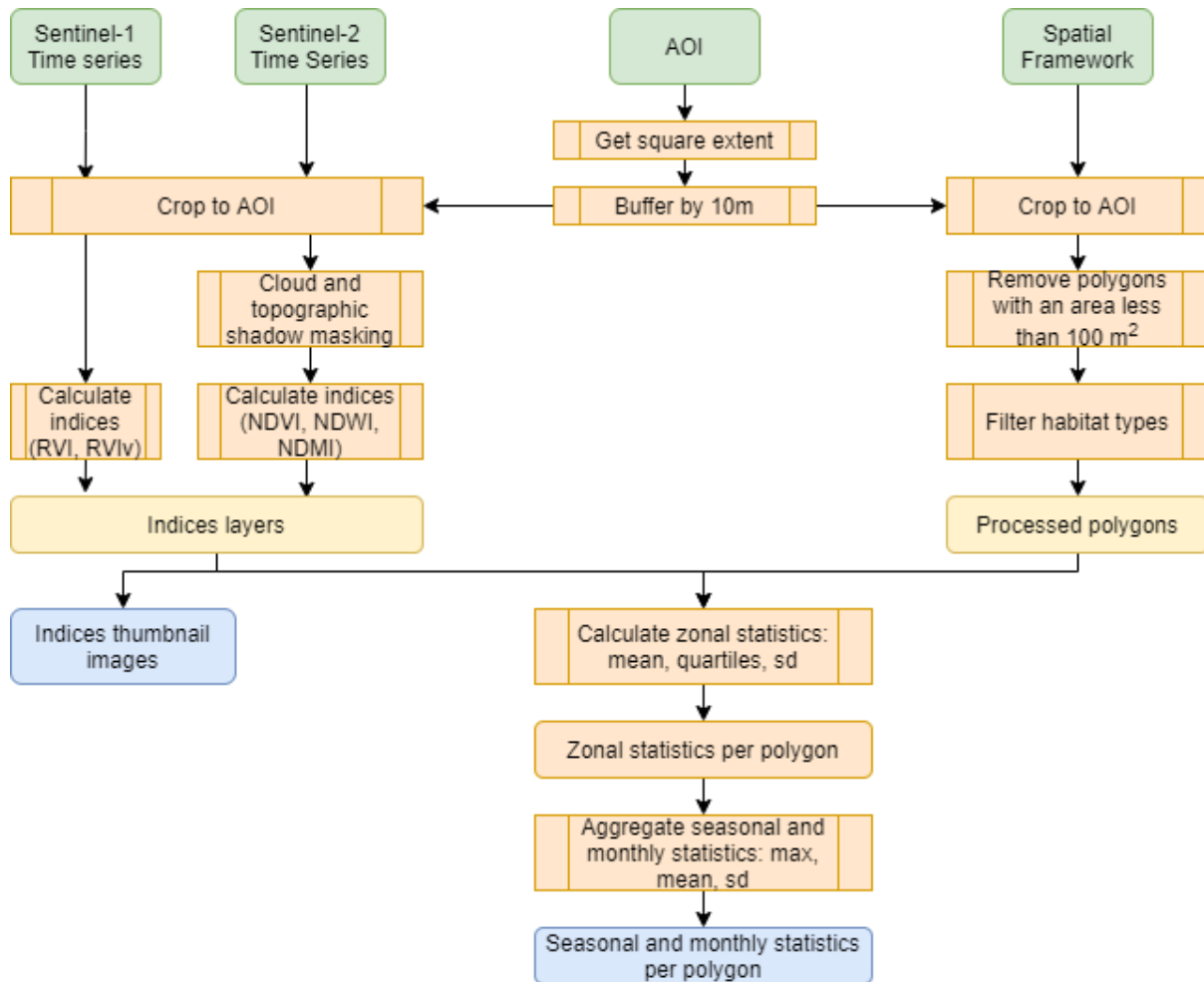


Figure 2. Diagram illustrating the workflow to process data for use in the landscape monitoring app. Input data is shown in green, processing steps in orange, intermediate data in yellow and output data for use in the app in blue.

The data processing workflow was developed using R version 3.6.1 (R Core Team 2020). The R scripts and functions are publicly available on JNCC's [GitHub repository](#).

3.4 Landscape monitoring app

The Landscape Monitoring Application was built using the R package's 'shiny' version 1.5.0 (Chang *et al.* 2020) and 'shinydashboard' version 0.7.1 (Chang *et al.* 2018). This open-source software was chosen for the application development due to its flexibility in both design and functionality, allowing user communication in an easy to use interface integrating maps, images and plots. Such web applications allow non-technical users to view and query the data in a user-friendly way, as well as downloading the results.

The application integrates all the site results into one dashboard, displayed in Figure 3.

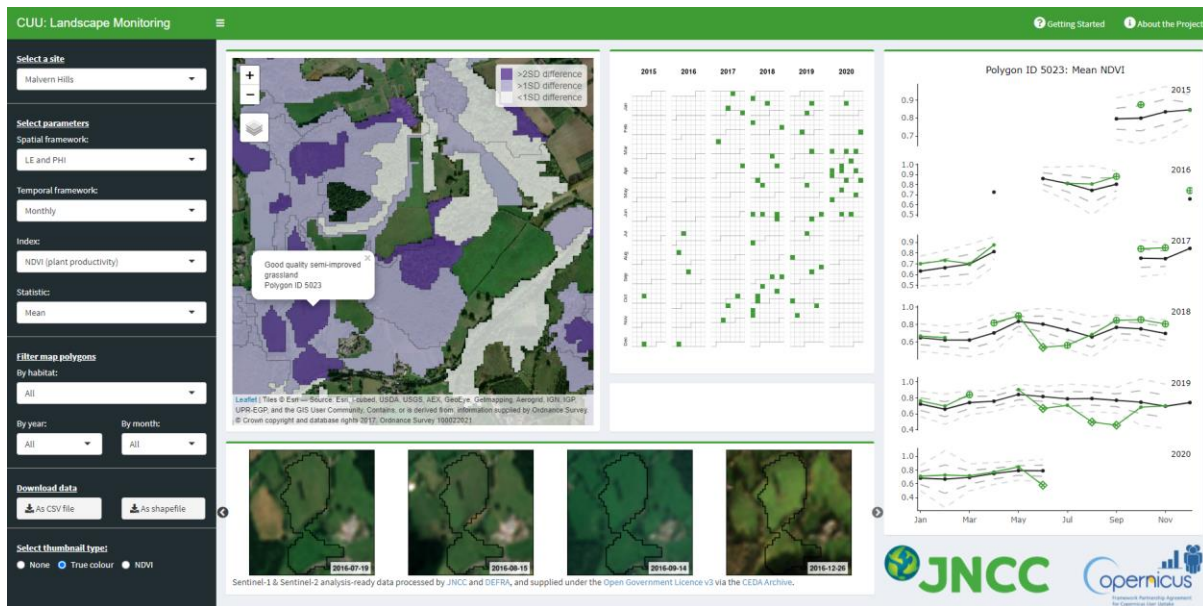


Figure 3. A screenshot of the Landscape Monitoring Application interface. This shows the second iteration of the app which contains several improvements implemented in response to user feedback.

From this dashboard the user can select the site, filter by the spatial framework, seasonal or monthly statistics, indices and statistic for which they wish to view the results. They can also filter the polygons by habitat, year or temporal increment. The available polygons are displayed on an interactive map, plotted against ESRI world imagery integrated using 'leaflet' version 2.0.3 (Cheng *et al.* 2019). Here, users can select a polygon of interest and the reactive interface will update the plotted results of the chosen polygon. Polygons are shaded pale lilac if their mean index value is ≥ 1 standard deviation above or below the mean index value for all polygons of that habitat at that site. Polygons are shaded purple if their mean index value is ≥ 2 standard deviations above or below the mean index value for all polygons of that habitat at that site.

A calendar displays the dates of all the available imagery for the polygon of interest and a line plot describes how the index statistic values for the polygon compares to the mean statistics for the habitat type. Months or seasons in which a polygon's index value differs from the mean value for all polygons of that habitat at that site by more than 1 or 2 standard deviations are highlighted on the line plot as circles or diamonds respectively. The user can cycle through a carousel of thumbnails of the imagery or indices either at a whole site or polygon level, integrated using the package 'slickR' version 0.4.9 (Sidi 2020). To guide the user, pop-up menus containing a walkthrough of the application's functionality and more information about the project were also integrated in the top right-hand corner of the application.

The application was deployed on shinyapps.io which is a server hosted by RStudio (RStudio 2020) deployed using the 'rsconnect' package version 0.8.16 (Allaire 2019). This allowed public access to the application with integrated deployment through RStudio and monitoring of analytics through their online hosting webpages. The application generates the polygon level thumbnails within the app from the original imagery and indices layers. This involves a significantly large amount of data, for example for a single 10 x 10km site this contained 106 Sentinel-1 scenes, 78 Sentinel-2 scenes and requires 3.5GB of data to query within the application. Therefore, for deployment purposes, the data for generating polygon-level thumbnails were stored externally from the application using Amazon Web Services (AWS) cloud storage.

4 User Testing

The landscape monitoring app was tested by habitat and site specialists in each of the four partner organisations between August and November 2020. The objectives of user testing were to:

- Engage users in the concept of using EO to support conservation management, raise awareness of the possibilities and develop understanding of limitations.
- Get feedback on the usability of the app to inform future development.
- Get feedback on accuracy and effectiveness of the approach to change detection, i.e., the indices, statistics and thresholds used for highlighting polygons.
- Document evidence of user demand and potential impact to help make the business case for resourcing future development.

Prior to testing, staff at JNCC and the partner organisations held initial meetings with users to ensure that they all approached the test with the same background knowledge and expectations. A set of PowerPoint slides was used for all meetings to ensure the information presented was consistent across the organisations. The presentation covered:

- The project's aim and objectives.
- Why testers had been asked to take part, i.e., due to their site knowledge and land management responsibilities.
- Start and end dates of testing periods and the type of feedback required.
- How the app works.
- Caveats about possible limitations of the data and methods, and a reminder that the app was just a prototype.
- How project staff would respond to feedback and how the feedback would be used.

4.1 Usability

After the initial meeting, testers were provided with the URL for the landscape monitoring app and invited to test it at their convenience at any time over a three-week period in August-September. During that period, at least one member of staff per organisation had a one-to-one session with the project lead in their organisation, during which they used the app together and discussed the outputs.

At the end of the testing period, users were asked to fill in an online survey. This was completed by fifteen users. Their feedback was very high quality and detailed, covering their first impressions of the app and offering useful suggestions for improvements. All but one user spent at least one to two hours testing the app, with seven users spending over two hours. All sites and indices were used, although only NDVI was used by all users, probably because it is the default setting. Based on first impressions, 80% were likely or very likely to use the app in their work, while 20% were somewhat likely to do so. 87% were likely or very likely to recommend the app to others, while 13% were somewhat likely to do so. The complete results of the survey can be found in Appendix 2.

Table 4 summarises key feedback arising from the first phase of user testing and shows how each point led to improvements to the app.

Table 4. Feedback and improvements arising from the first phase of user testing

Feedback	Improvements to the app
<p>Launching the app presents users with a set of filters and a blank screen. More information would be useful to help them get started.</p>	<p>An information page was added which opens automatically when the app is launched. It contains information about the data, indices and how the app works. There are links to details on how indices are calculated and the information they provide. Prominent 'Getting started' and 'About the project' buttons were added to the top menu, enabling users to open the walkthrough or the information page at any time.</p> <p>To reduce blank screen time, graphs are now generated as soon as a user selects a site, index and habitat – previously graphs were not generated until a polygon was selected.</p>
<p>Thumbnails take too long to generate.</p>	<p>The 'select thumbnail type' filter defaults to 'None', saving time by giving the user control over whether to generate thumbnails for a selected site or polygon. The 'creating images' progress bar was moved to a prominent position.</p>
<p>Thumbnails and their labels are not clear or consistent.</p>	<p>True colour Sentinel-2 thumbnails were made brighter and sharper. Different colour stretches were applied to the surface water and plant moisture indices to make it easier to differentiate them. Date format was made consistent (yyyy-mm-dd) and date labels were produced in a larger font on a white background to make them easier to read.</p>
<p>Thumbnails are too small.</p>	<p>Information was added to the walkthrough to tell users that larger versions of the thumbnails can be viewed by right-clicking and selecting 'open image in a new tab'.</p>
<p>The interactive map is not easy to navigate due to lack of detail on the base map.</p>	<p>The map was upgraded to offer users a choice of high-resolution aerial/satellite imagery or a greyscale map.</p>
<p>The map zooms to full extent when the user changes any filter. It is difficult and time-consuming to navigate back to the area of interest.</p>	<p>The map settings were changed so that the map extent persists, i.e., it stays zoomed to the area the user was looking at, when any filters are changed.</p> <p>If the user has selected a polygon, it remains selected when the filters are changed, e.g., to select a different index.</p>
<p>Highlighted polygons are all the same colour which is not easy to interpret.</p>	<p>The map was updated to shade habitat polygons in three different colours based on whether their index value differs from the mean by <1 standard deviation (white), 1-2 standard deviations (lilac) or >2 standard deviations (purple). Users can select which polygons to display based on their deviation from the habitat mean, e.g., display only those which differ from the mean by >2 standard deviations.</p>
<p>The graphs are difficult to interpret. Gaps between datapoints (e.g., due to cloud in Sentinel-2) are joined by a straight line, which could be misleading.</p>	<p>Graphs were made clearer by representing 1 and 2 standard deviations by dashed lines rather than shaded ribbons. Gaps in the time series were represented by voids on the graph rather than a straight line.</p> <p>Hover-over information was added, enabling users to see date, mean index value and other details for datapoints.</p>
<p>The calendar is unclear when the temporal framework is set to 'season'.</p>	<p>Month and seasons were written as three-letter (rather than single letter) abbreviations. Information was added to the walkthrough to specify the months in each season.</p>

Following these improvements, users were sent the URL for the new version of the app together with a document summarising the changes which had been made. They were invited to test it at their convenience over a three-week period in November. At the end of the testing period, they were asked to fill in an online survey. In addition to asking for feedback on the improvements, the survey asked users about priorities for future development and how they would use the app in their work. The survey was completed by eleven users. The complete survey results are shown in Appendix 3.

Overall, users felt the changes made the app easier to navigate and more intuitive. The information screen, improved backdrop mapping and the hover-over information on the graphs were particularly well received. Users agreed that the thumbnails were better but felt there was still room for improvement in terms of clarity, loading time and ease of scrolling through the gallery. One user suggested improving efficiency by enabling users to restrict thumbnail generation to a time period (e.g., just before and just after a change occurred). Three of the top four priorities for future development related to thumbnails, namely:

- Link thumbnails, calendar and graphs so that when a user selects a point on the graph, the app navigates to the matching thumbnail and highlights the calendar date.
- Enable users to open the map/thumbnail full screen to see more detail.
- Give users the option of viewing all thumbnails (currently the default setting) or only those used in analysis, i.e., omitting thumbnails of partially cloudy Sentinel-2 imagery.

The top priority for future development was to give users the option of viewing all time-series data on a single graph (i.e., with the x-axis from 2015 to the present). Users would like to be able to switch between the two graph layout options because the current display of stacked single-year graphs has the benefit of showing seasonal patterns more clearly, but a single graph may show longer-term trends.

