Remote Sensing Subsurface Ruins in the British Isles

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Abstract

During the summer of 2018, the British Isles experienced one of the hottest summers on record resulting in the appearance of crop markings which indicate the presence of buried ruins. This study investigates methods for detecting new subsurface ruin locations without relying on extreme weather events using NDVIs produced from satellite imagery and LiDAR-based digital terrain models. Know subsurface ruin sites in Brú na Bóinne, Ireland, and two locations in Wales: Cross Oak Hillfort and Castel Lywun Gwinau, are compared to determine if they exhibit consistent, reliable criteria that can compose a framework to be applied to locating new sites. NDVI analysis of the crop circles displayed useful dimensional characteristic but did not exhibit any consistent pattern. This study also determined that aerial imaging is an alternative to NDVI which is less intensive and yields the same conclusions. LiDAR observations of the two Wales sites produced varying results as a spatial profile across the crop circle at Cross Oak did not display any detectable topographical change, while Castel Lywun Gwinau did display a detectable annulus height of 0.285m. With a LiDAR site sample size of two, no trend was obtained in this study. However, given the successful detection of a feature using LiDAR, a large-scale survey encompassing a multitude of known ruin sites would provide the criteria needed to deduce if any correlation exists.

Keywords:

Remote Sensing, Subsurface Ruins, Crop Circles, NDVI, LiDAR

1) Introduction

The summer of 2018 was a very hot season for the British Isles and made international headlines around the world (NHS England, 2018). The hot weather the region experienced over the summer months outlined an abundance of field markings in crops suffering from the intense heat. Based on the history of the surrounding lands and other discovered man-made structures (O'Kelly et al., 1985; O'Kelly & O'Kelly, 1982; Stout, 2002), the new sites are speculated to contain ancient ruins ranging in age from hundreds to thousands of years old (Brady et al., 2009; Driver, 2018a, 2018b; Dúchas, 2002; Fenwick, 2018; Lock & Ralston, 2017a).

Crop patterns revealed by prolonged high temperatures across The United Kingdom and The Republic of Ireland are investigated using a Normalized Difference Vegetation Index (NDVI) to establish if possible trends exists in the health of the crops between sites. NDVI may also provide insight on the physical characteristics and proportions for known ruin locations. As the sites have yet to be excavated, the only evidence of the ruin's existence has occurred during instances of drought. In order to determine if new archeological sites can be found without such extreme weather events, this study will investigate the relationship the crop marks have with the topography of the sites using LiDAR (Light Detection And Ranging) mapping. If the underlying ruins revealed by the hot weather show consistent detectable topographic signatures between site locations, then it is plausible that LiDAR mapping can be used as the primary method for locating new sites by searching for similar topographic patterns under normal annual weather conditions.

2) Background

2.1) Precipitation, Temperature and State of Climate for the UK and Ireland

For this study weather data was gathered from The Irish Meteorological Service (Met Éireann) and The UK Meteorological Office (Met Office) which commission weather stations across each of the respective nations. For historical data, thirty-year averages in the time frames of 1981-2010, 1971-2001, and 1961-1991 were considered. In the summer of 2018, The Republic of Ireland and The United Kingdom experienced weather conditions that reflect that of a drought. Drought must factor a regional bias since water supply is a function of the local climate (Wilhite & Glantz, 1985). In this study, the term "drought" is applied in a circumstance where a natural reduction in the amount of precipitation has extended to a season or more in length where climate factors such as: below average amounts of precipitation along with high temperatures contribute to the severity of the event (Wilhite, 2000).

Total rainfall in millimetres for Dublin_Airport

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
2018	93.1	36.9	100.0	68.9	19.1	4.8	40.0	48.0	43.3				454.1
2017	21.9	41.6	67.2	10.0	43.5	86.4	42.2	73.2	82.3	47.8	81.5	63.1	660.7
2016	118.4	59.7	36.3	88.2	46.8	58.5	43.7	61.9	56.6	60.0	36.9	46.6	713.6
2015	47.7	34.6	57.5	43.9	90.5	14.1	69.2	100.1	56.6	49.1	121.6	193.5	878.4
mean	62.6	48.8	52.6	54.1	59.5	66.7	56.2	73.3	59.5	79.0	72.9	72.7	757.9

Figure 1 | Rainfall for the Republic of Ireland, measured at the Dublin Airport. June 2018 had the largest deviation from the historical (1981-2010) mean, which recorded only 4.8 millimeters of rainfall – which is a reduction of 61.9 millimeters. During the spring & summer months (May, June, July, and August) the region experienced a reduction of 36.0 mm from the historical average. ("Monthly Data - Met Éireann," 2018)

Spring and summer are traditionally the dry seasons for both Ireland and the UK with May, June, July, and August regarded as the warm period for the local climates (*Figure 1*Figure 2 *& Figure 2*). During the drought period of 2018, the

Mean temperature in degrees Celsius for Dublin_Airport

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
2018	5.3	3.4	4.3	8.1	11.4	14.5	16.1	15.3	12.5				10.1
2017	5.7	6.2	7.7	8.0	11.6	14.4	15.0	14.6	12.4	11.2	6.5	5.3	9.9
2016	5.7	4.4	5.9	6.2	11.1	14.0	15.7	15.4	14.3	10.4	5.6	6.7	9.6
2015	4.7	4.0	5.8	7.4	9.6	12.9	13.8	14.0	11.8	10.2	8.7	8.6	9.3
mean	5.3	5.3	6.7	8.1	10.7	13.4	15.4	15.1	13.1	10.3	7.3	5.6	9.7

Figure 2 | Mean temperature data for Dublin Airport (Republic of Ireland). The month with the most substantial deviation is June where the 2018 temperature was 0.9 degrees Celsius warmer than that month's average temperature from the last thirty-year survey (1981-2010). ("Monthly Data - Met Éireann," 2018) monthly mean rainfall collected at the Dublin airport was below that of the averages for all of the last three tri-decadal summaries (1981-2010, 1971-2000 and 1961-1990) ("30 Year Averages - Met Éireann - The Irish Meteorological Service," 2018). The UK is also found to historically average the lowest amounts of rainfall during the spring and summer months (*Figure 3*) ("Historical Data - MET Office," 2018).

Although relative warmth is characteristic for the climate of the British Isles during the summer months (Walsh, 2012), temperatures recorded in 2018 were historically warmer than the thirty-year averages for all of the last three tri-decadal summaries (*Figure 4*). ("Historical Data - Met Éireann," 2018; "Historical Data - MET Office," 2018). The Dublin airport recorded an average historical temperature deviation of half a degree Celsius during May, June, July and August 2018 (Figure 2).

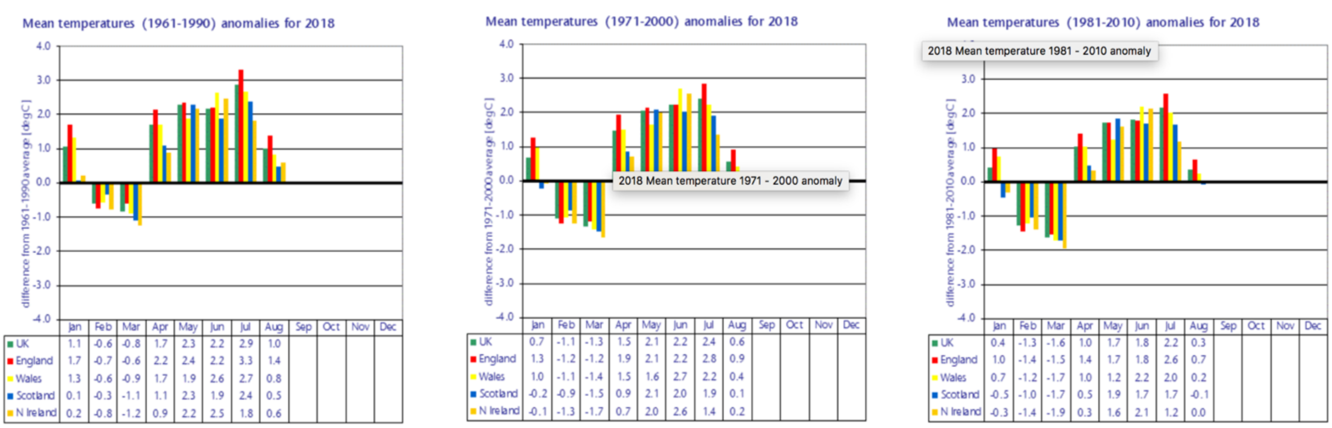

Figure 3 | Graphs for the mean temperature anomalies during 2018 when compared the thirty-year averages as a baseline. Data from September to December was not yet recorded at the time this study was conducted.
Spring and summer months (May-August) recorded a mean deviation of +1.5 degrees Celsius from the 1981-2010 average, with largest anomaly consistently occurring in July ("UK Weather Anomalies," 2018; "Historical Data - MET Office," 2018).
This high temperature was a major contributing factor to the drought the region experienced. A notable trend in the average UK temperature anomalies' is that for July the oldest thirty-year average (1961-1990) has the largest deviation. The next two tri-decadal comparisons (1971-2000 and 1981-2010) each calculated a smaller anomaly then the previous one did This trend suggests that the higher than average temperatures recorded year over year is raising the average temperature.

2.2) Brú na Bóinne, Ireland

The first archeological site what will be investigated is located adjacent to the River Bóinne, in the Irish county of Meath (*Figure 5*), forty kilometers north of Dublin. Brú na Bóinne is home to a dense distribution of archaeological complexes where ninety known monuments have been discovered since the first signs of ancient civilizations were found in 1699 (*Figure 6*). Brú na Bóinne is recognized as a World Heritage Site and is an attraction for its three main passage tombs: Knowth, Newgrange, and Dowth (*Figure 7*). Today the protected area occupies approximately 780 hectares with an addition 2,500-hectare buffer zone (Dúchas, 2002). The local geology of the lowland areas along the river Bóinne consists of carboniferous limestone, and the ridge in which all three of the large tombs sit is primarily composed of shale (Walsh, 2012). As human evolution allowed for the development of agriculture, the Brú na Bóinne landscape has continuously been resurfaced by plowing resulting in smaller burial mounds being damaged (Stout, 2002, p. 83). The tilled lands eventually blended the structures into the surrounding topography where they awaited rediscovery (*Figure 5*).

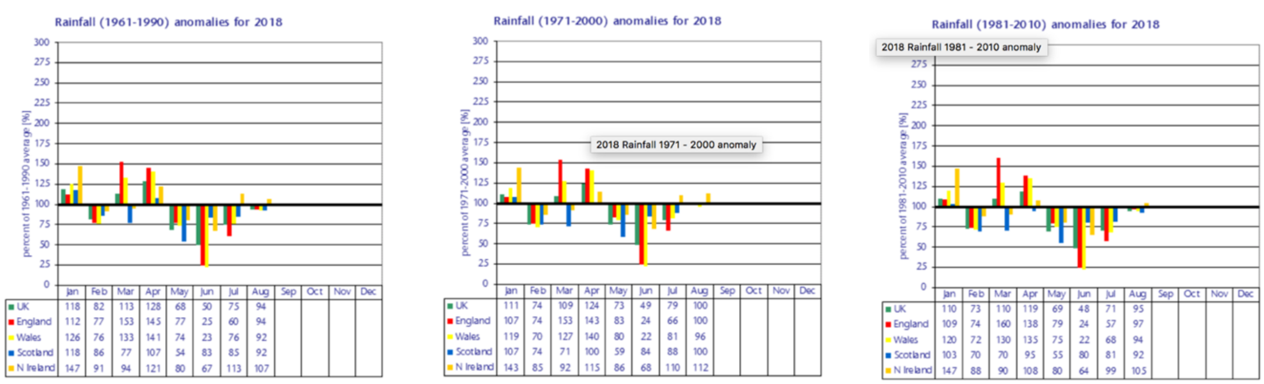

Figure 4 | UK MET Office graphs for the rainfall anomalies during 2018 when compared the thirty-year averages as a baseline. Data for of September to December was not yet recorded at the time this study was conducted.

During the summer of 2018, the largest precipitation deviation occurred during the month of July. As a whole, the UK received only 48% the amount of rainfall as it did during the July thirty-year average between 1981 and 2010.("UK Weather Anomalies," 2018)

All three of the last published thirty-year averages when compared to 2018 show a substantial decrease in the amount of rainfall received over May, June, July, August ("UK Weather Anomalies," 2018; "Historical Data - MET Office," 2018).

Figure 5 | Image "A" is a north-east facing aerial photo of the UNESCO Brú na Bóinne World Heritage Site taken summer 2018. The excavated burial tomb of Newgrange (1) is visible along with two previously known ruin locations which are denoted by crop circles and remain buried (2 & 3). The new ruin locations found in the summer of 2018 were discovered due to the extraordinarily warm temperatures and lack of precipitation (4 & 5). The Bóinne River is a visible green belt south of the ruins. Today many ruins on this site lie subsurface to accommodate crops.

Image "B" is an eastward facing aerial photo of three large crop circles (3, 4, & 5) which are estimated to span between 130 to 200 meters in diameter.

Image "C" depicts crop circle (4) in a high contract back and white filter. A series of ditches and post holes in a rectangular shape can be seen at the bottom portion of the crop circle. (Photos: National Monuments Service).

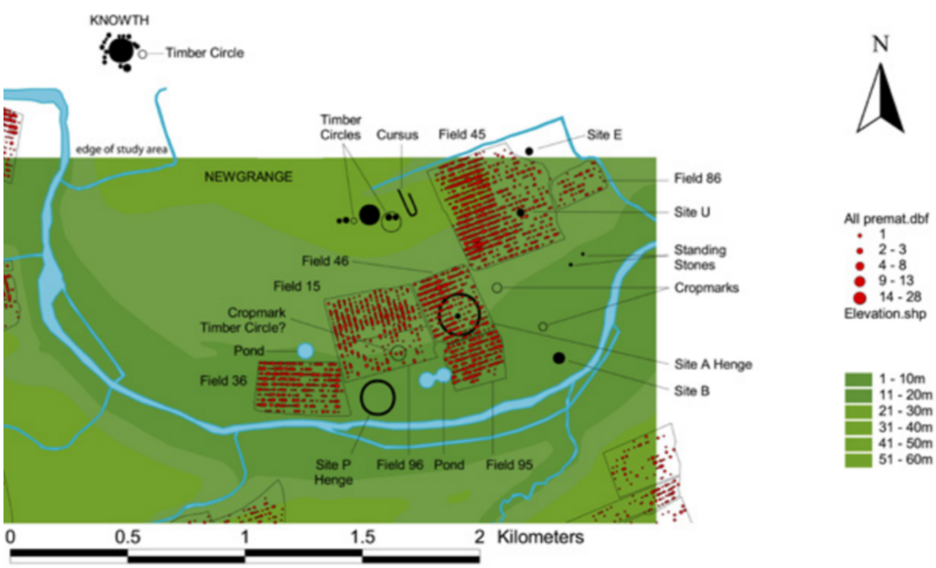

Figure 6 | World Heritage Site core area diagram depicting the abundance of features surrounding the main passage tombs of Newgrange and Knowth. [Conor Brady]
The 2018 crop circles are situated in "field 36" and are not illustrated in the diagram which has been composed of features detected on the Brú no Bóinne fieldwalking program.

(Brady et al., 2009).

Human activity in the Brú na Bóinne region was traced back to the Later Mesolithic period (c.5,500 - 4,000 BC) during excavations of the Newgrange burial tomb. Evidence of agriculture has been dated to the Early Neolithic Period (c.4,000-3,600 BC) (O'Kelly et al., 1985). Other manmade features surrounding the main tombs are comprised of ringforts, large embanked circles, pit circles, and or wooden post circles which have been categorized as 'henges,' while other features are cursus, comprising a network of parallel banks and ditches *(Figure 8)* (Brady et al., 2009). Brú na Bóinne may be one of the most heavily researched regions