Testers identified several areas of their current and potential future work where the app could provide benefits. Staff felt it had significant potential to support protected site monitoring and archaeological asset monitoring, particularly in areas which are not clearly visible or accessible to ground surveyors. The app could help to prioritise and target monitoring visits, making best use of limited field staff resources. In between monitoring visits, the app could highlight the need for management change.

4.2 Effectiveness

Before using the app, habitat and historic environment specialists were asked to consider where, when and for what reason they expected change to have taken place at each site. They then tested whether the app highlighted these areas and time periods in accordance with their expectations. This approach provided valuable qualitative information on the app's change detection capabilities and insight into which indices were most effective at detecting different types of change.

Overall, users from all organisations were satisfied that the app was able to detect the types of change of interest to them. These included gross landscape change such as tree felling, upland wildfires and flood, as well as more subtle changes such as landowners taking hay cuts too late, not grazing the aftermath or not doing scrub removal. Nevertheless, there were examples of polygons being highlighted incorrectly (false positives) and of real change being missed (false negatives). Examples of each are provided in the following sections.

4.2.1 Correct detection of condition change

Clear felling of woodland is likely to manifest as decreased NDVI and NDMI values and increased RVI and RViv values. In this example from Insh Marshes, a parcel of coniferous woodland was partly felled in October 2018, more extensively felled in February 2019 and completely cleared by May 2019. Graphs generated by the app show that the polygon would be highlighted from May 2019 onwards due to NDVI values over two standard deviations lower than the habitat-mean (Figure 4). There is no cloud-free Sentinel-2 imagery available for March or April, and the NDVI values for December 2018 and February 2019 do not deviate significantly from the habitat-mean. RViv values increase in October 2018 due to the partial felling and remain above the habitat-mean from that point onwards, but they are within one standard deviation of the habitat-mean so the polygon would not be highlighted using this index. NDMI values performed the same as NDVI in this example, and RVI performed the same as RViv.

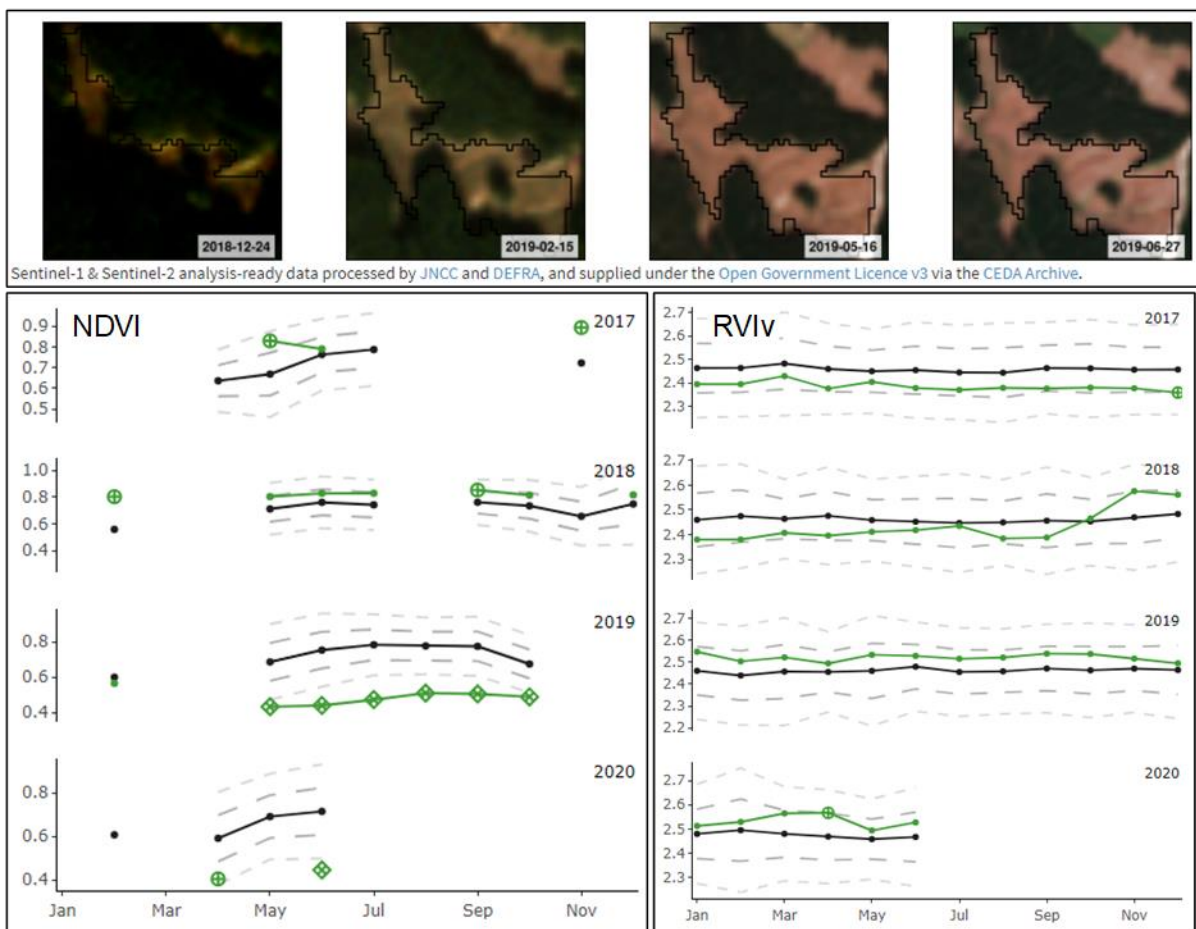


Figure 4. Sentinel-2 thumbnails from December 2018 to June 2019 (top), NDVI (bottom left) and RViv (bottom right) graphs for a parcel of coniferous woodland undergoing felling at Insh Marshes.

Erosion and trampling of grassland are likely to produce low NDVI and NDMI values. In this example from the Malvern Hills, a parcel of lowland dry acid grassland suffers from erosion during the summer months due to high levels of recreational activities. This polygon would be highlighted for a four-month period by NDMI values and for a three-month period by NDVI values. The month in which the polygon would first be highlighted is the same for both indices.

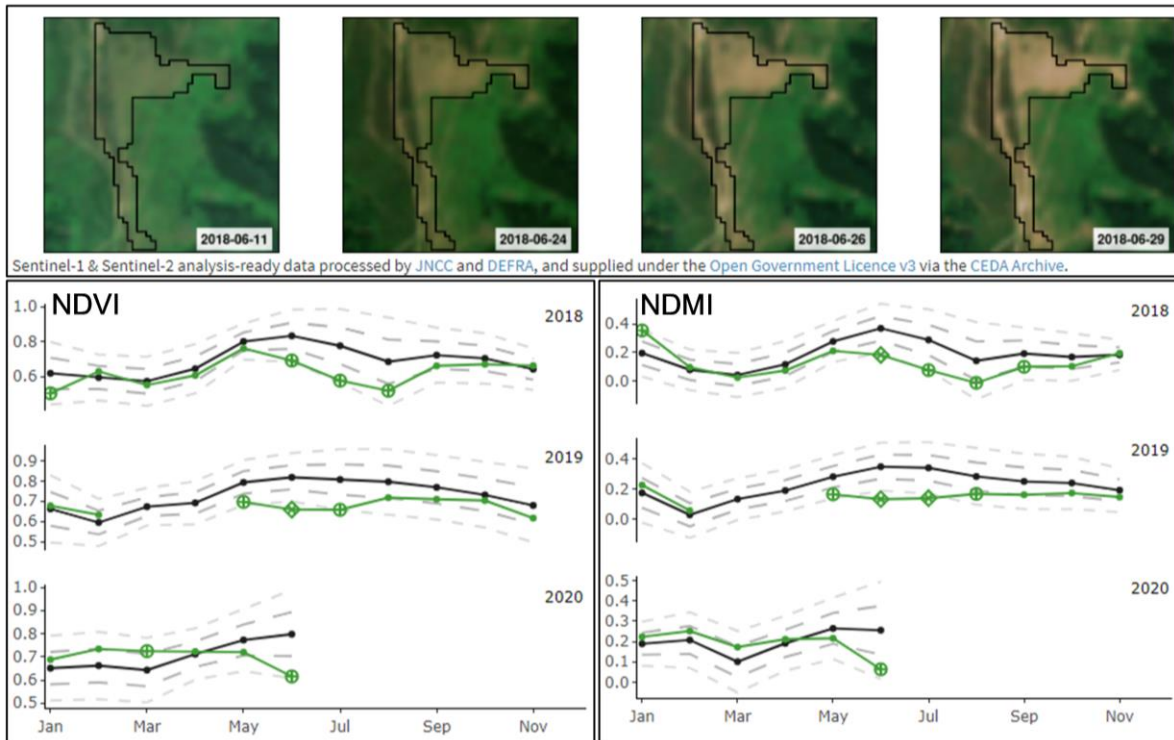


Figure 5. Sentinel-2 thumbnails for June 2018 (top), NDVI (bottom left) and NDMI (bottom right) graphs for a parcel of lowland dry acid grassland affected by erosion in the Malvern Hills.

Grassland management practices such as cutting, grazing and scrub clearance can also influence index values, as these examples from the Malvern Hills demonstrate. One lowland meadow parcel consistently has below average NDVI and NDMI values in winter and above average NDVI and NDMI values in summer due to late grazing (Figure 6).

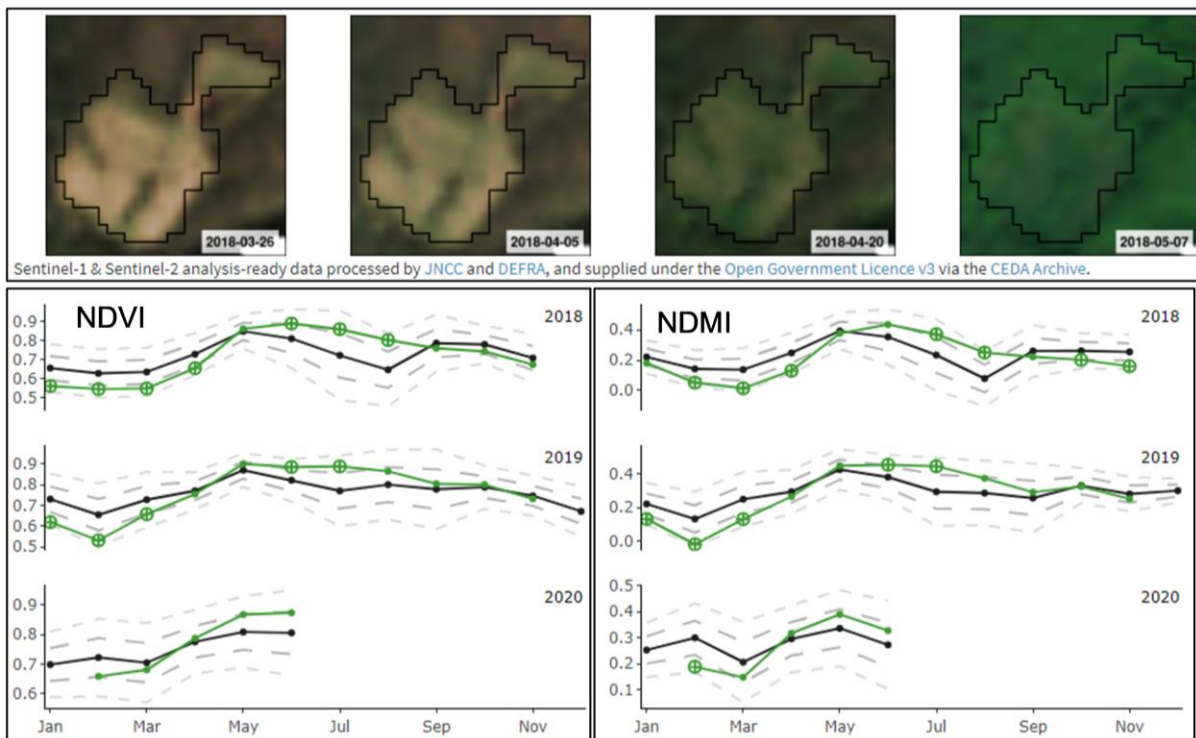


Figure 6. Sentinel-2 thumbnails for March-May 2018 (top), NDVI (bottom left) and NDMI (bottom right) graphs for 2018-2020 for a lowland meadow with high productivity in summer due to late grazing.

This field would be highlighted by the app in both winter and summer 2018 and 2019 due to NDVI values over one standard deviation above or below the habitat mean. It would not be highlighted in summer 2020 because although it clearly follows the same pattern as previous years, the NDVI and NDMI values are just within one standard deviation of the habitat mean.

Another lowland meadow polygon exhibits a significant drop in NDVI and NDMI values in September caused by a late hay cut, followed by an increase in November because the aftermath is not grazed (Figure 7).

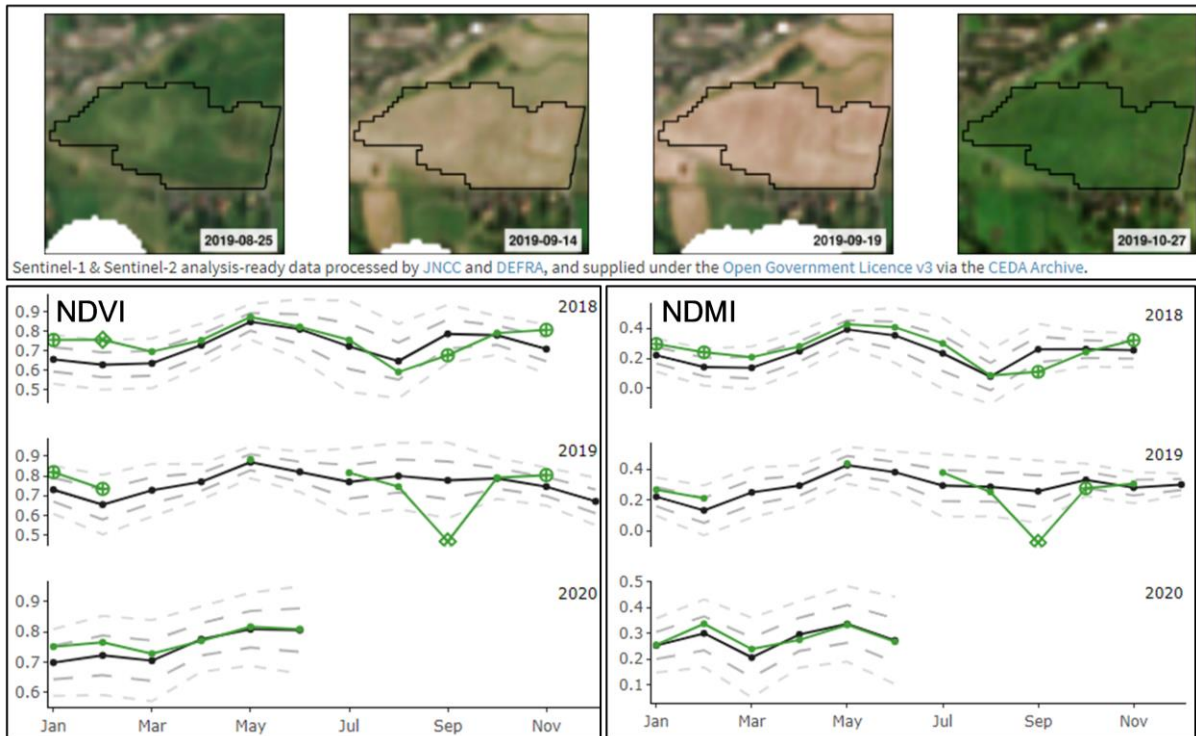


Figure 7. Sentinel-2 thumbnails for August to October 2019 (top), NDVI (bottom left) and NDMI (bottom right) graphs for 2018 to 2020 for a lowland meadow which had a late hay cut in September 2019.