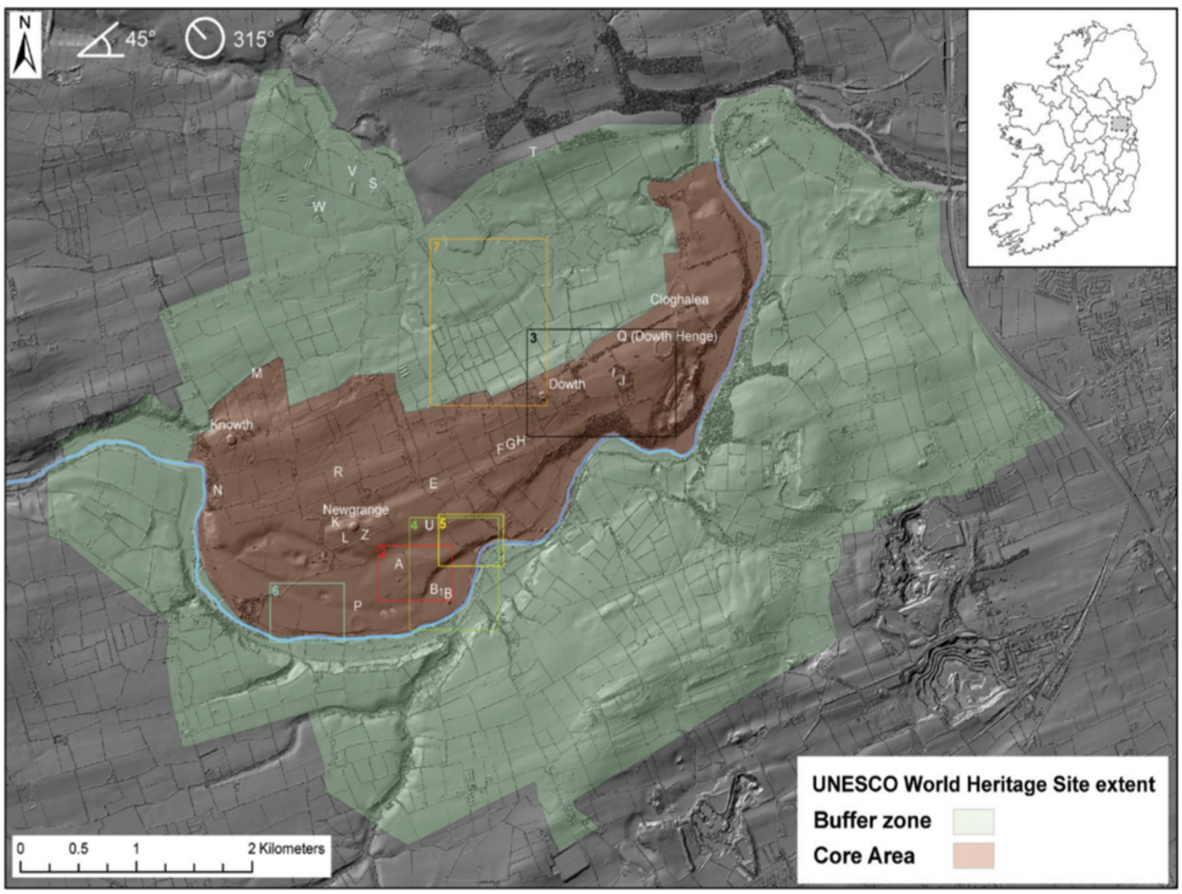

Figure 7 | Digital surface model (DSM) base map of the Brú na Bóinne compiled from a 2007 LiDAR survey of the World Heritage Site. (Davis et al., 2013)

Much of which this map denotes has been built off of the original monograph of the World Heritage Site made by George Coffey published in 1912 (Coffey, 1912; O'Kelly & O'Kelly, 1982).

The three main passage tombs: Knowth, Newgrange, and Dowth are denoted on the map and are visible based on their topographical relief compared to the surrounding area.

Area 6 is where the 2018 crop marks were discovered – see ***Error! Reference source not found.*** *for detailed aerial photography.*

in Ireland, yet with all of the work that has been done an unknown quantity of unrecorded sites may remain along the low-lying floodplain adjacent to the river (Brady et al., 2009). It is speculated that some of the unrecorded sites may have been smaller tombs that today lie preserved below the surface in surrounding fields (Fenwick, 2017).

Figure 8 | Center of image "A" is the main passage tomb of Newgrange on the Brú na Bóinne World Heritage Site. Situated in front of it are boulders placed in a linear formation referred to as standing stones. In the adjacent field to the east is a formation of cursus [Photo by Con Brogan].

Image B is one of six known ring forts present on the World Heritage Site and is situated 500 meters south of Knowth with a strategic position adjacent to the Bóinne River. Dating to the Iron Age, it does not have any relation to the main tombs but demonstrates the rich history of the area [Photo by Con Brogan].

Image "C" is a wooden post circle which lies in front of Knowth. Post circles found on at Brú na Bóinne vary in size from tight clusters to circles spanning several meters [Photo by George Eogan].

(Brady et al., 2009)

2.3) New Feature Discovery

In 1890, archaeology conducted by George Coffey resulted in the publication of the monograph that for the first time labeled and listed many of the site's features in a systematic manner (Coffey, 1912). New iterations of Coffey's monograph have been expanded on by others and most of which are still referenced today (*Figure 7*) (O'Kelly & O'Kelly, 1982). Since the large-scale efforts needed to excavate the large passage tombs of Newgrange and Knowth, modern research on the site has since been conducted on a much smaller scale. Methods involving remote sensing have been used on the surrounding landscape to understand the connection the passage tombs have with the surrounding area and the civilizations that occupied the lands. As only a small portion of the land encompassed by the World Heritage Site is under state ownership, airborne and satellite-based remotely sensed data provides a means to collecting data without treading on private land and disturbing the natural landscape (Davis et al., 2013).

In the summer of 2018, a discovery was made within the core area of the World Heritage Site where the differences in crop colour outlined a subsurface formation (*Figure 5*) (Hutton, 2018). The discovery was made during a drone fly-over conducted by Bóinne Valley researcher Anthony Murphy and Ken Williams. The Irish Department of Culture's National Monuments Service then followed up the discovery with flyovers of their own, concluding that the dry weather conditions will result in a high potential for other sites to become visible via cropmarks ("Minister for Culture announces discovery at Brú na Bóinne," 2018). The field where the new sites were discovered has been noted in previous site studies; however, in-depth investigation of these features has not occurred (Davis et al., 2013). Large boulders are present in some of the fields on the World Heritage Site (*Figure 9*) – some of which are embedded in the ground, while others lie in a disturbed manner arranged in some geometric formation. The presence of arranged boulders has led researchers to conduct geophysical surveys which have revealed cursus as well as other formations (Brady et al., 2009; Fenwick et al., 2009). A possible reason that the field in which the new features were found was not further studied prior to the change in crop health (*Figure 5*), is that it may lack the boulders which have intrigued hands-on investigation in other nearby fields. Boulders have not been inheritably visible using remote sensing methods such as satellite imagery and LiDAR mapping (Fenwick, 2017). As the field which the new features are located is heavily used for agriculture, the soil is consistently tilled and cultivated; thus large surface boulders are unlikely.

Figure 9 | Main image shows the overgrowth on the Newgrange passage tomb prior to excavation by O'Kelly in 1962. Visible are four standing stones in geometric alignment, the significance of which lead researchers to uncover the Newgrange tomb and further investigate the immediate surrounding area. Supporting images show the scale of boulders which have been found on the World Heritage Site [O'kelly archive, DoEHLG] (Brady et al., 2009).

2.4) Cross Oak, Wales

The United Kingdom also had an abundance of archeological sites appear during the drought of 2018. Wales, in particular, had an abundance of locations documented and imaged during this period by Dr. Toby Driver of the Royal Commission on Ancient and Historic Monuments of Wales ("RCAHMW | Cropmarks 2018," 2018). The first archeological site in Wales is located in the village of Cross Oak in the community of Talyont-on-Usk (51.903367ºN 3.294632 ºW) and is made visible by a crop circle formation very similar to those observed in Brú na Bóinne Ireland (*Figure 10*). The circular feature has been spotted numerous times over past years and was initially thought to be the old field banks of the river (Driver, 2018b). Its 2018 appearance allowed for clear aerial photographs showing the entity of the circular formation allowing researchers to deduce that it had previously been miss identified and is now thought to be the remains of an Iron Age ringfort (Driver, 2018b). The knoll which the ruins are situated is strategically well positioned for defensive purposes along the western edge of the River Usk's escarpment. Substantial releveling of the field surface for agriculture purposes has hidden the ruins of the ringfort from view at ground level; however the parching of the field which composes the crop circle has revealed the former ramparts which now lie subsurface (Lock & Ralston, 2017b).

Figure 10 | RCHMW south facing image taken during the summer months of 2018 when the drought was at its most intense period, thus revealing the crop circle representing the ruins of the Iron Age Cross Oak Hillfort. The crop circle is estimated to be 120 meters in diameter.
[Photo by Dr. Toby Driver] (Driver, 2018)

2.5) Castel Liwyn Gwinau, Wales

The second site can be found near the central west coast of Wales, approximately 3.2 kilometers north of the town of Treagon and 59 kilometers to the north-west of the crop marking at Cross Oak (*Figure 11*) (51.25297ºN 3.95128ºW). In contrast to the crop markings found at Brú na Bóinne and Cross Oak which are ring-like, the primary Liwyn Gwinau marking is a mostly solid circular feature some 33 meters in diameter (Driver, 2018b). Within the primary marking, a smaller ring-like structure resembles that found at Cross Oak as it is made visible by the parched crop ring some 2 meters wide and 18.5 meters across; it is speculated to be displaying the remains of a stone wall (Poucher, 2010). A geophysical survey of the site conducted in 2009 by the Dyefd Archaeological Trust Field Services confirmed speculation

Figure 11 | TOP: RCHMW north facing image captured summer 2018. The crop markings in the center of the image features of the buried ruins of Castel Lywyn Gwinau [Photo by Dr. Toby Driver] (Driver, 2018)
BOTTOM: High contrast aerial image looking to the south-east [Photo Ref: AP89-B32] (Poucher, 2010)

that vestiges of the site still lie below ground at this location (Poucher, 2010). The entire feature sits atop a mound about 1.6 meters high which is the highest topographical location in the surrounding area and was encompassed by a medieval motte which is visible in aerial photographs around the perimeter of the crop mark (*Figure 11*) (Driver, 2018b). In the sites immediate vicinity to the south, the 2009 field study found faint traces of linear features and possible postholes which have been mostly obscured by agricultural activity and are not visible in aerial photography (Poucher, 2010). To date, there is no known history of Castel Liwyn Gwinau as it has not been archaeologically investigated.