In the next example, a polygon classified as lowland dry acid grassland in the Malvern Hills has above average NDVI values in spring due to bracken encroachment, followed by below average values when the bracken is cleared as part of a management programme (Figure 8).

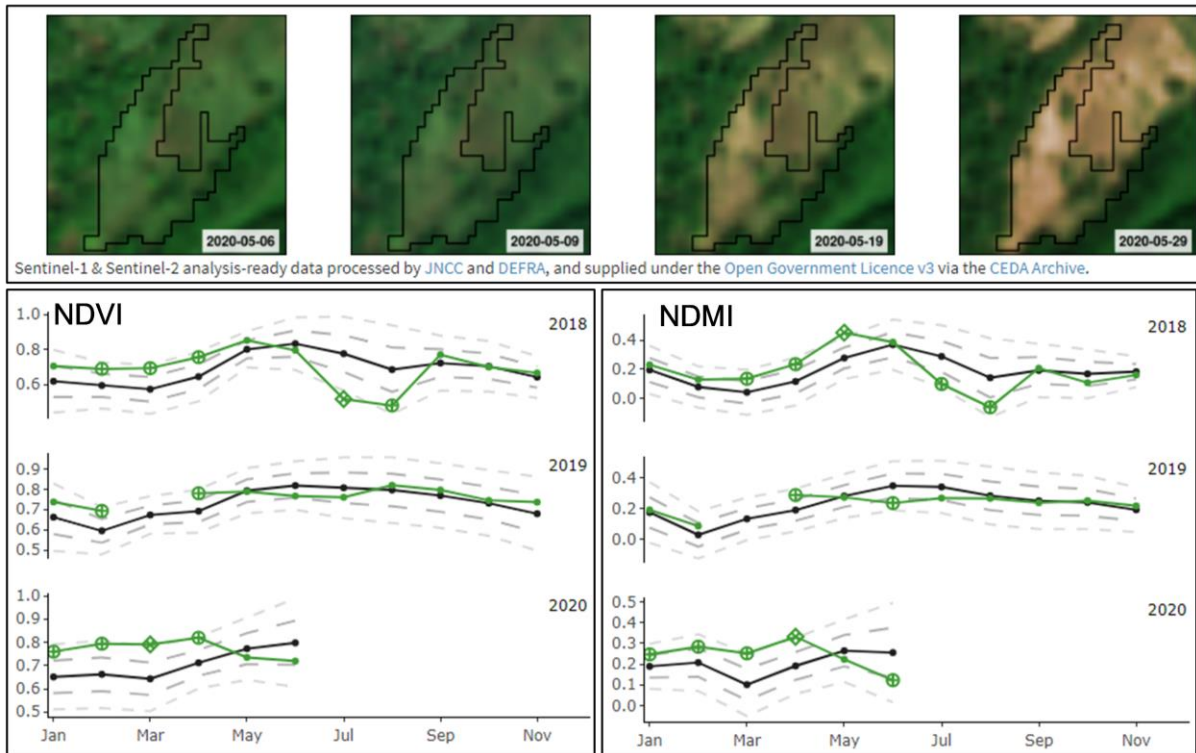


Figure 8. Sentinel-2 thumbnails for May 2020, NDVI (bottom left) and NDMI (bottom right) graphs for 2018 to 2020 for a lowland dry acid grassland polygon undergoing management for bracken encroachment.

Burning in upland habitats leads to reduced NDVI and NDMI values and increased RVI and RViv values. The impact of the Saddleworth Moor wildfire, which started on 25 June 2018, can clearly be seen in the index values for blanket bog habitat parcels at the Dark Peak site. In the example below, the app would highlight the selected blanket bog polygon in June 2018 and consecutive months (Figure 9). The Sentinel-2 derived indices initially show greater deviation from the habitat-mean than the radar vegetation indices, but there is no cloud-free Sentinel-2 imagery for this polygon from 5 August 2018 to 26 February 2019, limiting the ability to use optical indices to monitor the aftermath of the fire.

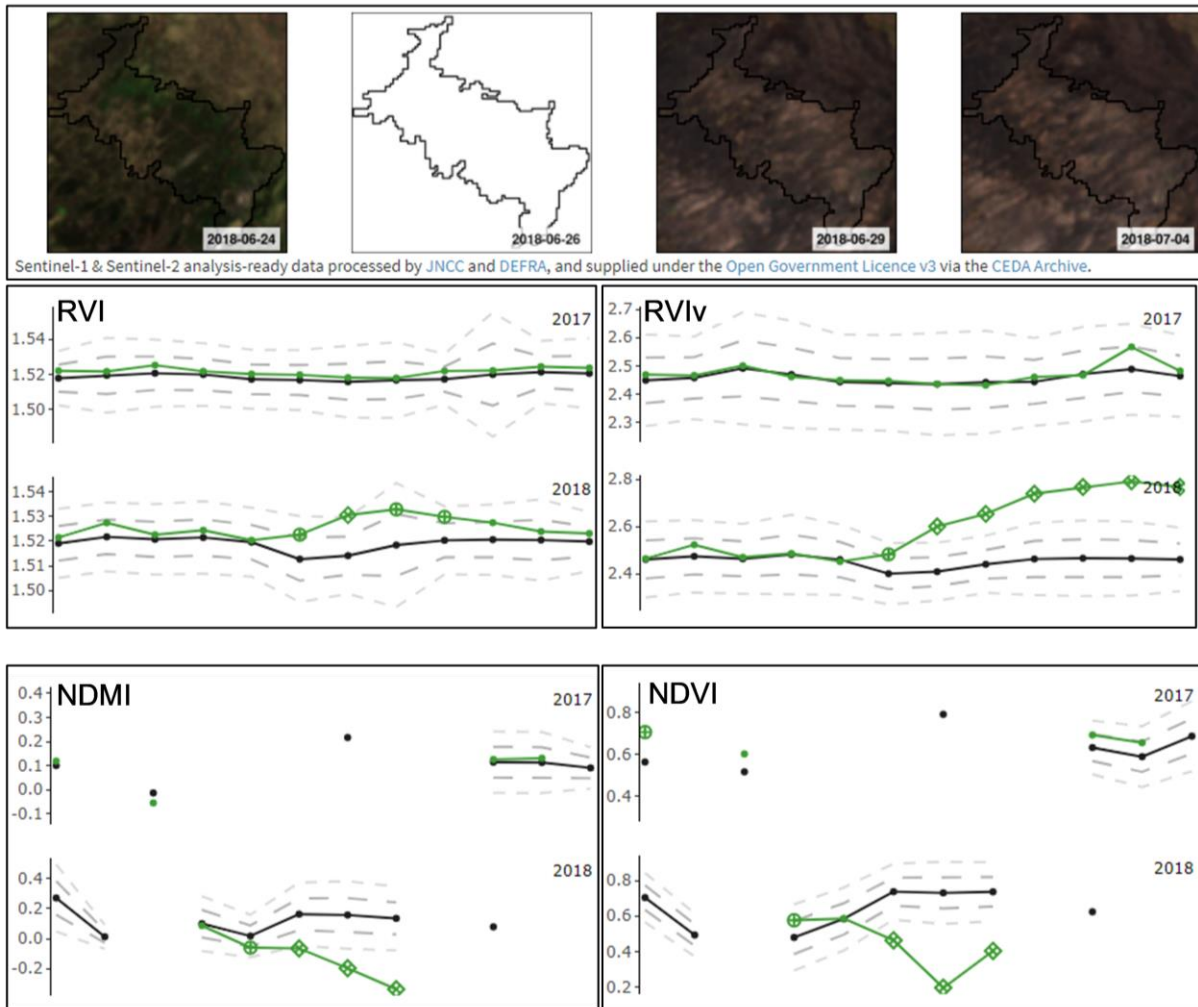


Figure 9. Sentinel-2 thumbnails from 24 June 2018 to 4 July 2018 (top), RVI values (middle left), RViv values (middle right), NDMI values (bottom left) and NDVI values from 2017 to 2018 for a blanket bog parcel at the Dark Peak site. Graph x-axis values are January to December.

4.2.2 False positives

User testing identified several instances of polygons being highlighted by the app where no change in condition was expected or observed on the ground. The principal cause of these ‘false positives’ was habitat misclassification in the habitat maps that were used as the spatial framework for generating the index statistics. In the example below, a polygon classified as broadleaved deciduous woodland actually consists of improved grassland (Figure 10). Its NDVI values are consistently above the habitat-mean for deciduous woodland, exceeding the habitat-mean by more than one standard deviation on five out of thirteen months for which imagery is available from 2018 to 2020. Its RViv values are above the habitat-mean in winter and below the habitat mean in summer and would lead to it being highlighted by the app in 10 months between 2018 and 2020.

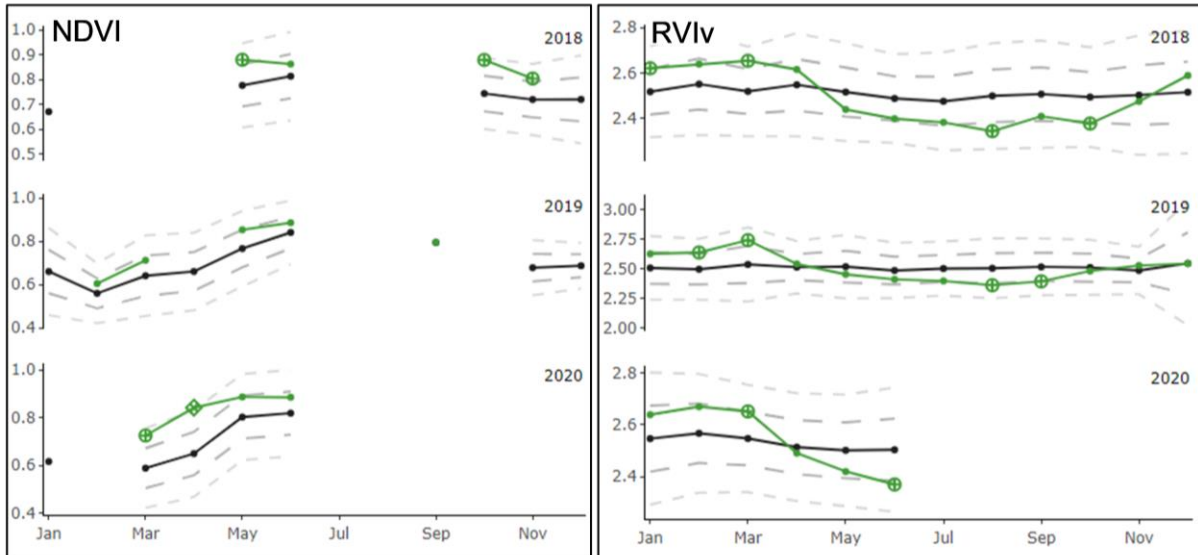
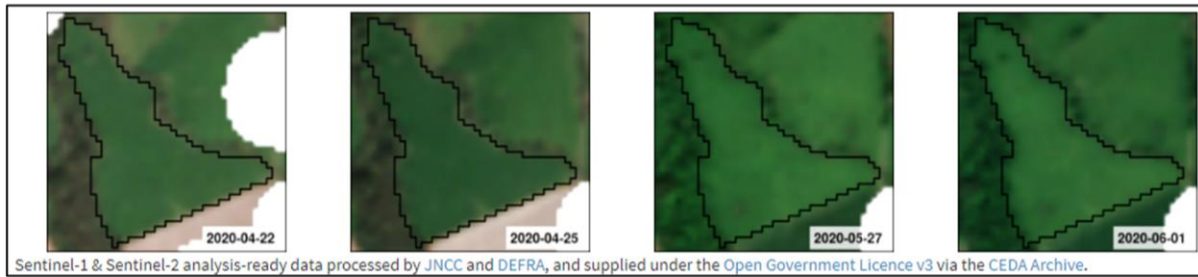


Figure 10. Sentinel-2 thumbnails from April to June 2020 (top), NDVI (bottom left) and RViv (bottom right) values from 2018 to 2020 for a polygon incorrectly classified as broadleaved deciduous woodland.

Another cause of false positives is cloud in Sentinel-2 imagery where this has been missed by the cloud mask. In this example, a polygon classified as broadleaved deciduous woodland in the Malvern Hills is highlighted in April 2017 as its mean NDVI value is over two standard deviations below the habitat-mean (Figure 11). However, the Sentinel-2 thumbnails show that there is unmasked cloud in the imagery on this date which has caused the low NDVI value. This polygon's NDVI values follow the habitat-mean closely in all other months where imagery is available.

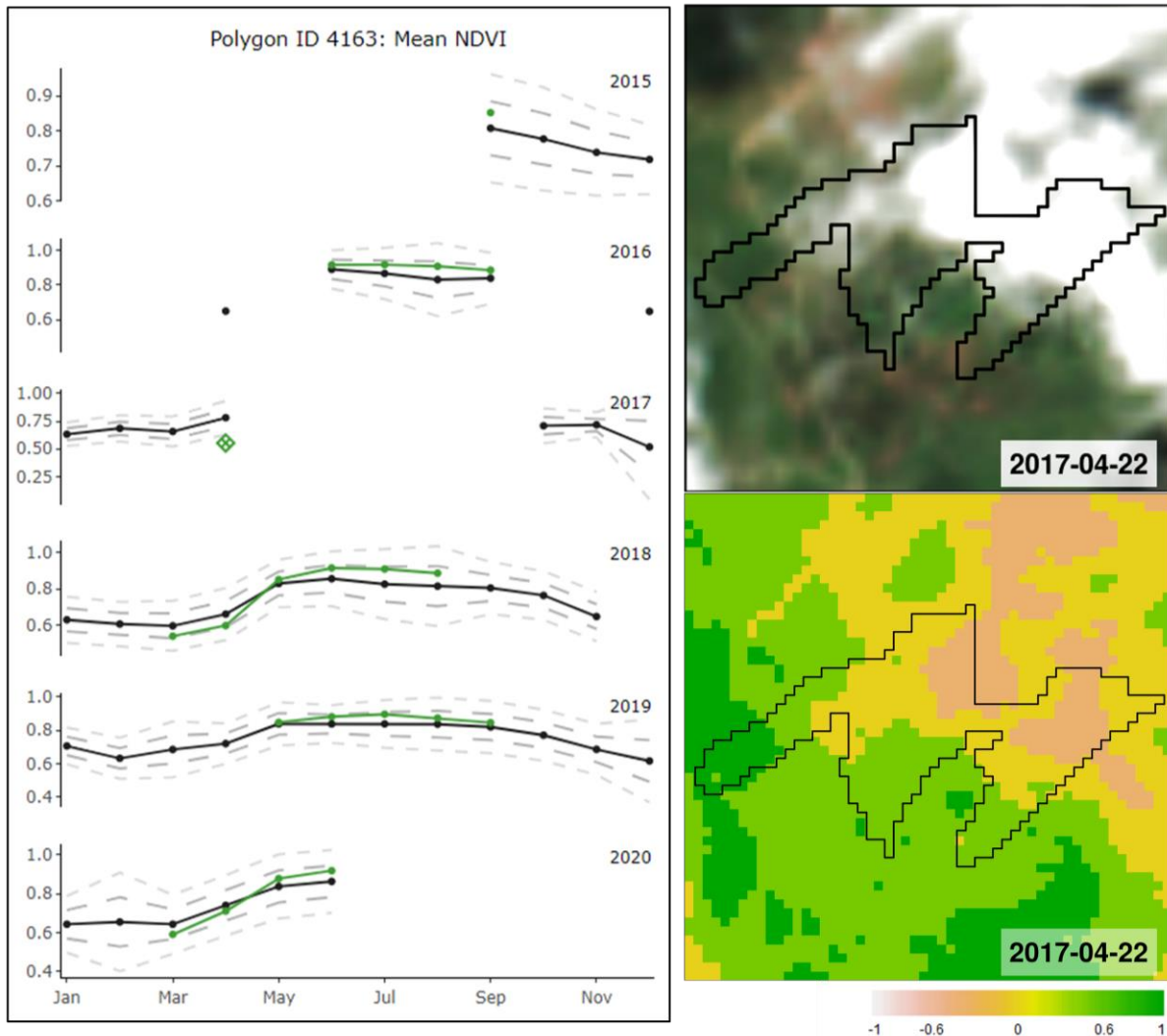


Figure 11. NDVI graphs for a deciduous woodland polygon in the Malvern Hills (left), Sentinel-2 thumbnail showing unmasked cloud in the imagery on 22 April 2017 (top right) and NDVI thumbnail for the same date showing low values caused by the unmasked cloud (bottom right).

Snow masks are not created as part of the Sentinel-2 ARD workflow. Snow in Sentinel-2 imagery causes low NDVI values and high NDMI and NDWI values, which can lead to polygons being highlighted by the app. In this example from Insh Marshes, a polygon classified as temperate shrub heathland is highlighted by the app in March 2016, February 2018 and April 2020 (Figure 12). Investigation of the thumbnail imagery shows that this is caused by snow covering the heath in all three cases.

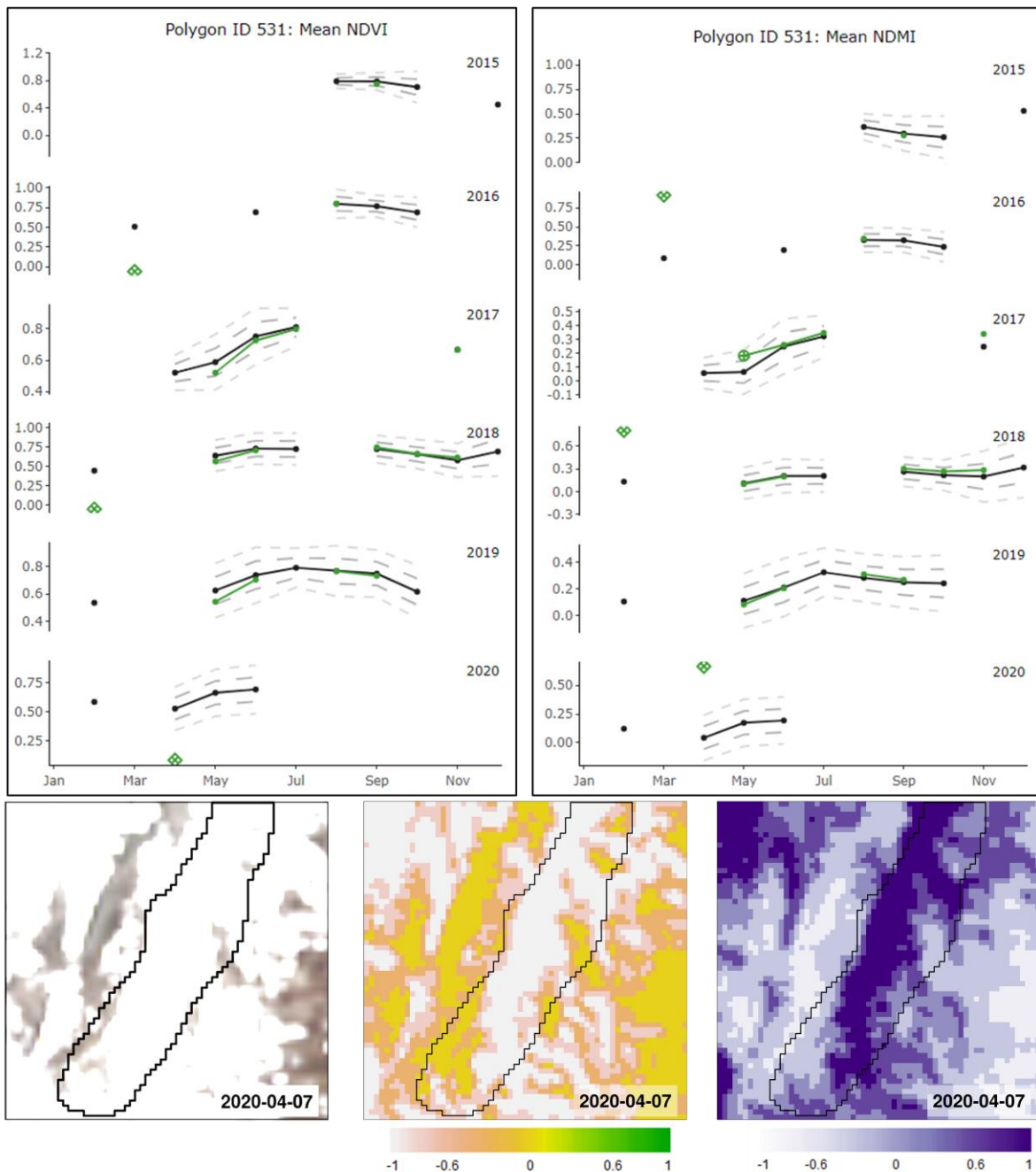


Figure 12. NDVI (top left) and NDMI (top right) graphs for a temperate shrub heathland polygon at Insh Marshes. Thumbnails showing the Sentinel-2 imagery (bottom left), NDVI (bottom middle) and NDMI for this polygon on 7 April 2020.

Artefacts in the Sentinel-1 or Sentinel-2 data can also cause polygons to be highlighted when there has been no change in their condition. In the example below, radio frequency interference (RFI) artefacts in Sentinel-1 data captured on 30 January 2017 produces anomalously low RVI and RVIv values in the north part of Cors Bodeilio (Figure 13). RFI distorts the radar signal and can be seen here as ‘ripples’ in the imagery.

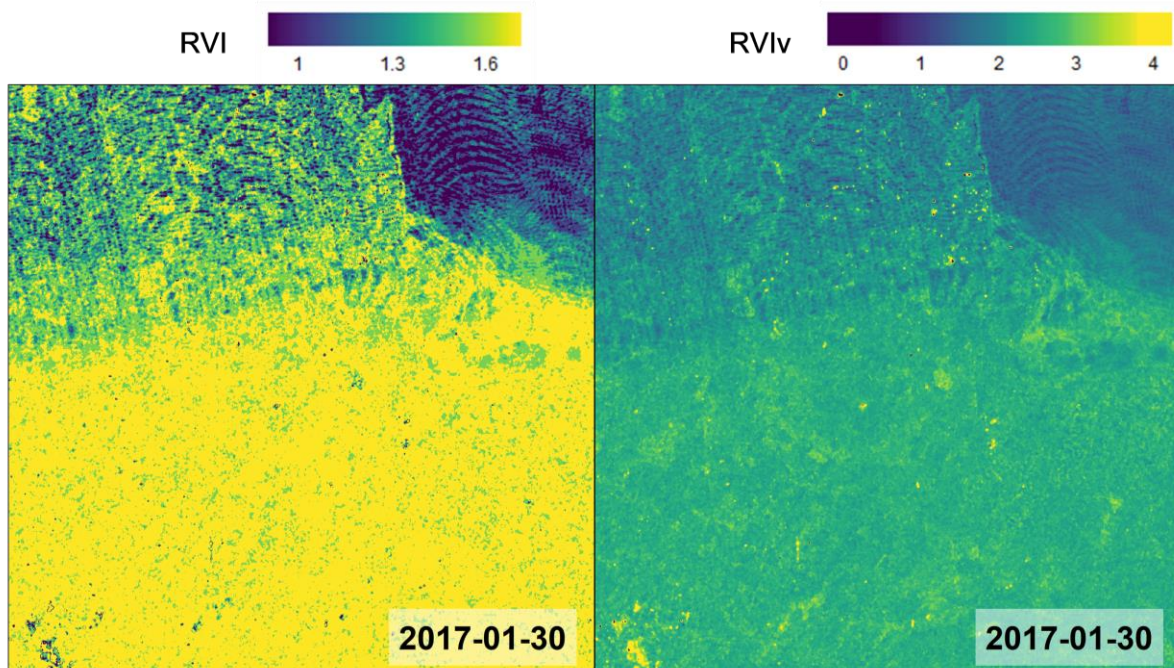


Figure 13. RVI and RVlv derived from Sentinel-1 data captured on 30 January 2017 showing RFI artefacts in the north part of Cors Bodeilio.

The low vegetation structure index values caused by these artefacts would cause the app to highlight affected polygons. This is illustrated here by an improved grassland polygon whose RVI and RVlv values are below the habitat-mean by more than one standard deviation in January 2017 (Figure 14).

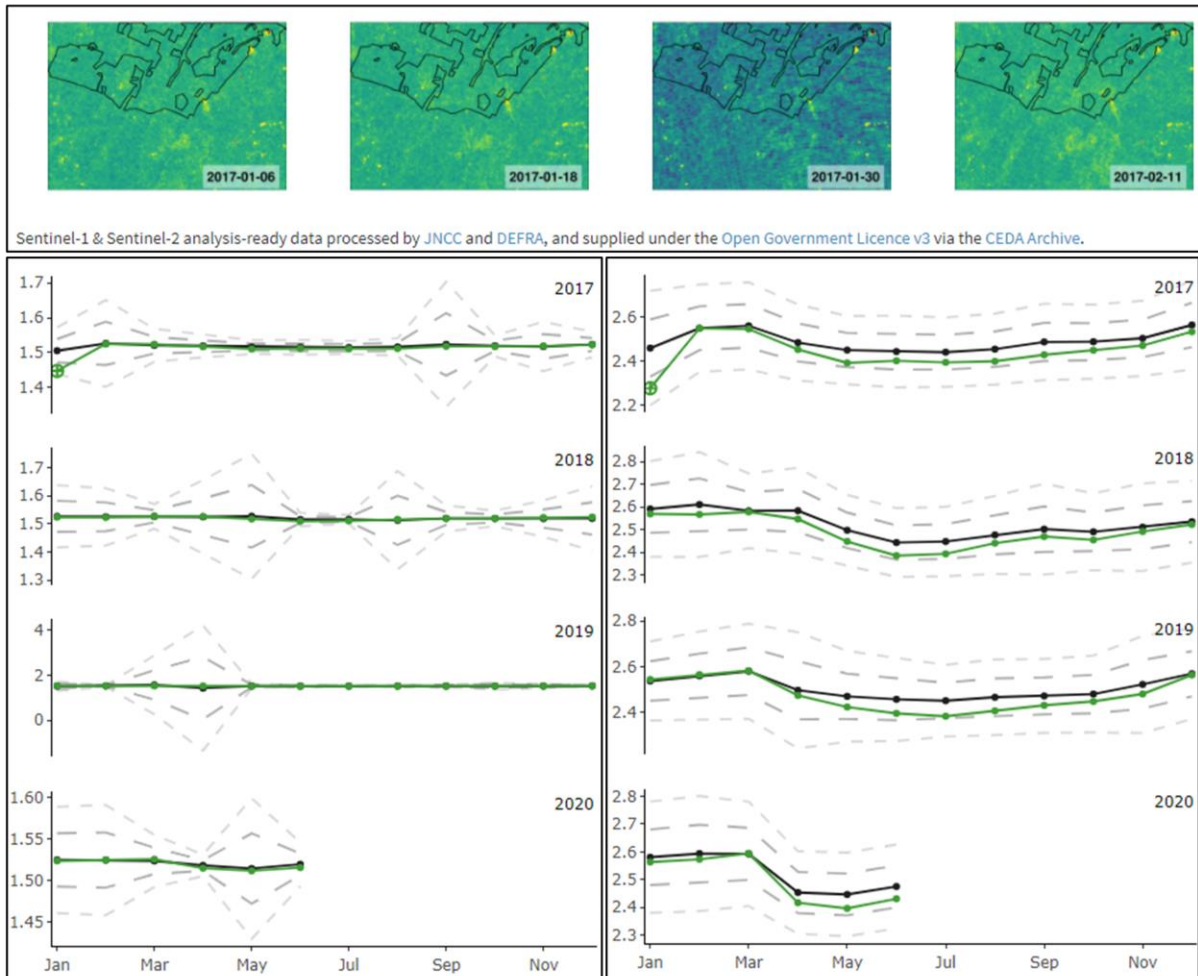


Figure 14. RVIv thumbnails for January 2017 (top), RVI (bottom left) and RVIv (bottom right) graphs for an improved grassland polygon affected by RFI artefacts in Sentinel-1 data in January 2017.

4.2.3 False negatives

As described above, polygons are highlighted when their index value exceeds the habitat-mean by more than one or two standard deviations. If outlier values skew the mean and standard deviation values for a given month, most polygon values will fall within one standard deviation which could result in change being undetected. In this example from the Malvern Hills, a few polygons classified as broadleaved deciduous woodland contain extreme outlier RVI values in certain months, likely due to a combination of habitat misclassification and artefacts in the data. Figure 15 shows that polygon 4315 has extreme RVI values in several months, creating large standard deviation values (grey dashed lines) in those months. Polygon 2900 is highlighted by the app in March and May 2017 but is not highlighted in April 2017. Because of polygon 4315's outlier values, the mean RVI for deciduous woodland in April 2017 is -71.768 with a standard deviation of 1981.82. Polygon 2900's mean RVI values for that period are: March = 4.289, April = 5.937, May = 3.146. The mean RVI for deciduous woodland at this site is between 1.4 and 1.7 when no outliers are present, so it is likely that polygon 2900 would have been highlighted by the app in April 2017 were it not for the outliers.