3) Data

3.1) Visible and Near-Infrared Image Info

Images of the Irish Brú na Bóinne World Heritage Site as well as the UK sites were obtained via request using Planet's explorer[1], where the 4-band PlanetScope orthorectified analytic scene was selected. These images are acquired by the PlanetScope Satellite Constellation which boasts a spatial resolution at nadir of approximately 3.0 meters and consists of more than 120 CubeSats ("Planet Imagery Product Specification," 2016). This constellation can image the entire earth on a daily basis (~150 million square kilometers) and carries a sensor with spectral bands ranging from blue to the near-infrared (*Figure 12*) ("Planet Imagery Product Specification," 2016).

Blue	455 - 515 nm
Green	500 - 590 nm
Red	590 - 670 nm
NIR	780 - 860 nm

Figure 12 | Wavelength regions in nanometers covered by the PlanetScope Satellite Constellation. ("Planet Imagery Product Specification," 2016)

[1] Planet's portal for satellite imagery: https://www.planet.com/explorer/

Images were selected under the criteria that they have less than 5% cloud cover over the areas of study and were acquired during the period of drought (June to August). Vegetation was the most stressed during this time frame, thus revealing the crop patterns. Images either before or after the point of maximum severity in the drought will also be referenced in order to depict the change in crop health and the "disappearance" of the ruins. In this paper, images will be referred too based on which site they picture and the date they were captured (*Figure 13*).

The PlanetScope constellation is the best possible instrument in which orbital imagery can be acquired at no cost. Difficulties in acquiring images for sites within the UK was encountered due to many crop features being undetectable. Factors pertaining to this lack of visibility are that crop marks are only visible for a short number of days and the revisit time for the PlanetScope satellites is variable, thus it is possible for image capture of the patterns to be missed. Additionally, some surface features are too small to be detected at 3 m/pixel. The result of these complications will thus limit the number of sites that this paper will explore in the UK.

A

Figure 13 |
Image A: BruNaBoinne_June06.

PlanetScope 3-meter resized image of the Brú na Bóinne research site captured June 6, 2018. The image is displayed in visible light using bands 1, 2, and 3.

Notable features visible in the image are the main passage tombs of Knowth and Newgrange as well as the Bóinne River (north is up).

The features discovered in 2018 are located just north of the Bóinne River in the center of the image and is denoted by the arrow.

B

Image B: CrossOak_June28.

PlanetScope 3-meter resized image of the Cross Oak Hillfort captured June 28, 2018. The image is displayed in visible light using bands 1, 2, and 3.

The crop circle studied in this paper is denoted by the arrow.

The town of Talyont-on-Usk is visible in the center of the image.

C

Image C: Tregaron_July7.

PlanetScope 3-meter resized image of Castel Lywun Gwinau captured July 7, 2018. The image is displayed in visible light using bands 1, 2, and 3.

The crop circle studied in this paper is denoted by the arrow. Adjacent to the study site is an active farming operation which retains ownership of the land in which the buried ruins of Castel Lywun Gwnau are located.

3.2) LiDAR Data

There are multiple studies mentioned above that have involved the use of LiDAR data for the detection of subsurface ruins on the Brú na Bóinne World Heritage Site. LiDAR data for the World Heritage Site is available at a cost via the Ordnance Survey of Ireland (OSI), thus will not be directly incorporated into this study.

Wales has an open database of LiDAR data[2] available as a Composite Digital Terrain Model (DTM). This data, made available by Natural Resources Wales (NRW), uses up to 100,000 aircraft to ground laser measurements per second, which generates terrain models with a spatial resolution between 0.25 to 2.00 meters ("Wales Composite LiDAR Dataset," 2018). The DTM topographic measurements have an absolute height (vertical) error of less than ± 15cm, for more recent data NRW expects the relative height error to be no more than ± 5cm ("LiDAR Guidance 2018, NRW," 2018). Horizontal (planar) accuracy for NRW LiDAR data is ± 40cm, and is determined by specifications provided by the manufacturer of the instrument: 1/5500 x altitude (meters above ground level) ("LiDAR Guidance 2018, NRW," 2018).

This study makes use of the 2-meter DTM at the Cross Oak Hillfort site and the 1-meter spatial resolution DTM at the Castel Lywun Gwinau site (*Figure 14*). The variation in spatial resolution of the DTM at each of the sites is a factor of data availability, although NRW's composite dataset covers approximately 70% of Wales, the majority of that area is covered at the 2-meter resolution ("Wales Composite LiDAR Dataset," 2018). The areas for which 1-, 0.5-, 0.25-meter is available is significantly less. The highest resolution available is used for each site as smaller terrain features will be visible with a smaller spatial resolution.

[2] Wales LiDAR Data: https://lle.gov.wales/GridProducts#&data=LidarCompositeDataset

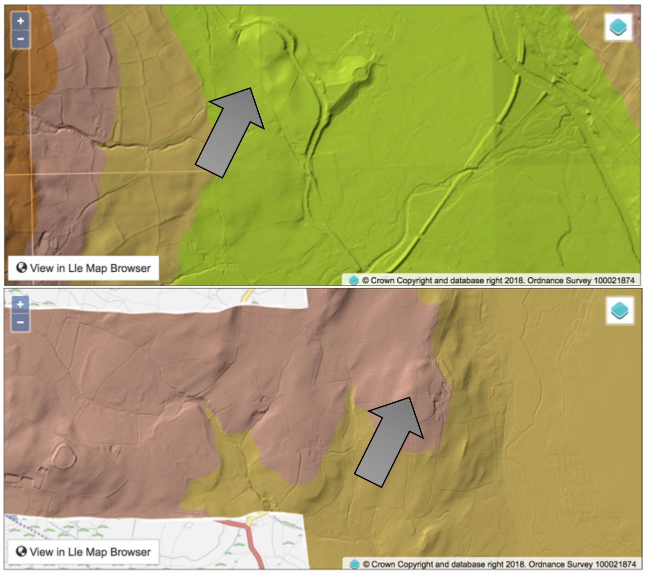

Figure 14 |
TOP: LiDAR DTM of Cross Oak Hillfort at 2-meter spatial resolution.

BOTTOM: LiDAR DTM of Castel Lywun Gwinau at 1-meter spatial resolution.

The arrows denote the terrain in which the studied crop circles sit in each of the respective images.

These images are screen captures from the Lle Composite Dataset Previewer.[2]

4) Methods

4.1) Satellite Multispectral Imagery Survey and NDVI

This study uses multispectral imagery, which has proven useful for detecting subtle crop marks caused by subsurface ruins of previous civilizations (Megarry & Davis, 2013). In addition to spotting patterns in fields in the visible part of the electromagnetic spectrum, a Normalized Difference Vegetation Index (NDVI) was generated for each image and location in order to determine how the crops are affected by the drought. NDVI relies upon the absorption within the red region of the spectrum (600-700 nm), where chlorophyll in plants absorbs light when vegetation is healthy to undergo the natural process of photosynthesis (Lasaponara & Masini, 2007). For healthy vegetation, NDVI processing returns a value closer to +1. As vegetation becomes stressed, more light is reflected by plants in the red part of the spectrum (Weier & Herring, 2000). This is known as a “blue shift,” where the red edge moves toward the blue end of the spectrum and will result in an NDVI score closer to that of -1. No score of less than 0 will result for any calculation involving vegetation. NDVI is a practical index as it reduces the effects caused by atmospheric contaminations, and is calculated using the mathematical formula: NDVI = (NIR — RED) / (NIR + RED) (Lasaponara & Masini, 2007; Weier & Herring, 2000; Harris Geospatial Solutions, 2018a).

The NDVI images for each of the three study sites were then classified using a density slice; this groups ranges of NDVI values together and is useful for observing trends in the NDVI data. Customized ranges were made for each of the three research locations which sought to isolate the crop circles from their surrounding crops (*Figure 15*).