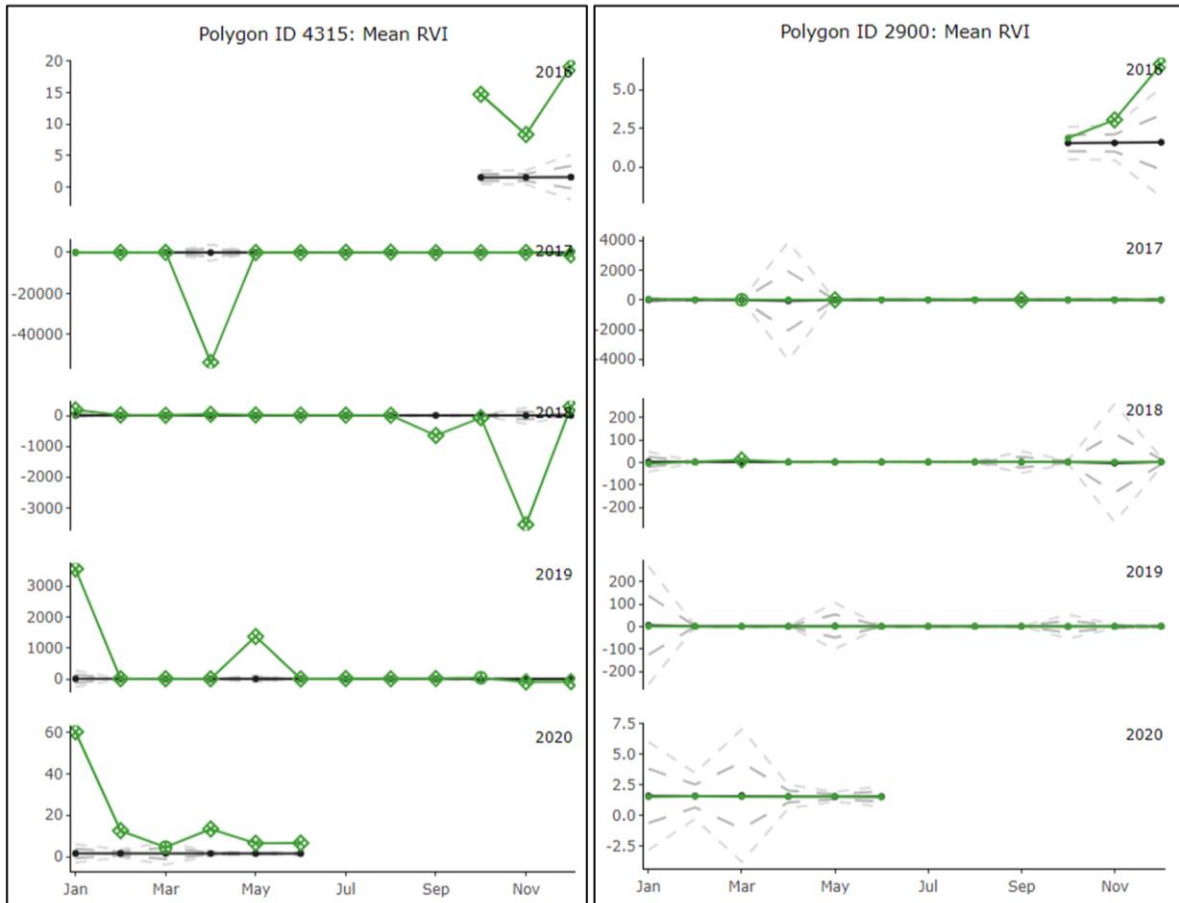


Figure 15. RVI graphs for two polygons classified as broadleaved deciduous woodland in the Malvern Hills demonstrating outliers skewing the mean and standard deviation values in several months.

Because the app works by comparing a polygon to all other polygons of the same habitat, it will not detect change if most polygons of a given habitat change in the same way in the same month or season. This could occur when many land parcels are in similar management regimes or when they are all affected by natural phenomena such as flooding.

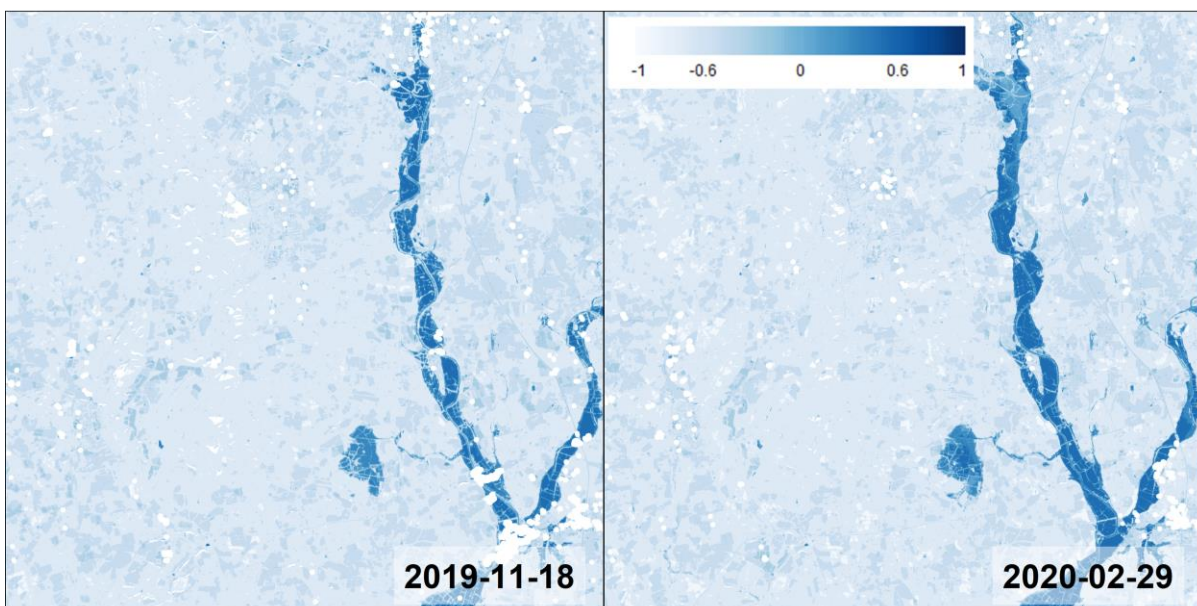


Figure 16. NDWI derived from Sentinel-2 imagery over the Malvern Hills showing the River Sever in flood in November 2019 and February 2020.

The River Severn broke its banks in November 2019 and February 2020, inundating much of the surrounding floodplain grazing marsh (Figure 16). As the floods were more extensive in February than in November, most polygons classified as floodplain grazing marsh around the Malvern Hills were flooded. This caused the app to highlight polygons that were not flooded, rather than highlighting those that were flooded (Figure 17).

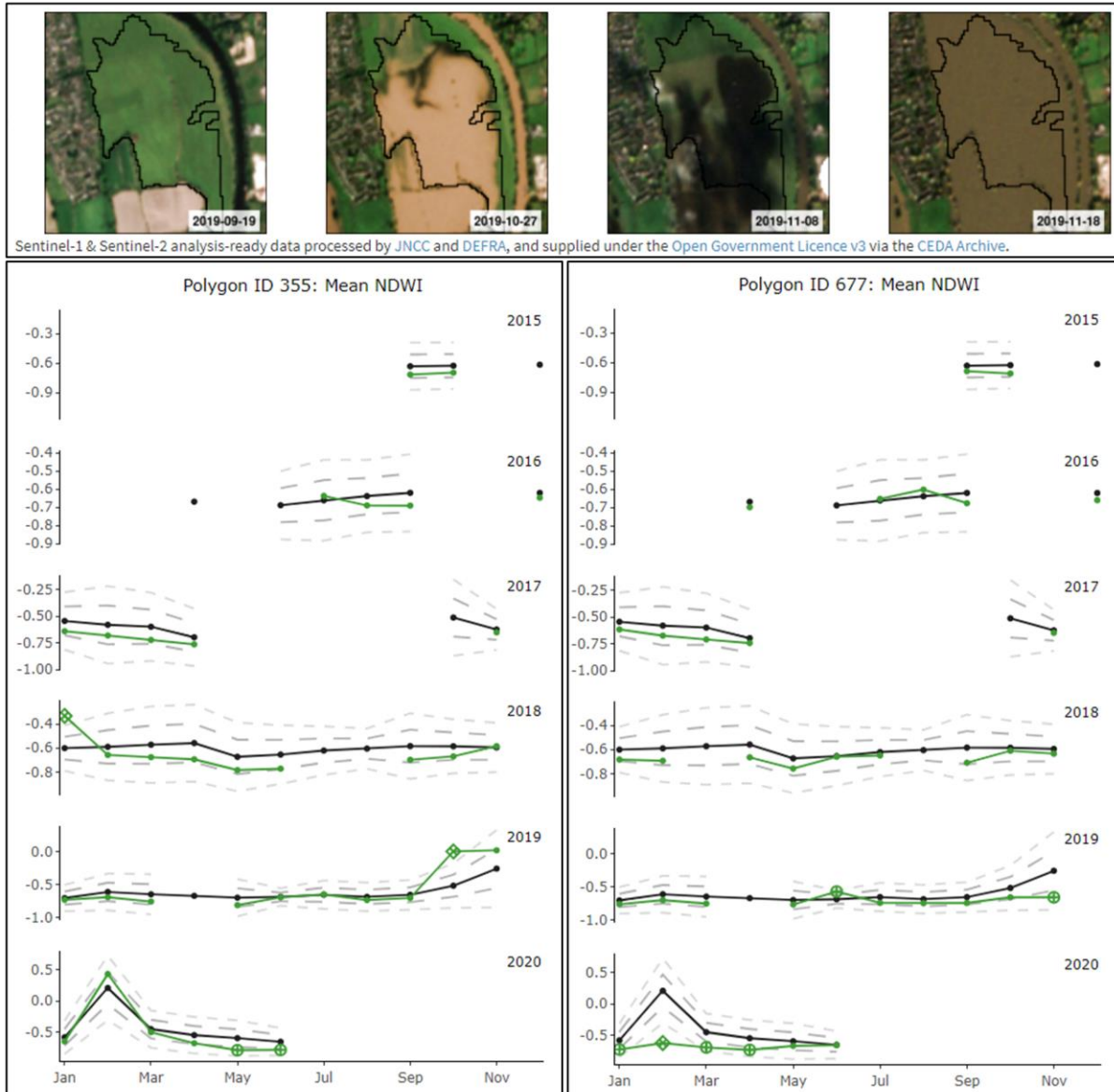


Figure 17 NDWI graphs for two polygons classified as floodplain grazing marsh around the Malvern Hills (bottom). Sentinel-2 thumbnails (top) show that polygon 355 was flooded in October 2019 and February 2020 although it was only highlighted in November 2019. In contrast, polygon 677 is highlighted in February 2020 because it did not flood.

In this example from the Dark Peak, a blanket bog polygon was expected to be highlighted for condition change due to increased heather cutting intensity as part of a management regime. Cut areas are visible on the thumbnails but NDVI and NDMI values for this polygon were very close to the habitat-mean for blanket bog, so the polygon was not highlighted by the app using these indices (Figure 18). This could be because surrounding blanket bog habitats are in similar management regimes. Habitat and site specialists felt that change detection is particularly challenging in upland sites due to the many factors which can affect habitat condition, such as water levels, fire, scrub encroachment and different types of management. It was found that the habitat polygons at Dark Peak were too large and often

contained multiple sub-habitats with different spectral signatures. There was also evidence of confusion between blanket bog and upland heath in the habitat maps.

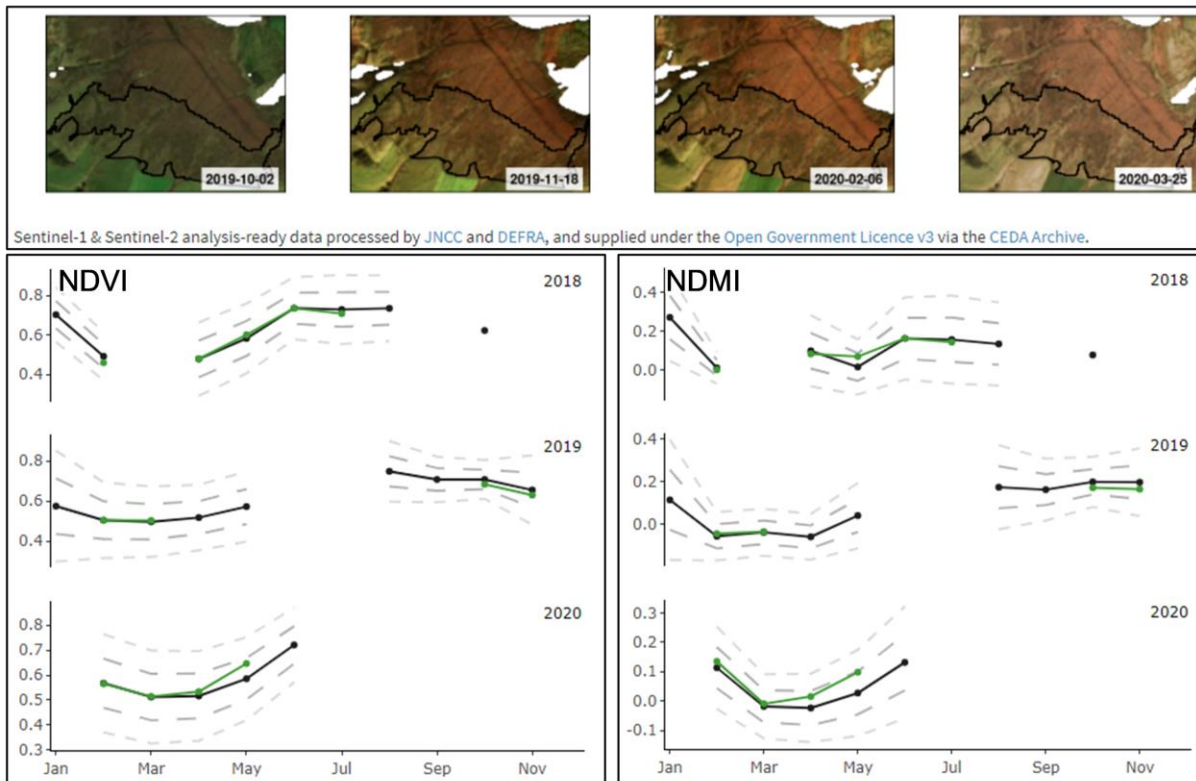


Figure 18. Sentinel-2 thumbnails from October 2019 to March 2020, NDVI (bottom left) and NDMI (bottom right) graphs for 2018 to 2020 for a blanket bog polygon in the Dark Peak.

A change in habitat condition can be missed if the app does not have data for the period when the change took place. Gaps in the Sentinel-2 time series due to cloud are inevitable. This issue is exacerbated because the current cloud masking method in the ARD workflow tends to over-predict cloud, often classifying bare soil, sand or built-up areas as cloud due to their high brightness value. If a polygon is even partially covered by a cloud mask on a given date, that date is omitted from the time-series for that polygon. This can lead to significant loss of data if a feature in the polygon is repeatedly misclassified as cloud. In the example below, a polygon classified as improved grassland at Cors Bodeilio slightly overlaps the carpark of an industrial building at its northern extent. This building and carpark are frequently misclassified as cloud, and the resultant cloud mask extends into the grassland polygon. As a result, Sentinel-2 data is available for this polygon on only seven dates over a four-year period, and perfectly useable imagery has been discarded (Figure 19). For comparison, the Sentinel-2 time-series for the Cors Bodeilio site as a whole comprises 78 dates.