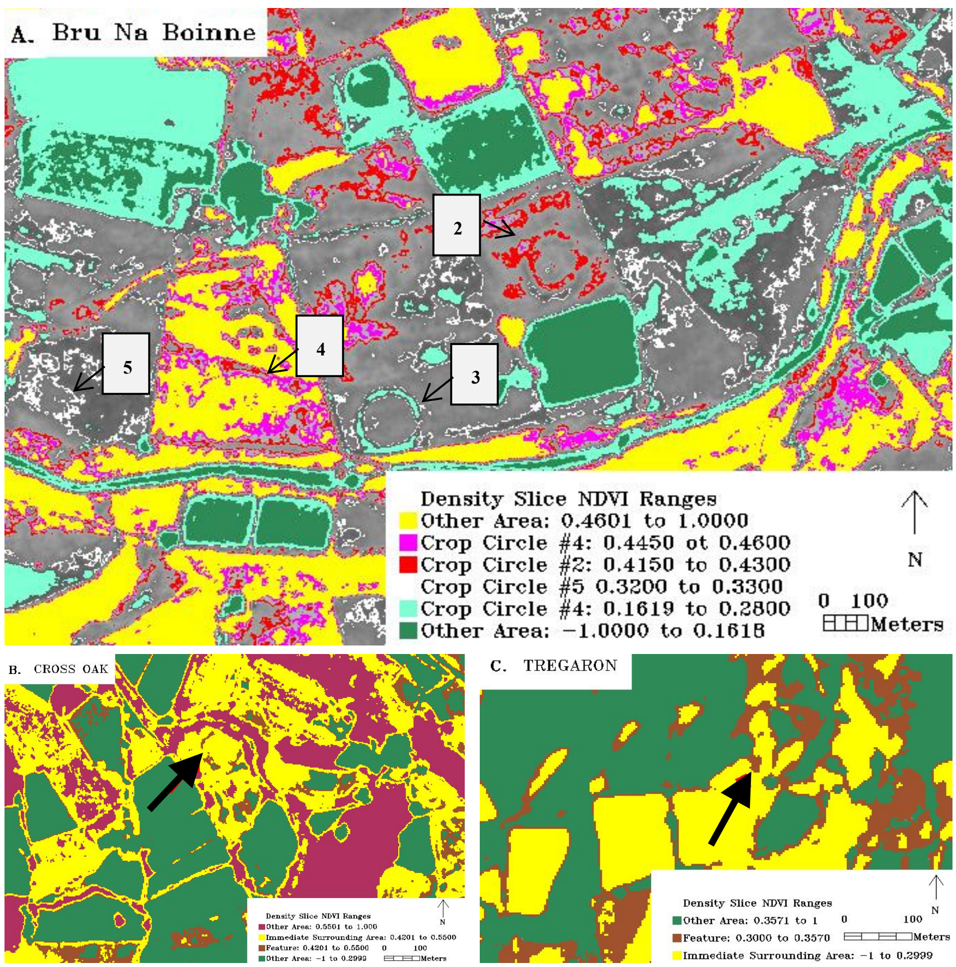

Figure 15 | Images of the three density slices performed for NDVI analysis.
A) the Brú na Boínne World Heritage Site with the five main crop circles categorized by colour and NDVI Range, they are labelled according to Figure 5.
B) Cross Oak site with the crop circle feature denoted by the black arrows.
C) Tregaron site with the crop circle feature denoted by the red arrow. There are numerous other circles similar in scale to the solid crop circle - these circles are trees or large shrubs.

4.2) Applications of Light Detection and Ranging (LiDAR)

A newer approach to remote sensing has been conducted using Light Detection and Ranging (LiDAR) surveys. LiDAR is well suited for the landscape of the Brú na Bóinne World Heritage Site and Wales sites as many low relief land features may otherwise go unnoticed when using methods of fieldwalking or aerial photography. This study employed similar LiDAR processing techniques to Megarry and Davis (2013; *Figure 16*) for data at Cross Oak and Tregaron. First elevation contours were set at 10 meters increments around the location of the buried ruins. Two spatial profiles were then drawn across the features and spatial profile graphs were produced. The spatial profile graphs generated from the topography of the two sites were then broken down into two components. One being the height of the hill in which the features sit, and the second being the height of the features themselves as measured from the top of the hill.

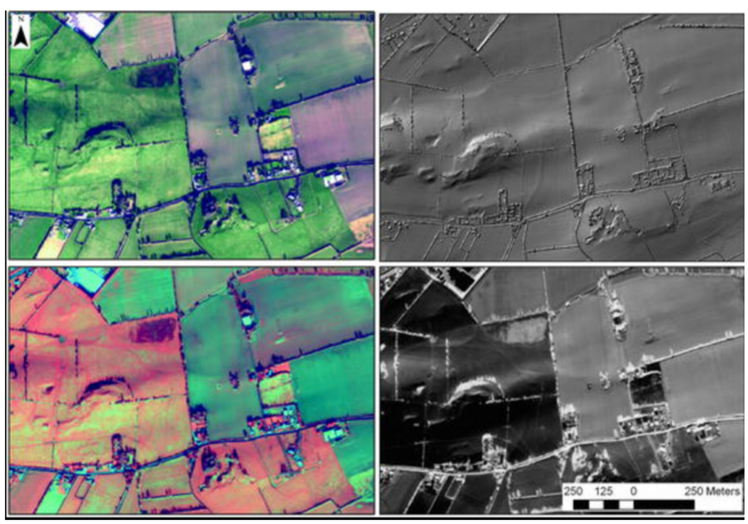

Figure 16 | Composite image displaying the analysis methods used on the World Heritage Site in a study done by Megarry & Davis (2013).
Top left*: Pan-sharpened Worldview2 RGB image.*
Top right*: Lidar hillshade model (Azimuth 315°, Inclination 45°).*
Bottom left*: Pan-sharpened NDVI index generated using Worldview2* red *and* red *edge bands.*
Bottom right*: Tasseled-cap transformation showing wetness (Coefficients from Yarborogh and Ravi* forthcoming*)*
(Megarry & Davis, 2013)

Due to anthropogenic activities such as field plowing, surface features have had their topographical signatures extended over a larger area, smoothing out their topographical relief (Megarry & Davis, 2013). In order to extrapolate the features from the landscape more clearly a hillshade was generated for each image, where the elevation contours and spatial profile pathways were overlain. For Cross Oak the hillshade's sun elevation angle was set to 20 degrees, while the sun azimuth angle was set to 145 degrees. In turn, Tregaron's hillshade was composed at a sun elevation angle of 50 degrees and a sun azimuth angle of 50 degrees. These angles chosen as they produce the best feature visibility and clarity. A Roberts filter was then added to each image to further improve edge detection clarity (Harris Geospatial Solutions, 2018b). The combined hillshade and Roberts image file was then draped across the DTM, displaying it in 3D where a vertical exaggeration was applied to the LiDAR DTM's surface elevation values in 1x, 2x, and 5x to extend patterned features, thus making them more detectable (*Figure 17*). The limit as to what features are detectable with LiDAR is directly correlated to the spatial resolution and accuracy of the data set (*3.2 - LiDAR Data*).

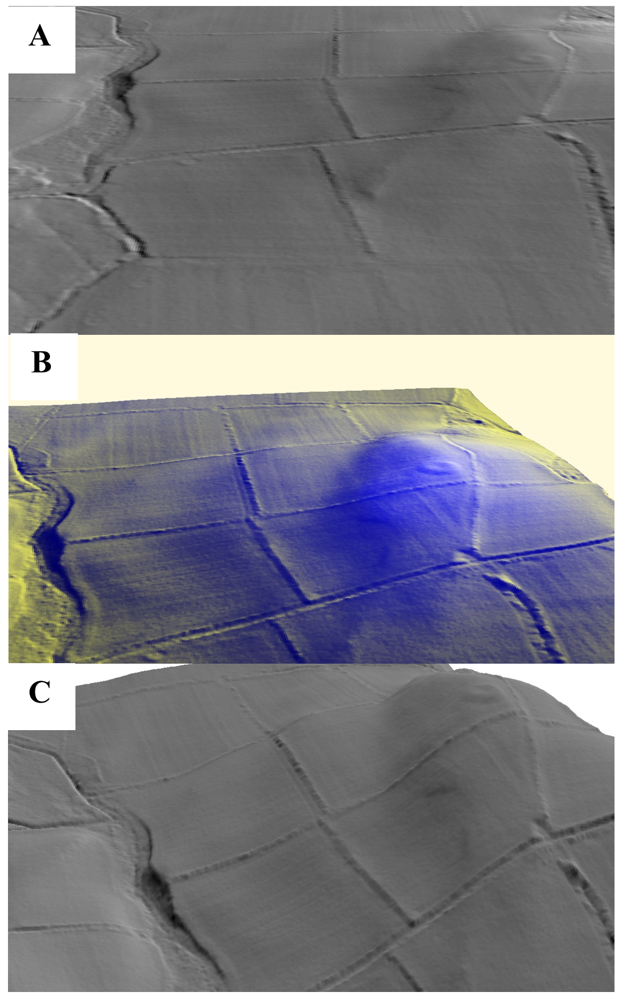

Figure 17 | Hillshade of Cross Oak Hillfort show draped across the LiDAR DTM facing north. Vertical exaggeration has been modified for each image: A-1x, B- 2x, C-5x.
The Colouring in image B corresponds to band variation in the Hillshade, denoting the blue as higher elevation.