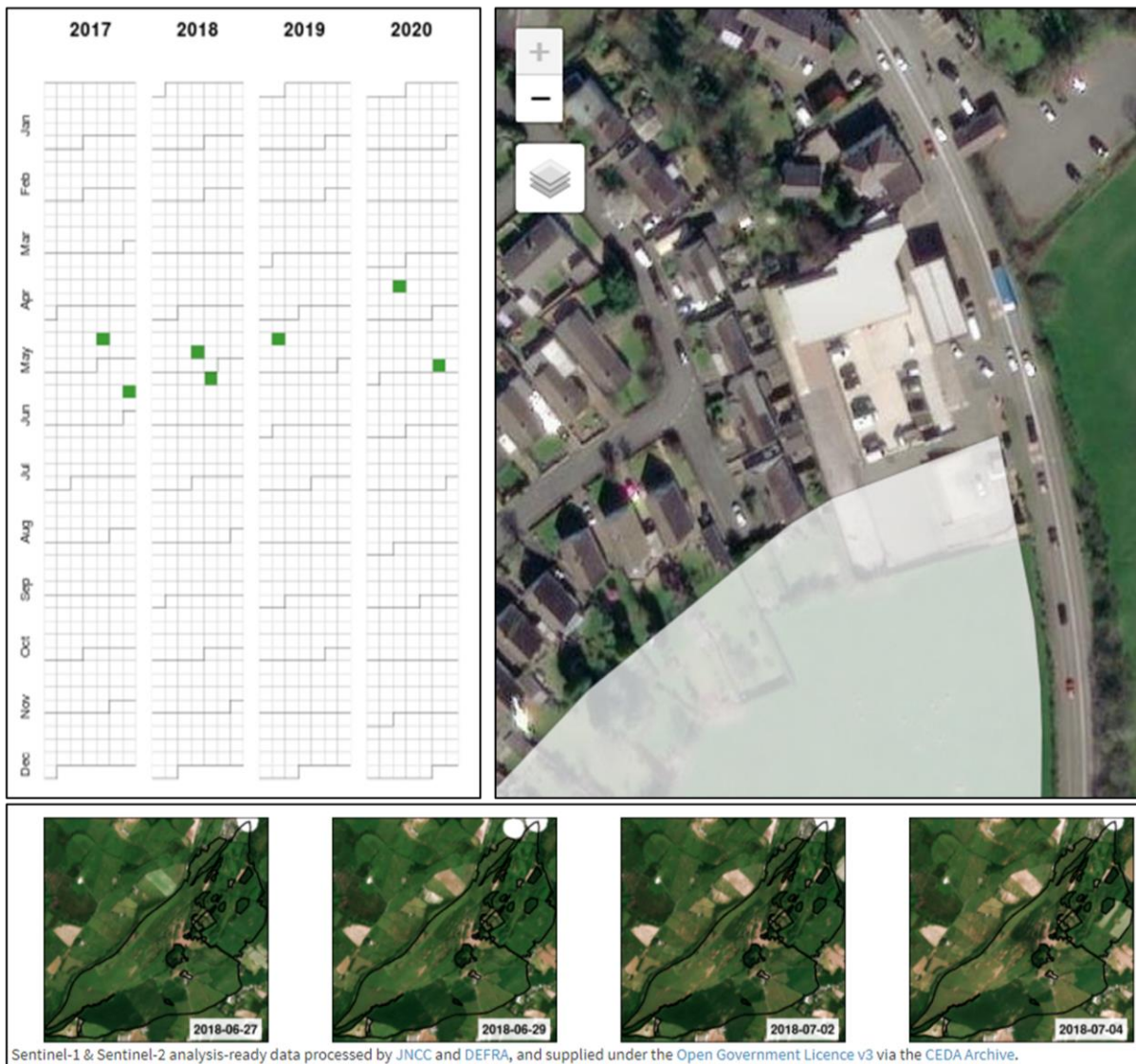


Figure 19. Calendar of available Sentinel-2 imagery for an improved grassland polygon at the Cors Bodeilio site (top left) showing that this polygon has data for only seven dates. Thumbnail images (bottom) show a small area in the north of the polygon is repeatedly obscured by the cloud mask. This is because a white building and car park (top right) on the edge of the polygon have been misclassified as cloud on many dates.

5 Discussion

By creating a functional prototype, this project has demonstrated the potential of using Sentinel-1 and Sentinel-2 data to monitor habitats and historic landscape features. Thanks to a high level of user input, it has built understanding of how the app could be used operationally to deliver environmental benefits. The types of landscape change highlighted by the app, such as erosion, scrub encroachment and changes in tree cover, are relevant to the management of protected sites and to the conservation of historic landscape features. Crucially, it has provided valuable insight into a number of challenges and how they might be addressed. The knowledge generated by this project will inform future work to deliver EO-based monitoring at regional and eventually national scales.

Because the app was a prototype intended for testing purposes there were limitations both in the technological infrastructure and in the approach adopted to detect change. There is also

a clear need for improved understanding of how to interpret outputs. This section discusses the current limitations and opportunities for improvements in these areas.

5.1 Change detection approaches

The approach to detecting change was relatively simple, consisting of comparing a polygon's mean index value with the mean index value for all polygons of that habitat at that site. This approach failed to detect change if the majority of polygons changed in the same way in the same month or season. This approach is not likely to be scalable to larger geographic areas, but geographical weighting could be used to select only local polygons for the generation of mean index values rather than using all available polygons. In theory, this could be enhanced by generating the habitat-mean from local polygons expected to be in similar management regimes or habitat condition to the target polygon, but current data on condition and management is unlikely to be available for all sites.

Other approaches to change detection were considered and discussed with project partners. One possible approach, which was used in the 2019 proof-of-concept app, would be to detect change based on deviation from the selected polygon's index value in the previous month. This is effective at detecting sudden gross change such as flood, burning, tree felling or hay mowing, but is less capable of detecting subtle change and cannot be used where there is no data available for the previous month.

Another approach would be to detect change based on deviation from the selected polygon's mean index value in the same month or season calculated from all available previous years. This was considered by project partners to be a more intuitive and potentially more robust method, but the time-series is currently too short to produce meaningful results.

These three approaches all have potential benefits and it may prove effective to use them in combination. A more sophisticated approach would be to generate standard response curves for different habitat types in different regions and highlight areas where there is a meaningful deviation from those curves (Zhao *et al.* 2019).

The change detection thresholds of one and two standard deviations were chosen for trial purposes. These may not be sensitive enough to detect change using some habitat-index combinations but may be too sensitive in other situations. This seems to have been the case at the Dark Peak site, where users felt that too many polygons were being highlighted unnecessarily.

5.2 Infrastructure and input data

The indices, zonal statistics and site-level thumbnails were prepared in advance and uploaded, rather than being generated and updated automatically. Polygon-level thumbnails were generated 'on-the-fly' but delivery was slow and the data for generating the thumbnails had to be stored externally to the application. This approach is not scalable to larger geographic areas and does not easily allow updates as new data becomes available. Automated processing using cloud-computing facilities should be explored in future.

The issue of false positives caused by habitat misclassification should be relatively easy to address by using more recent and better quality habitat maps such as the latest version of Living England produced by Natural England (Kilcoyne *et al.* 2021), or the [habitat map of Scotland](#) produced in 2021 by Space Intelligence for NatureScot.

The reduction of available data due to poor quality cloud masking is more challenging but could be addressed in future through improvements to the ARD workflow. The Fmask cloud masking algorithm (Zhu & Woodcock 2012) which is currently used has been found to perform less accurately than other available algorithms (Zekoll *et al.* 2021). Multitemporal approaches to cloud and cloud shadow masking have been shown to produce more accurate results (Candra *et al.* 2020).

The presence of outlier values in the RVI and RVIv index data could be resolved by using median instead of mean values, a choice which is already offered in the current app. Masking artefacts in data that cause the index outlier values could also be effective, but the most pragmatic approach may be to set thresholds for maximum and minimum index values to prevent the generation of outliers.

Using Sentinel data, the app only covers the time period from 2015 onwards, which may be too short to build up a picture of typical seasonal curves in index values and is certainly too short to detect any long-term trends. If a longer time-series is needed, this might be achieved through harmonisation and integration of Landsat data (Shang & Zhu 2019; Awty-Carroll *et al.* 2019).

5.3 Interpretation of outputs

As it stands, the app requires users to have detailed knowledge of the site, habitats and management practices in order to interpret outputs. Further development would be needed to make the app accessible and useful to a wider range of users with land management responsibilities. Some form of reporting functionality containing automated interpretation of outputs would be desirable.

Further research is needed to develop understanding of how to interpret outputs so that this information can be communicated to users, for example which indices are best at detecting different types of change, when to use mean and standard deviation to detect change, and when to use median and quartiles. This is particularly important for the indices derived from radar data. These are less well understood and less intuitive than the Sentinel-2 derived indices, but radar data provides a denser time-series and therefore greater capacity to detect change which could be missed due to gaps in Sentinel-2 data. As the example from Insh Marshes (Figure 4) shows, RVI may be more reliable than Sentinel-2 derived indices as an early indicator of woodland felling or storm damage, but the threshold may need to be set lower than one standard deviation for highlighting polygons.

The app could be made more sophisticated through integration of data and ecological intelligence to aid interpretation of outputs. The integration of field data on habitats and species would be particularly desirable for identifying relationships between index values and habitat condition. Very high resolution (VHR) optical satellite imagery used for visualisation could help provide context for the analytical outputs from Sentinel data.

A particularly exciting opportunity lies in the development of a UK habitat-based taxonomy of change which takes account of drivers and impacts. This framework is currently being developed by Aberystwyth University, building on work by Lucas and Mitchell (2017), which combines the Food and Agriculture Organisation's Land Cover Classification System (LCCS) and the European Environment Agency's Driver-Pressure-State-Impact-Response (DPSIR) framework. Further collaborative research should explore how to make best use of this framework within future iterations of the landscape monitoring app.

5.4 Recommendations for future work

The issues and opportunities outlined above will shape future work. The recommended enhancements have been prioritised for phased delivery, preceded by further research where needed. It will therefore be necessary to manage expectations while not underestimating the considerable value of putting EO-derived information on the desktops of non-EO specialists, producing outputs that they understand and that relate to real change on the ground.

Based on lessons learned from this project and input from project partners and end users, the following recommendations are identified as the highest priorities for delivery in the short term:

- Investigate methods of scaling-up the technical infrastructure to enable cost-effective and user-friendly delivery at regional geographic scales. This should include fully automating the preparation and updating of input data and accelerating the delivery of thumbnails.
- Address the factors which were shown to cause false positives or false negatives during this project, in particular:
 - Trial the use of improved and updated habitat maps to reduce false positives due to habitat misclassification.
 - Explore potential to improve cloud masking algorithms as part of the Sentinel-2 ARD workflow to reduce data loss.
 - Investigate the use of geographical weighting to select local polygons of a given habitat as baseline for comparison of index values, rather than using all available polygons of that habitat.
- Improve understanding of how field data on habitats and species, including citizen science data, can be integrated into the app to aid understanding of habitat condition and change.
- Further develop understanding of the relationships between spectral signature and habitat condition, especially with regard to indices derived from radar data.
- Begin to explore how best to integrate the UK habitat-based taxonomy of change.

The following recommendations are made for longer-term research and development:

- Further scale-up the technical infrastructure to deliver at national geographic scales.
- Investigate the possibility of enabling users to inform custodians of errors in the habitat maps so that these can be corrected on an ongoing basis.
- Trial the integration of VHR optical satellite imagery to aid users in interpreting the app's outputs.
- Investigate more sophisticated statistical approaches to detecting change from EO-derived indices.
- Collaborate with partners to test specific operational applications for the app, such as monitoring the impact of drought on wetlands or pathogens on woodland.
- Investigate the integration of additional data, for example from the Landsat archives, to provide a longer time-series for detection of trends.
- Integrate the UK habitat-based taxonomy of change.

Throughout all future phases of this work, ongoing stakeholder engagement, user testing and feedback will continue to be crucial to successful delivery.

6 Conclusions

JNCC has a strong culture of partnership working and innovation, sharing expertise and cost-effective solutions with partners and stakeholders across the UK and internationally. In this project, JNCC brought together site, habitat and EO experts from four different organisations and engaged them from the outset in project co-creation and delivery. Outputs and findings have been presented to a wider audience through networks such as the Defra Earth Observation Centre of Excellence and the UK Government Data Science Festival.

This project achieved a great deal in a very short space of time thanks to the strength of the collaboration and the partners' generosity with their time and expertise. The pilot study demonstrated the potential of giving non-EO specialists the ability to use the vast archive of Sentinel data to detect change in the landscape. It showed that enabling site and habitat experts to interact with EO data could provide new insight into management practices and their impact. Despite technical and methodological limitations, user testing demonstrated the app's ability to detect gross change such as forest felling or upland burning as well as more subtle changes in habitat condition.

Users agreed that this type of decision-support tool has the potential to reduce costs and improve policy delivery through more effective targeting of survey and management resources. Their feedback helped to create a more user-friendly interface and provided insight into the circumstances under which the app produced false positives and false negatives, information which will be crucial for guiding future research and development.

Ongoing user dialogue will ensure the success of future stages of this work, enabling operational delivery of an innovative service that supports all UK countries to monitor environmental change and make informed decisions about land management. This service will facilitate monitoring and assessment across whole landscapes, rather than just in designated sites or particular habitats. The ability to monitor landscape change on an almost daily basis could contribute significantly to multiple policy areas, including agri-environment scheme delivery, site management, natural capital assessment, biodiversity conservation and nature recovery networks.

This project raised awareness and generated enthusiasm by giving users hands-on experience of using EO for landscape monitoring. It was a key step towards routine operational use of Sentinel data for detecting change in habitats and historic landscape features. In this way, it has made an important contribution to the wider [JNCC Copernicus Project](#) aim of increasing uptake of Copernicus data, products and services to deliver public environmental functions across multiple policy areas.

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Appendix 1: Analysis-Ready Data

Sentinel-1 analysis-ready data are backscatter products generated from data collected in the Interferometric Wide (IW) swath mode and processed from the Ground Range Detected (GRD) version of the data made available by ESA. These Sentinel-1 data are obtained in the DV mode, where both VV and VH polarisations are collected. The raw scenes were terrain corrected, radiometrically normalised and processed to Gamma-0 backscatter coefficient in decibels (dB) using the SNAP Toolbox (ESA SNAP). This is as per the processing chain developed by JNCC as part of the Sentinel-1 Backscatter Data Provision Service (Minchella 2018). Processing included the following steps: apply orbit file, border and thermal noise removal, radiometric calibration, multilook, terrain correction using the Aerial Photography Great Britain (APGB) 10m resolution DEM, radiometric normalisation (Kellndorfer approach, (Kellndorfer *et al.* 1998)) and refined Lee speckle filter. Data was outputted on a linear scale in dB. The processed product is stacked, containing VV_dB in Band 1 and VH_dB in Band 2.

The Sentinel-2 imagery was processed to analysis-ready data (ARD) using processing chains established through previous project work at JNCC (Jones *et al.* 2017). Sentinel-2 data are transformed to produce a topographically corrected surface reflectance product using the Atmospheric and Radiometric Correction of Satellite Imagery ([ARCSI](#)) software. During processing, the 20m image bands are sharpened to 10m through application of linear regression models. The 60m bands are primarily used for atmospheric aerosol correction and processes and are therefore removed from the final surface reflectance product. Table 5 shows the central wavelengths, capture resolution and band numbers of Sentinel-2 ARD.

Table 5. Band numbers, spatial resolution and wavelengths of Sentinel-2 original data and ARD.

Band number and name in original data	Sentinel 2A Central wavelength (nm)	Sentinel 2B Central wavelength (nm)	Capture resolution (m)	Band number in ARD
Band 1: Coastal aerosol	442.7	442.2	60	
Band 2: Blue	492.4	492.1	10	1
Band 3: Green	559.8	559.0	10	2
Band 4: Red	664.6	664.9	10	3
Band 5: Vegetation red edge	704.1	703.8	20	4
Band 6: Vegetation red edge	740.5	739.1	20	5
Band 7: Vegetation red edge	782.8	779.7	20	6
Band 8: NIR	832.8	832.9	10	7
Band 8A: Narrow NIR	864.7	864.0	20	8
Band 9: Water vapour	945.1	943.2	60	
Band 10: SWIR – Cirrus	1373.5	1376.9	60	
Band 11: SWIR	1613.7	1610.4	20	9
Band 12: SWIR	2202.4	2185.7	20	10

Appendix 2: Results of first user feedback survey

1. Which organisation do you work for?

Natural England (5)
 Historic Environment Scotland (3)
 Natural Resources Wales (3)
 NatureScot (4)

2. What is your role / job title?

Senior Grassland Specialist
 Landscape Mapping Officer
 Lead adviser for a protected site (3)
 Environmental Data Collection Officer
 Rapid Archaeological Mapping Programme Manager
 Area Officer, Southern Scotland
 Remote Sensing Mapping Manager
 Terrestrial Monitoring Ecologist (2)
 Lowland Grassland Adviser / Site Condition Monitoring Officer
 Wetland Ecology Adviser
 Protected Areas and Nature Reserves Manager
 Earth Observation Ecologist

3. Approximately how many hours did you spend testing the app?

<1 hour (1)
 1-2 hours (7)
 2-5 hours (4)
 5-10 hours (3)

4. Please tell us about the device you used to test the app:

Type of device

Lenovo laptop (Thinkpad X270, X230, X230i) (4)
 HP Elitebook (5)
 Desktop PC – HP Elitedesk 800
 Laptop unspecified (3)
 Desktop PC unspecified (2)

Operating system

Windows Vista
 Windows 6.1
 Windows 7 (3)
 Windows 10 / Windows 10 Enterprise (9)
 Unknown

Internet browser *

Google Chrome (6)
 Microsoft Edge (6)
 Internet Explorer (2)
 Unknown (3)

* One user tested three different browsers.

5. Which site(s) did you look at?

Cors Bodeilio (1)
 Dark Peak (3)
 Flanders Moss (5)

HES site 2 (3)
 Insh Marshes (4)
 Malvern Hills (3)
 Rhos Tonyrefail (2)
 Skyreburn (5)

6. Which indices did you look at?

NDVI (plant productivity) (15)
 NDWI (surface water) (13)
 NDMI (plant water content) (9)
 RVI (vegetation structure) (13)
 RVlv (vegetation structure) (8)

7. Which statistics did you look at?

Mean (15)
 Median (10)
 First quartile (6)
 Third quartile (5)

8. What was your overall impression of the app?

- Really impressed. Easy to use and quick to react, even on my very old computer. Very impressed with the results it has presented.
- Very straightforward to use and looked clear and uncluttered.
- Straightforward and thought it worked quite well.
- Easy to use menus, uncluttered interface, clear presentation of data.
- Intuitive and easy to use.
- I think the overall impression of the app was that it looked quite easy to use, very straight forward, nice graphics although the parts that had been removed from the analysis of the thumbnails the white 'cut out' sections looked untidy, maybe this could have a blurred edge?
- It works well for thinking through some of the issues over what is being flagged, but for HES its main function is to facilitate exploring shapefile data - which it did perfectly satisfactorily.
- Promising in terms of information that can be gained, but not had enough time to practice using it to see its full potential.
- I like the app and it is really user-friendly. We need more time to see the effectiveness of the data for our purposes.
- Contained a lot of information, adequate options re Phase 1 categories, useful thumb nail visualisations etc. Straightforward to use.
- Really exciting stuff! Great to see but then realised it was only on a short run of rears data and the change I was looking for was more (long-term - 10 years?) The reverting back to original scale and mid-point of square location was annoying and the lack of OS backdrop and designated site boundaries was frustrating. Spent most of the time trying to relocate the site I was looking at. Know I could have downloaded it and

uploaded to GIS but that is a step I did not manage despite guidance as time and good internet connection did not coincide.

- The app is quite intuitive and straightforward to use. The more complicated step is interpreting what the information displayed actually indicates. This next step is not necessarily straightforward and may require additional detailed information about the site, e.g., vegetation mapping, site management history, water level data, rainfall data etc.
- Unfortunately, only the main map window in the top left of the screen seemed to work, and I couldn't see any of the charts, graphs or thumbnails, so there was no way to interpret the results. I was therefore unable to see the app working as it should. If it had worked as the presentation illustrated I think it could be a useful tool. (user had connection issues)
- The app looks to be a very powerful tool to quickly and easily identify polygons which have diverged from those in the same area hosting the same habitat type. The initial look of the app when first opening it up would not encourage use due to the blank panes and any obvious prompt of how to get started. Once up and running it is very easy to use and navigate through and the results displayed are very impressive.
- I think it works really well and quite exciting to use as for each segment flagged as change for a selected habitat you can investigate its drop or increase in NDVI or NDMI easily using the graph that shows all years that have changed, not just year selected to see seasonal patterns across years and pin point period of change in relation to mean for that habitat across the site. Great for Wildfire and lowland meadow grazing management where expect drops in productivity. Then can look at NDMI and NDWI for changes to see if relates to weather patterns or storm events or drought conditions having both can relate Surface water NDWI to storm events or flooding increasing water table then seen time lag after in NDMI of water held in plant community. Then look at thumbprint giving very handy visual that further helps understand change. Then can relate to flooding events or management on site to infer what is causing change that could lead to further investigation across all sites flagged for that habitat type with similar patterns or fingerprints of change. A powerful tool. Could be used to inform effectiveness of management or monitor change, then trigger investigation of change.

9. How did the app compare with what you expected?

Better than expected / easier to use / more detailed (3)

Worked as expected (6)

Didn't know what to expect (3)

Unable to operate / connection problem (1)

- Exceeded expectation in term of functionality. However, more work needs to be done on the User interface - perhaps with a simple flow-diagram to take users through the stages to generate the map. For the occasional GIS/EO data user, there needs to be more explanation of the indices used and what they might indicate about condition - perhaps a tutorial and supporting Help tabs.
- I think it has met and gone beyond what I expected and I did have high expectations. I have been asked in the past could we provide just imagery or outputs of NDVI and other indicators derived from Sentinel for advisors to use. But this app is providing statistical information on the fly in an easily visual and readable way. The graphs work really well and highlight differences from the mean easily and then can visually see the Sentinel imagery of change in thumbnail or the indicator. It would be great if thumbnail

when clicked on could open into a larger pop up and maybe the Map into a larger pop up.

10. What was the best thing about the app?

- The information it is giving is really useful for a range of habitats. These are listed below in the section on what it can be used for.
- The initial walkthrough was very helpful to get started using the app straight away.
- I like the way that all the controls and results are immediately visible on the same screen.
- Provides easy access to Sentinel data for non-Earth Obs specialists. Access through the web portal makes access without ArcGIS/specialist software possible.
- The user interface is very clear and intuitive; easy to retrieve data.
- It identified where there were areas of change- this is important in identifying areas that need attention by the monitoring staff and others - it can provide guidance to which sites need to be prioritised, e.g., those with most change may need to be surveyed earliest. The best thing is that you could identify within the polygon what areas showed the most changed via the thumbnails.
- Capacity to export data!
- Being able to compare changes on a site and look at comparative data to look at trends.
- Visibility, ease of use, data download.
- Easy to navigate, lots of interesting information. Thumbnails useful.
- Comparing a single polygon between years and seasons to spot change within polygon.
- It is easy to use and enables comparisons over time. Given the long (and potentially increasing) gaps between SCM visits, this has the potential to flag need for site management changes. It is useful to see the seasonal and annual changes. These are currently displayed as a series of graphs of difference - it would be useful if these could also be amalgamated into one time series display.
- I was still able to download the data so I could if needed work out where the change was and attempt to produce my own graphs and charts. Without the thumb nails showing the visual data, it would not be possible to interpret what change if any had occurred. (user had connection issues)
- Ability to highlight apparent change to polygons compared to like areas in the vicinity.
- Ability to get on the fly info on NDVI, NDMI, NDWI change areas on an online open app that could be used by any organisation or staff member in Natural England as is accessible and a simple tool for visually showing a potentially complex set of values and images. If can be made scale-able for all of England or UK that would be a thing to aim for which would depend on the spatial framework being used for each country. Really like when hover over points on graph gives you indicator values

11. What was the worst thing about the app?

- Data download slowed the app down to the extent that I had to close it down and re-open.
- I thought that it could do with a better base map and possibly an aerial would be helpful, largely when comparing with other online maps such as Webmap or GIS software. When I change the index setting the map seems to reset and zoom out some distance from the site I am looking at. I found examples of incorrect classification of habitat, e.g., lowland meadow which was actually woodland.
- Basemap detail makes navigation & interpretation difficult for large scale areas such as the Dark Peak SSSI. Segmentation and accuracy of the PHI makes analysis of trends difficult (see comments for pilot area change prediction).
- If you zoom in on a segment then want to change the index, the screen goes back to full extent, making it hard to return to your area of interest.
- The screen did freeze a few times and I wasn't able to move the map or zoom in and out.
- The thumbnails are slow to load and it's not obvious that the images were loading due to the box being small and not very visible. This led to me clicking on lots of other buttons and just slowed down the process. The date format could be better on the thumbnails. You lose the year/ month selection when the index changes - a little annoying if you want to look at different indexes with the same info input. When moving between different 'change detected' polygons the year box went blank - this had previously been on 2019 - not sure if this is a glitch? The thumbnail clicker is slow to move between images. I'm not sure how accurately the months / seasons are represented due to the lack of presumably cloud free days.
- A couple of times I had to cycle back through the filters to ensure I was getting what I expected - not sure if that is my competence or if the arrangement of the filters lacked a slight clarity. Not an issue as familiarity grew.
- Not having a good OS backdrop to the map and have it zoom out again when you change the detection parameters.
- Possibility of more help with interpretation of results/graphs, but maybe this should be elsewhere (a link with different scenarios and facts?). Scrolling backwards through the thumbnail images wasn't working. The true colour was a bit murky and needed a bigger scale or to be able to zoom in. The graphs with timings of images.
- The poor backdrop mapping to place the polygons location in the landscape.
- 1) Every time you change the change detection parameter, or the filter criteria, the map window zooms right out and you then have to zoom back in and find the polygon of interest again (and it is no longer highlighted). 2) As above, it would be useful to display the time series data in one display as well as in individual graphs. 3) The habitat data was inaccurate in some cases meaning that some polygons were wrongly labelled (I realise that this is not a problem with the design of the app - but it does mean that a note of caution is required in its use).4) It looks at differences between stands of a habitat type on a site - but if the site is being managed as one large management unit (or the individual polygons are managed under the same regime), or

are subject to the same pressures - then there is still the potential that a change over time would be missed.

- The thumbnail, and chart/graph windows didn't work and the whole app seemed to hang quite frequently. (user had connection issues).
- Initial user experience (i.e., more help on getting started when first opening the app).
- When you click on a thumbnail it moves along the reel - it would be great if it could become a larger pop-up. Plus transparency of change segments as can't see underlying map

12. How likely are you to use this app in your work?

Very likely (6)

Likely (6)

Somewhat likely (3)

Unlikely (0)

13. How would you use this app in your work?

- The app could be used in monitoring how sites that are not clearly visible on the ground are being managed. It clearly shows where owners are taking hay cuts too late, not grazing the aftermath or not doing scrub removal. This would be beneficial where advisers cannot cover the ground in such a well hedged landscape as the western lowlands. It is also providing evidence of changing habitats in a beneficial way, such as the increase in heath on previously degraded grassland areas, as a result of re-introduced grazing. This is particularly obvious in the lowland acid grassland habitat.
- It is also providing useful information on the flood plain meadows on possible enrichment of these habitats and which ones are being hit the most by this. This could provide pointers for areas of further research on the ground.
- It is also providing possible evidence on recreational pressures- or where to look into this in more detail on the ground.
- There are elements of SSSI condition assessment that could be assessed through this, but not all attributes could be measured and further ground trothing would be needed. It would provide a pointer to areas of concern though and so particular sites could be targeted on the basis of the information from this app.
- To identify locations of change for potential archaeological remains.
- To add evidence to determining habitat change through management, such as from lowland meadow to arable.
- Reviewing change over time of blanket bog habitat, particularly in response to management interventions and restoration work – e.g., monitoring the effectiveness of re-wetting work.
- Monitoring response of habitats to seasonal weather events/climate change, e.g., prolonged periods of drought.
- To detect change in moorland management.

- It would be a useful tool to inform us where there is change in condition, species change via vegetation structure maybe indication of invasive non-natives if they are noticeable.
- Exploring habitat change and exporting data for analysis in GIS.
- Look for long term changes on designated sites. I feel I would need to learn more about its full potential.
- At this stage we will use the app to download the data, which will be thereafter mapped against our datasets. This, however, might change over time with growing experience in using the data provided.
- To try and assess whether gross changes on SSSI were detectable and meaningful, without visiting the site, or as a trigger to visit.
- To look at change in grassland condition such as SSSI and agri-environment schemes. Looking for things such as build-up of dead leaf material, ploughing or the richer growth if fertiliser has been applied.
- In its current form, I would be likely to use the app in relation to queries about whether specific wetland sites are becoming wetter, are scrubbing up due to lack of/ changes in management, or possibly are changing due to the expansion of competitive species. For the app to be used more widely - e.g., as a tool to flag up potential changes from the suite of wetland sites, then some method of machine learning would be required.
- I would aim to use it to check for unexpected changes in the condition of habitats. I might look for ways to use changes of a minimum magnitude to trigger the requirement of whether further investigation is required.
- Better target fieldwork where change flagged up. Pick up damage not flagged by other means (e.g., smaller wildfires). Consider whether changes in management have resulted in changes to habitat.
- Great for climate change projects for comparison of weather data against change segments such as the Long-Term Monitoring Network to look at influence of storm events, droughts, higher rainfall, higher temps against seasonal and annual vegetation change patterns, etc. Ideal for protected sites monitoring and for monitoring effectiveness and targeting of agri-environment schemes such as Environmental Land Management Scheme (ELMS) in future. Link into the Living England mapping approach for applying change mapping to Living England once mapping accuracy has developed further. Living England was always meant to be a change product and integrating this approach into Living England could develop this capability.

14. What would stop you from using this app?

- Coverage. It will be good when coverage is across the country.
- The relevance of the data to my particular job.
- Some concerns around segmentation & interpretation of the data - will describe this in the Dark Peak pilot area change prediction work.
- Length of time to retrieve thumbnails.

- If it became irrelevant to the work I was doing or if the app was giving wildly inaccurate answers.
- Any loss of functionality, or step back from the current standard. If the ARD data was not refreshed that would also limit or curtail its usefulness.
- If the information is hard to interpret or doesn't really add to the knowledge of the site and changes over time.
- If the data is not fit for our purposes.
- I would need to establish it is accurate and meaningful. This can be tested more, e.g., when we meet as a group to discuss Rhos Tonyrefail and see what has and hasn't been picked up as change.
- Time - it needs to be quick to use so once again backdrop mapping is the issue
- 1) Lack of background habitat data (or inaccurate data) on sites. 2) Lack of other background data that could help with interpreting changes highlighted by the app. I recognise that the app is not likely to replace the need for detailed site investigations where possible change has been highlighted - but some knowledge of the site/habitat is still required in order to interpret the outputs of the app.
- If the current bugs were not fixed. (User had connection issues)
- Getting started and not understanding what the indices were telling me.

15. How likely are you to recommend this app to others?

Very likely (4)
Likely (9)
Somewhat likely (2)
Unlikely (0)

16. Who else do you think would benefit from using this app?

- It has implications for anyone interested in land management, so I wonder about people like the Agricultural Colleges/Universities, e.g., SRUC.
- Any colleagues working with Protected Sites.
- Depending on its accuracy the Conservation Officers in the Environment Teams at NRW, when looking after their SSSI. In fact a variety of staff, including regulatory officers, e.g., if it can detect landfilling on habitat.
- Possibly agriculture scheme advisors and assessors once we have a clearer picture of which indices are really indicating what, e.g., can we identify rank grasslands or lower productivity but species rich (rough texture?) grassland.
- SEPA, Site managers.
- Land managers, farmers, wildlife crime officers, archaeologists.
- Area NatureScot staff. Partner organisations from public, private and voluntary sector. Agri-environment monitoring staff.