5) Results

5.1 – NDVI Results

None of the crop circles on the Brú na Bóinne World Heritage Site exhibit any overlap in their respective NDVI ranges when classified using density slice analysis (*Table 1*). Pattern interpretation with NDVI is similar in results to that of visible light analysis, but for the sites examined in this study, it is less effective for observing surface patterns than looking at visible- or infrared-spectrum during times of drought. Crop circles 4 and 5 are faint but are visible in the NDVI image, however, the range in which the circles exist is surrounded by a distribution of similar values (0.4400 – 0.5000 0.3000 – 0.3200 respectively), which makes the features difficult to distinguish. When this range is narrowed (*Table 1*), the formations do become more distinct, but they are still relatively blended into the surrounding field. These two features only became detectable after enhancing the stretch of the NDVI results at the Brú na Bóinne site. The crops surrounding circles 2 and 3 display a similar NDVI range although the features are located in separate fields; this relationship is not present between crop circles 4 and 5 (*Figure 5*). From the classification, the width of the rings which compose crop circles 2 and 3 were determined to be approximately 13 meters and 15 meters respectively while crop circles 4 and 5 are not broad enough for an accurate measurement to be attained. Non-circular land features such as the cursus adjacent to the Newgrange passage tomb (*Figure 15*) are not detectable using NDVI density slice classification. None of the crop circles on the Brú na Bóinne World Heritage Site exhibit any overlap in their respective NDVI ranges when classified using density slice analysis (*Table 1*). The crops surrounding features 2 and 3 are have a similar NDVI range. From the classification, the width of the rings which compose crop circles 2 and 3 were determined to be approximately 13 meters and 15 meters respectively. Pattern interpretation with NDVI is similar in results to that of visible light analysis, but for the sites examined in this study, it is less effective for observing surface patterns than looking at visible- or infrared-spectrum during times of drought (*Figure 10; Figure 11; Figure 15*).

In Wales, the NDVI range of NDVI values for the crop circle displaying the existence of Cross Oak's hillfort (*Table 1*). does not form a complete circle when a density slice overlay is performed but is the optimal range to separate the formation from the surrounding crop and depict portions of the circular formation. From the NDVI classification, the width of the Cross Oak annulus is determined to be approximate 7.5 meters. The area surrounding the crop circle both inside and outside covers the same NDVI range and has higher NDVI values than that of the formation (*Table 1*). Vegetation in the Usk River valley with a higher NDVI range of 0.5700-0.6300, prevents completion of the north-east portion of the crop circle. The Tregaron crop circle's NDVI range (*Table 1*) forms a solid circular feature when classified and covers an area of approximately 423 meters squared with a diameter of 16.8 meters. The NDVI values of the surrounding area are lower than the values depicting Castel Liwyn Gwinau.

Table 1

NDVI Analysis Data			
	Site Feature	**NDVI Range**	**Pattern**
Brú na Bóinne	Crop Circle #2	0.4150-0.4300	Circular Outline
	Crop Circle #3	0.1619-0.2800	Circular Outline
	Crop Circle #4	0.4450-.4600	Visible, not distingushed
	Crop Circle #5	0.3200- 0.3300	Visible, not distingushed
	Newgrange Cursus	-	Not Visible
Cross Oak			
	Crop Circle	0.3800-0.4200	Semi-Circular Outline
	Surrounding Area	0.4201-0.5500	
Tregaron			
	Crop Circle	0.3000-0.3570	Solid Circle
	Surrounding Area	0.1700-2.999	

Range of NDVI values for each crop circle. The features for the Brú na Bóinne site are numbered according to Figure 5.The NDVI ranges of the area surrounding the features at the respective sites displays the variation in health that the crops circles experience. For the World Heritage site, the NDVI ranges of the crops surrounding the features are not included in this table as they vary between different fields.

5.2 – LiDAR Results

The height change of the topography (*Table 2*) in which the features are located was calculated from a location in the adjacent field where the hill slope levels off in the surrounding fields to the outer edge of the crop circles (*Figure 18*). The average slope of the two arbitrary transects performed on the CrossOak site is 35 ± 3 degrees and for Castel Liwyn Gwinau in Tregaron the average slope is 14 ± 1 degrees. The slope of the hills were calculated from the spatial profile graphs (*Figure 19*) to determine how significant the hills are compared to the surrounding topography.

Table 2

LiDAR Analysis Data					
	Spatial Profile	Hill Height	Hill Slope	Annulus Height
Cross Oak	Profile 1	8.9 m	44.5 degrees	NA
Cross Oak	Profile 2	6.9 m	26.8 degrees	NA
Tregaron	Profile 1	7.0 m	12.1 degrees	0.285 m
Tregaron	Profile 2	12.0 m	16.0 degrees	NA

Results of spatial profile analysis for each of the two research sites in Wales. Height is calculated from each end of the two spatial profiles then averaged for each site. At the Cross Oak site, the height of the Usk River was used as the base reference point and the height of the plateau for the high point, the Tregaron site used the point at which the hill levels out to the surrounding land as the base and the top of the crop ring for the top. The slopes were calculated from the same arbitrary locations as the height.
A topographical height change for the crop circle's annulus was only detectable at the Tregaron site, in which spatial profile #1 was analyzed.

In order to measure the topographical significance of the crop circles, the outer and inner edges of the formations were measured to the highest point on the annuli. The spatial profile of Cross Oak Hillfort represents a plateau, with embankments on all sides and a flat portion in which the perimeter of the Hillfort is perceptible by the crop markings. The crop circle's annulus is coincident with the elevation of the plateau and has no detectable elevation change from its edge to its innermost portion. The plateau has a linear elevation change of approximately 2.0 ± 0.2 meters from one side of the to the other when measured east-west. Tregaron's spatial profile graph (*Figure 19*) does display topographical relief of the crop circle's annulus with a height of 0.4 ± 0.2 meters in addition to that of the hill in which it is located on. At the center of the crop ring, a negative relief feature dips down to the approximated natural height of the hill (225.0 ± 0.2 meters above sea level). Both of the studied features are the largest formations their respective landscapes within a one-kilometer radius (*Figure 20*).

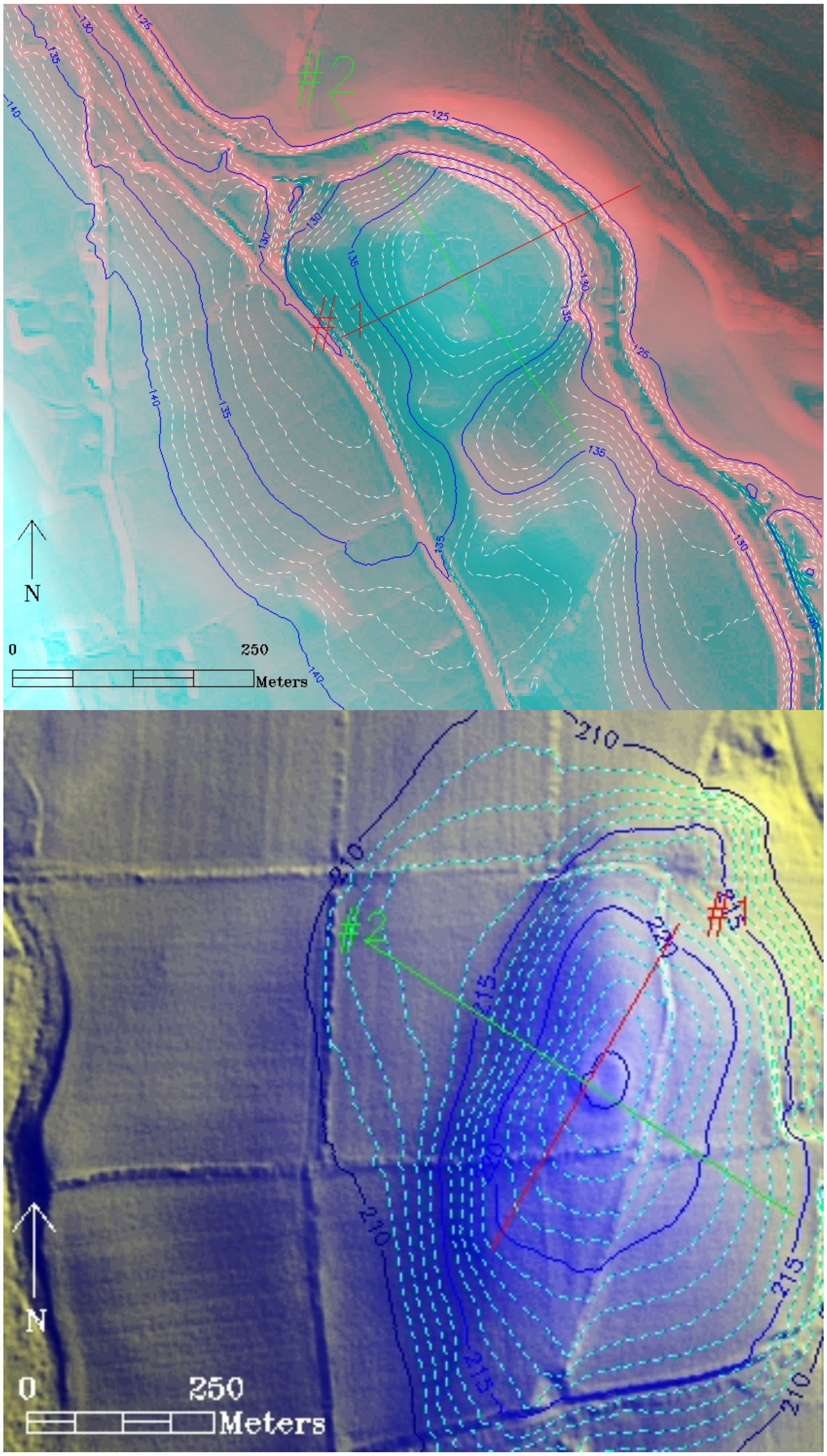

Figure 18 | Displays topographical hillshade maps of Cross Oak Hillfort (TOP) and Tregaron's Castel Liwyn Gwinau (BOTTOM). The maps were produced from LiDAR data where the sun elevation angle was set at 20 degrees and 50 degrees, and where the sun azimuth angle was 145 degrees and 50 degrees for Cross Oak Hillfort and Tregaron respectively. The elevation contour lines are set at 1-meter intervals where the total elevation is measured in meters above sea level. The two straight perpendicular lines which transect the features are the paths in which the spatial profile graphs (Fig ure 19) were drawn.

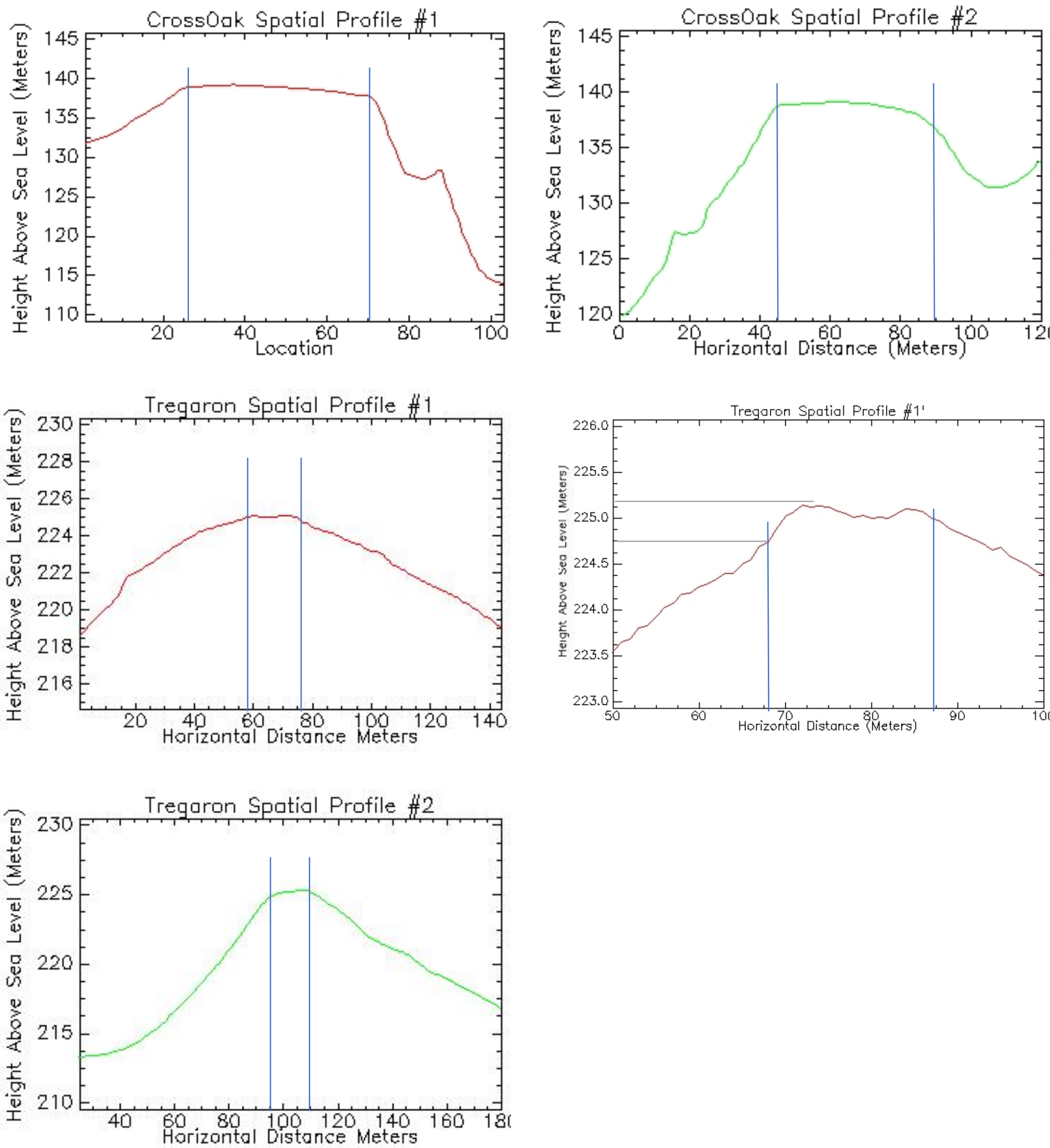

Figure 19 | Graphs display the spatial profiles (SP) of the two Wales sites: Cross Oak and Tregaron. The profiles of Cross Oak were drawn from south-west to north-east and north-west to south-east respectively. While the profiles of Tregaron were drawn from north-east to south-west and north-west to south-east. In Cross Oak's SP#1 and SP#2, the plateau formed by the ringfort is visible between the vertical line markers and shows no indication of any elevation change denoting the crop mark. The SP of Tregaron does display an elevation change on top of the hill, indicative of the annulus forming the crop circle (located in the region between the vertical lines on Tregaron SP#1, #1' and #2). SP#1' is a larger scale profile of Tregaron SP#1 and the height change of the crop circle's topographical relief is visible. The formation begins at 224.75 meters and reaches a maximum height of 225.125 meters above sea level.

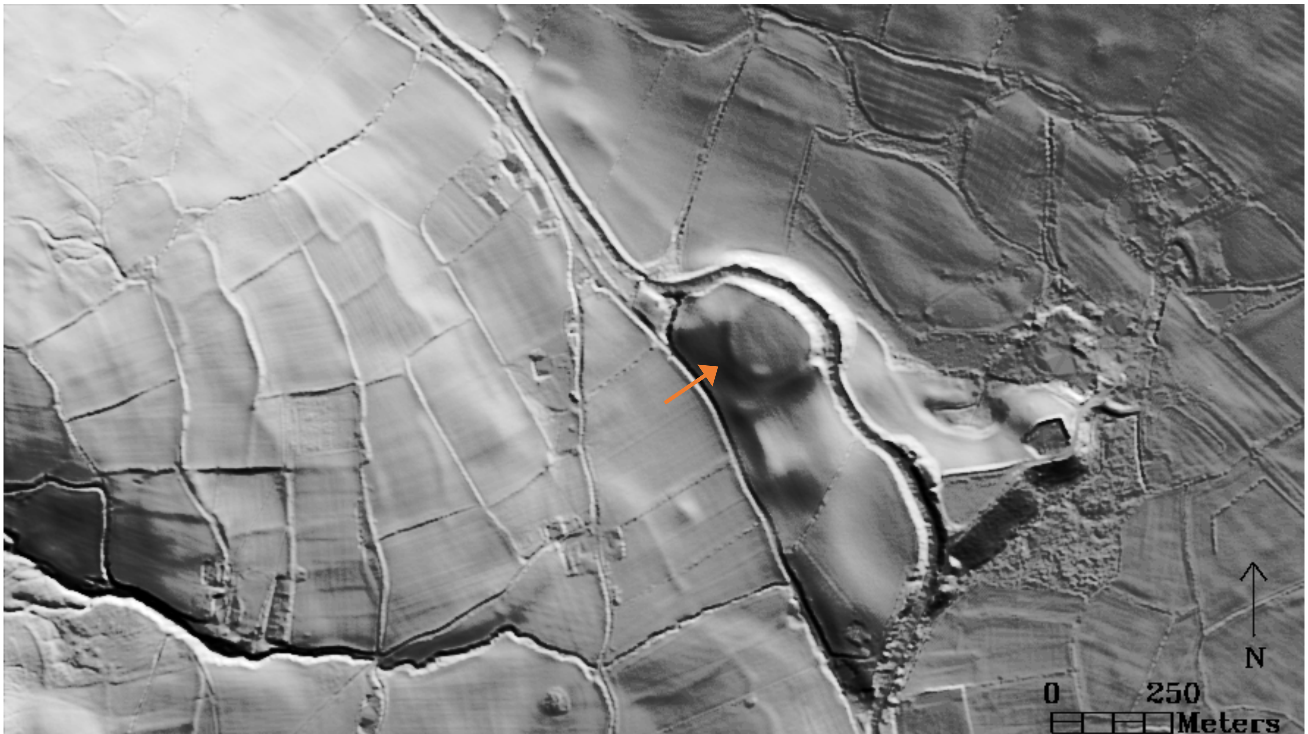

Figure 20 | TOP: Surrounding topography hillshade maps of Cross Oak Hillfort (TOP) and Castel Liwyn Gwinau (BOTTOM). The features are denoted by the arrows and clearly are the dominant features in the surrounding area.