- Partners to NE particularly those who manage sites in local Area teams, such as Moors for the Future, Wildlife Trusts, National Trust, National Parks, Local Authorities etc. who manage wildlife sites and reserves.

17. Please rate the app in terms of the following

App features	Poor	Fair	Good	Excellent
Legibility of text	0	2	9	4
Clarify of images	2	5	3	5
Ease of navigation	1	5	2	7
Speed of performance	1	4	8	2

Suggestions for improvement

- Most thumbnail images were good to excellent except the True Colour pictures. With these the font was also unclear. An OS base map would be useful behind the changed polygons, if possible for location purposes.
- it would be good to have a time series display that includes all of the years. it would be good if the map did not zoom out every time you change one of the search/filter criteria
- I think the app need speeding up so that images etc appear within a reasonable period.
- Simple flow diagram outlining the steps to take to get the graphs/thumbnails loaded
- Opportunity to choose whether graphs displayed as individual seasons/months or all on 1 graph. Thumbnails not included in the graphs (due to cloud) not uploaded to improve speed.
- When you click away from app for too long it loses its connection and you have to refresh all the map from beginning.

18. Please let us know what you thought of each element of the app?

App elements	Poor	Fair	Good	Excellent
'Walkthrough' of features launched by the Info button	2	4	5	4
Filters	0	1	11	3
Interactive map	2	4	7	2
Graphs	1	3	8	3
Thumbnails	1	4	8	2
Data download	1	3	7	4

Suggestions for improvement

- Data download slowed everything to a stop on my computer
- Change base-mapping that is shown on the overview map of change polygons. In upland sites pinpointing segment polygon locations is quite difficult, particularly where there are few features for orientation. Aerial photos would be ideal. Switching between Indices resets the extent/zoom of the overview map - it would be great useful if the same view could be maintained even as parameters are changed. It would be useful to have a 'refresh map data' button or similar - so the user could select/change parameters on the left and then choose when the map/graphs are updated. Black segment boundary lines are difficult to see against dark blanket bog/dry heath habitat on the thumbnail maps - alternative colour choice might make this easier. Some very large segments in the Dark Peak pilot are hard to review in the small thumbnail sizes. Might be good if we could explore the thumbnails - perhaps if clicking on one could take the user to a full view. Switching the

orientation of the calendar plot to match the time series plot might make them easier to interpret side-by-side – i.e., show years in rows in both panels. The index scale used on the graphs varies - if this could be kept constant it would help when trying to quickly pick out change between years. 'Cancel' and 'reload' buttons would be really helpful - so that you could cancel download of thumbnails, choose a different filter, and then restart. This seemed to cause problems when I tried it, and I had to reload the whole page. The walkthrough popups describes green polygons which show change - should this say purple? The download function could be improved with option to rename files & specify destination folders. It could be useful to be able to select a range of years – e.g., 2017-2019 - especially once additional years of data are available. Same applies to month ranges. This would speed thumbnail download time.

- Thumbnails take a while to download - is there a way to filter by time/periods with change?
- For NDWI, the pale blues aren't very clear - is it possible to have more gradations in colour or a different colour ramp? When switching between indices, the map returns to the full view - would it be possible to have a "back to previous extent" button or similar?
- In the walkthrough could show example graphs.
- Walkthrough of features - some of the info masks the area for selection - so an adjustment to that would be good.
- The 'i' button should be made a little brighter /larger, I didn't notice it at first! The information box itself obscures the first few sections it is giving info on. The info given about the graphs could be increased. Graphs: more info on the axes and sub axes (clearer labelling). Thumbnails, to be able to zoom in on true colour would be useful, may not be possible. Thumbnails: a slide bar would be useful rather than clicking through if possible. Data download question N/A -didn't work for me, but this is likely to do with my system not the app.
- Changing any of the filters seemed to reset the view of the map which was annoying if you wanted to focus on a particular area. Can prevent this? I also found the order of the filters unintuitive, though understand this may be linked to the way the tool functions. I would probably have Site, Spatial framework, habitat, index, temporal framework, year, months/season and statistics, though would probably get used to whatever order they were presented in eventually. In the downloadable data can you include the seasonal time period with year at the beginning followed by Q1, Q2 etc. so that the data can be easily sorted into chronological order and used as an X axis in graphs? I wasn't aware of the tiny "i" walk through option until I saw the below question. Can you make it clearer that there is a walkthrough available? When I tried it the first pop-up obscured what it was telling you about so I wasn't able to follow it

19. Is there anything you would change about the app?

- Use graph examples in the walkthrough - blank white boxes don't really give a clear example of what the user will see even with the description below, particularly for those that are more visual learners. Move the 'loading' box to the centre of the page so that the user knows what is going on and prevent clicking on different buttons/annoyance that it's not working when it is just loading. Have a scroll bar along the thumbnails.
- I am interested in how it will cope if all the wet heath (for example) has scrubbed up already, or half of it has, how will change be detected or presented for a particular polygon?

- Backdrop mapping. Keep zoom and location constant when moving between different filters. Habitat backdrop mapping poor and out of date but accept it is probably the best we have. Where we do have NVC being able to drop alternative habitat mapping in as base for polygons would be great but appreciate this may be technologically impractical.
- I would like to be able to query whether a change has taken place within a specific area within a specific time frame, e.g., has there been any changes within polygon X between January 2015 and January 2020. I was expecting the app to be able to do this but it only seems to detect change from the mean of that habitat type at the same time.
- Maybe colour of change layer.

20. Any further comments you would like to make about the app or this project?

- Fantastic app. Looking forward to its roll out.
- very interesting and admirable idea, need to test on the ground.
- Hope above does not sound too negative, it really is exciting work and I cannot wait to be able to use it to look at grasslands etc in the future.
- I think this is a really good idea and hope that the app is refined and made available. I can see it being a useful tool for habitat management and monitoring. I have some concerns about the underlying data being used to delineate polygons of similar types. The phase 1 dataset in Wales is very old and not nearly as up to date or accurate as the available phase 2 data. Where phase 2 data exists I'd recommend at least using it to update the phase 1 data.
- If we get this right could be a big step in use of Sentinel imagery for monitoring change for a whole range of environmental work areas, Protected Sites, Climate Change, Environmental Land Management schemes etc

Appendix 3: Results of second user feedback survey

1. Which organisation do you work for?

Natural England (3)
 Historic Environment Scotland (3)
 Natural Resources Wales (2)
 NatureScot (3)

2. What is your role / job title?

Environmental Data Collection Officer
 Lowland Grassland Adviser
 Rapid Archaeological Mapping Programme Manager
 Landscape Mapping Officer
 Lead adviser for a protected site (2)
 Remote Sensing Mapping Manager
 Terrestrial Monitoring Ecologist
 Wetland Ecology Adviser
 Senior Upland Adviser
 Earth Observation Analyst

3. What is your overall impression of the new version of the app?

- Lots of good changes introduced, i.e., better.
- The newer version is a lot neater and the first aerial is clearer, overall it looks sharper and more modern. The only thing I would say that detracting from that is the thumbnails.
- More user friendly to select attributes etc. Still quite difficult to get head around what the thumbnails actually mean. Good advice in introduction but some examples of interpretation of results would be good.
- Good. The layout appears to work less well on square screens, with the left hand menu slightly bigger than it need to be. All good once this is minimized.
- This is an improvement on the previous version.
- Very good - the zoom and aerial photograph as a basemap make it much more user friendly.
- The changes that have been made definitely improve the ease of use. A good understanding of the site and habitat are still essential to interpret the results.
- My general impression is good - the app is intuitive and tidy. We use the app to access the data, which we then reprocess in GIS but the app offers a nice look into what has been going on in study areas.
- It is much more user friendly but the time to load graphs for different indices appears to be much longer now.
- The changes have improved the app.
- Much improved from v1, especially the aerial photography backdrop and the colour distinction between 1SD and 2SD to focus on polygons most likely to have changed. More user information is an improvement too.

4. Please let us know what you thought of the changes to each element of the app

Changes to app elements	Room for improvement	OK	Much better!
FILTERS (thumbnails option defaults to 'none' when filters are changed)	0	5	6
INTERACTIVE MAP (high resolution backdrop map, polygons flagged in different colours based on extent of deviation, zoom extent persists when filters are changed)	0	3	8
GRAPHS (added 'hover-over' information, removed line between datapoints where there is no data)	0	2	9
THUMBNAILS (increased brightness, clearer labels, different colours for different indices)	2	4	5
DATA DOWNLOAD (Natural England only - Living England polygon IDs added to downloaded data)	0	9	2
LANDING PAGE - (new 'Information' page opens when the app is launched)	0	3	8

Comments

- Interactive map much better, but unless I am missing it, I would still find a more detailed OS base map useful to help navigate from field to field. Maybe cost is an issue and it's not the end of the world.
- All much clearer.
- The elements that I tried are all improvements. I still think it would be useful if it were possible to display the graph data as a time series through the years - even if that was on a separate screen. It is useful to be able to scroll through the thumbnails as a time sequence - and the improved colour definition of the thumbnails is helpful.
- The app did crash repeatedly after about 10 minutes. Much more user friendly. The background imagery and ability to switch layers on and off is really good. There is still the need to address the underlying data that the analysis is based on - I appreciate that that is not part of this exercise but wanted to flag it here.

5. The following suggested changes to the app user interface were not implemented in the current version. Please rank them in order of highest priority for future development (1 = highest priority).

Suggested changes to the app user interface	Ranking
Give users the option of viewing all time-series data on a single graph (x-axis from 2015 to present) rather than a separate graph for each year.	1
Link the thumbnails, calendar and results plots, so that when a user selects a point on the graph, the app navigates to the matching thumbnail and highlights the calendar date.	2
Enable users to open map/thumbnail in a larger window or full screen to see more detail	3
Give users the option of viewing all thumbnails or only thumbnails of imagery used in analysis (i.e., omit thumbnails of cloudy Sentinel-2 imagery)	4

Suggested changes to the app user interface	Ranking
Enable users to notify partners of misclassifications in the underlying habitat map	5
Add a "save polygon" option so that users can navigate back to the same polygon results	6
Add a button to clear selected polygon	7
Add button to cancel thumbnail generation	8
Add an option to save filters so that users can navigate back to the same parameter settings	9
Add annotated example graphs to the walk-through	10
Add a legend to the graphs	11

Comments

- Restricting thumbnail generation to a time period (i.e., just before and just after a possible change) would greatly speed up the use of the app.

6. The following suggested changes to the methods used in the app were not implemented in the current version. Please rank them in order of highest priority for future development (1 = highest priority).

Suggested changes to the methods used in the app	Ranking
Highlight polygons on the map using a colour gradient based on the number of times they deviate from the baseline (mean or median) index value by more than the set threshold.	1
Enable users to select the threshold used to highlight polygons based on their deviation from the baseline (mean or median) index value (e.g., % slider bar)	2
Highlight polygons on the map using a colour gradient based on the extent to which they deviate from the baseline (mean or median) index value.	3
Enable users to choose either the median or mean index value as a baseline for highlighting polygons based on their deviation from it. Graphs would display either mean and standard deviations (as currently) or median and interquartile range based on the user's choice.	4

7. The current app contains eight small pilot areas. We aim to scale this up to provide regional, and eventually national, coverage. In an app with regional or national coverage, how would you like to navigate to your area of interest?

Options for regional/national navigation	Number of positive responses
Draw a polygon on an interactive map	Yes (11)
Type a place name or postcode into a search box	Yes (11)
Type a designated site name into a search box	Yes (11)
Select designated site boundary / designated feature from an interactive map	Yes (11)
Upload your area of interest as a shapefile	Yes (11)

Other

- A combination of navigation options would be good.
- Just pan and zoom.

8. There are three possible options for detecting change in a habitat polygon based on satellite-derived indices (the first option is the method used in the current version of the app). Please let us know whether / how each of the following could provide information useful to you in your work.

Options for detecting change in a habitat polygon based on satellite-derived indices	Number of positive responses
Deviation from the mean index value for all polygons of the same habitat at that point in time	Yes (11)
Deviation from the selected polygon's mean index value for the same month in previous years	Yes (11)
Deviation from the selected polygon's own index value in the previous month (subject to data availability)	Yes (11)

9. Does your proposed use of the app reflect your current work, or are there new applications that you would use the app for?

- Yes, it does reflect my current work (2)
- As well as work on SSSI /SAC, I may become involved in semi-natural habitat monitoring/survey in the wider countryside, e.g., linked to connectivity. Currently it is early days and probably too soon to say, but if app. can detect change meaningfully in the future would be useful to save time and concentrate effort.
- Could be really good for targeting a field visit on a big site such as Insh Marshes so that the atypical bits could be seen to see if it is a good or a bad deviation.
- It is contributing to the development of our capacity to monitor landscape change, and its likely impact on cultural heritage assets.
- If VHR satellite data became available it would contribute to monitoring the condition of designated archaeological assets.
- It clearly has the potential to identify land management and other environmental changes that effect semi-natural habitats including those within statutory designations and as such inform on-going management and policy.
- It does reflect my current work. I have used earth observation time series data before when assessing casework on designated sites - and can see that this app could be useful in those types of cases.
- As it stands, the app requires a detailed knowledge of the site to interpret the results - so I think that it would need further development (e.g., machine learning) before it could be used widely as a screening tool. In the longer term that could be a really useful development. If the app could be used to flag up sites that are changing over time (either water levels or vegetation) then that could be used to target more detailed site visits by staff.

- We discussed a few possibilities during HES-JNCC meeting but otherwise we are happy with the app.
- It would provide the opportunity to approach existing work, e.g., SSSI condition assessment, impact of restoration works in a new and potentially more comprehensive way.
- Yes, change detection feeds into my current work of monitoring land use change as it affects survival of archaeological remains.
- Yes, largely we see this being used for SCM prioritisation but it could be useful for other queries we get in the EO team about whether Sentinel can pick up particular changes in the environment.

10. Any further comments you would like to make about the app or this project?

- I would be very interested in how the suggested polygons where change has occurred came out in the wash. Did they show significant change? e.g., >2SD, or only 1-2SD or none and have enough polygons thought not to have changed been checked?
- I think the thumbnail still needs work. The clicker to view each of the thumbnails is slow, a sliding bar would be so much better, it's tedious clicking through the images. Also the cut out of the thumbnails presumably where cloud has been looks untidy and some of the thumbnails are completely white so I don't understand what part of the image has been used for the analysis? These just seem pointless to add in. Also the box around the dates seems too large - perhaps a halo would be better as it doesn't take up as much of the screen. Overall though the project and the app is great, particularly for sites where the condition is declining and being able to spot changes, maybe even on a small scale, will provide some understanding on what habitat types/species are being affected first or more sensitive to changes
- Really interesting project, would be great if it could be rolled out nationwide.
- The PHI (priority habitats inventory map) is fairly limited and there are many relatively comprehensive and detailed habitat data sets that I'm sure could be used to inform this work
- The App has great potential but getting the base data on which the mean indices are based is absolutely crucial to be able to pick true change, not just difference from the mean value. And to develop "signatures" for different interventions, e.g., burning and cutting, and impacts, e.g., rewetting.
- Just to reiterate that thumbnail generation does really slow down utility so being able to select a narrowed time series would be highly beneficial.