6) Discussion

6.1) NDVI as a means of detection

This study used NDVI analysis on the drought generated crop circles to provide insight to the complexion of the subsurface ruins. Cross Oak displays a lower NDVI range compared its surrounding area, meaning that the crop composing the marking is suffering from the drought more so than the surrounding area (Weier & Herring, 2000). Tregaron's crop mark exhibited a higher range and therefore was healthier compared to the surrounding crop. The variability in how each crop circle responds to the drought is directly related to the type of ruins that lie beneath each feature (Melillos et al., 2016). Ruins that help the soil retain moisture have a higher NDVI value during drought conditions as the crops have more water available to them than the surrounding area which has no subsurface structures and allows water to permeate equally. These types of ruins are often former ditches or moats with a less permeable shell allowing the retention of soil moisture. (*Figure 21*) (Kiesow, 2005; Melillos et al., 2016). The inverse is true for ruins which are made of a denser material and thus shed subsurface moisture more effectively (Melillos et al., 2016). The denser feature causes the crops above to suffer and return a lower NDVI value (Kiesow, 2005).

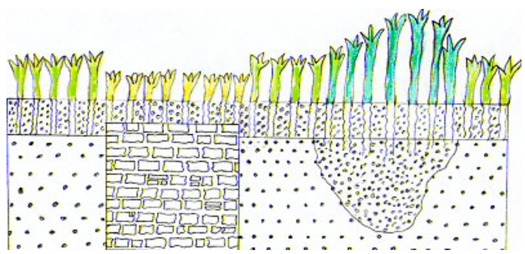

Figure 21 | Water shedding subsurface features (left) have a more dense composition to the surrounding soil, resulting in a moisture deficit and causes the above crop to suffer more readily (lower NDVI value). Compared to the infilled ditch (right) with a less dense composition retaining moisture benefiting the crop (higher NDVI value). (Melillos et al., 2016)

The previously known crop marks 2 and 3 at Brú na Bóinne are both moisture-shedding in nature and crop circles 4 and 5 detected in 2018 are moisture retaining (*Figure 5A*). A bias in detectability was initially considered towards moisture-shedding subsurface features as a much greater difficulty detecting circles 4 and 5 was experienced at the Brú na Bóinne World Heritage

Site (*Figure 15*). This bias was then disproven as both types of subsurface features are equally detectable at the sites in Wales. Therefore, there is no correlation between the type of subsurface ruin (moisture retaining or shedding) and its detectability. Qualitative analysis of the aerial visible light images produced identical conclusions to the NDVI: the crop circles which retain moisture during the drought are greener, while the crop circles which shed moisture are more yellowed and dry looking compared to the neighbouring crops and both are detectable.

When paired with other remote sensing tools such as LiDAR, NDVI can be used to determine the size and width of features if they are detectable – as was conducted in this study. However, NDVI classification is not the optimal means of providing dimensional characterises to support LiDAR analysis, as significant difficulty was encountered finding multispectral satellite data. For the type of analysis conducted in this study satellite imagery is required to have a very high spatial resolution (sub-3-meters) which not readily available within the public domain. Detection limitations were experienced at Brú na Bóinne crop circles 4 and 5, which were detectable under NDVI classification but were not well defined when compared to circles 2 and 3. Alternative detection methods such as aerial photography may be favourable as it is a less intensive analysis method and allows for crop health to be interpreted qualitatively rather than quantitatively. Drone technology was responsible for the new discovery at Brú na Bóinne (*Figure 5*) (Hutton, 2018) and has proven to be a compelling low-cost means for gathering aerial photography.

NDVI is not an effective method for conducting buried-ruin detection surveys as no trend was observed in the NDVI ranges of the crop circles (*Table 1*). As a result, no pattern can be applied in order to detect new sites. If a pattern had been present in the data, then ring-like features which display a similar change in their NDVI range could have had the potential to be subsurface ruin locations. As that is not the case, NDVI analysis provides no means for reliably detecting new sites without already knowing that the site is of interest. Additionally, NDVI relies on a change in crop health; thus, drought is still a necessary component when using NDVI analysis. The qualitative NDVI range is dependent on the type of crop species, which are each affected at varying levels of severity during drought (Weier & Herring, 2000). Without knowing the crops constitution, the measured NDVI range provides no useful data to enable further discoveries.

6.2) Using LiDAR as a means of detection

Using the LiDAR-based DTM, a height change in the topography of the crop circle was detectable for Castel Lwyn Giwnau; however, Cross Oak Hillfort did not display any detectable height change to its annulus. The Tregaron Castel was analyzed using a 1-meter LiDAR DTM while Cross Oak had a spatial resolution of 2-meters. This discrepancy in the LiDAR's spatial resolution is unlikely to have had an effect on the features' detectability as NDVI analysis of the hillfort estimated the width of the annulus to be approximately 7.5 meters. Therefore, the 2-meter spatial resolution would have not inhibited detectability of the hillfort. A second possibility as to why the Cross Oak annuli was not detectable may be due to the vertical resolution of the LiDAR data. Assuming the minimum detectable height change to be equal to that of the LiDAR data's expected error (*3.2 - LiDAR Data*), no feature under 0.15 meters would be detectable. It is plausible that a height change does exist within this range, although such a minimal change would be too insignificant with respect to the surrounding area to be considered a definite detection.

Both sites are located in operational farmlands and anthropogenic tilling activity is speculated to have caused significant enough damage to the Cross Oak site that the annulus' topographical relief has been blended seamlessly to the surrounding cropland leading to a speculated correlation between site age and relief (*Figure 22*). Cross Oak Hillfort has its origins dated to the Iron Age (Driver, 2018b), and while Castel Liwyn Gwinau has no specific date known to researchers, the age of other timber castles in Wales can be used as an approximation, providing an estimated date of existence to the medieval period around the eleventh or twelfth-century C.E ("Castell Llwyn Gwinau," 2016; Driver, 2018a). Without physical excavation and absolute dating of remains on the sites, the time estimates dictate that the hillfort at Cross Oak significantly predates that of Castel Liwyn Gwinau at Tregaron by around 1800 years. The time difference between the sites means that the hillfort at Cross Oak would have undergone a greater amount of resurfacing then Tregaron, hence why and annulus height change for the latter is currently detectable while the former is not. There are two factors that directly impact the topographical detection of a subsurface feature: one being the age of the feature, while the other being is its exposure to resurfacing. Based on this premise it is possible for a younger feature to not be detectable while an older feature is given that the younger one would have undergone a greater amount of resurfacing.

Figure 22 | Modern tilling of the farmland is capable of smoothing out both positive and negative relief features where the subsurface formations then only become distinguishable by the formations they inflict on the crops above them. The greater number of times the surface is retiled the more continuous the signatures of the ruins will be with the surrounding landscape, making them less and less distinguishable.
("RCAHMW | Cropmarks 2018," 2018)

The detection of the hills in which the crop circles are located was achieved through hillshade processing of the LiDAR data. A hillshade with lower sun angles emphasize smaller variations in topography than the base DTM which are less visible because of the display stretch. LiDAR is an effective tool for determining topographical properties for the crop circles and is used for calculating the corresponding hill height and slope. Both hills are the dominant features in their respective landscapes within a 1-kilometre radius and share similarities in height range (6.9 – 12.0 meters). The slopes of the hills vary by an average of 21 degrees due to the Usk River steepening the embankments at the Cross Oak site. These insights suggest that subsurface ruin detection using LiDAR is possible outside of drought conditions. However, the size of the features with respect to the vastness of the British Isles means that detection based on visual interpretation of topographical change would be difficult to detect even when observed by a trained human eye. Further investigation into the topographical trends exhibited by the ruins would allow for the aid of algorithmic detection, thus narrowing down possible site candidates.

7) Conclusion

The 2018 drought in the British Isles enabled the discovery of new ancient ruin sites piquing the interest of researchers. NDVI analysis of crop marks was determined not to be a functional method for determining new subsurface ruin locations as it directly relies on a change in crop health inflicted by drought conditions. NDVI may be used to provided additional feature information to that provided by LiDAR such as annulus width and size; however, optical aerial imagery is capable of providing the same insights with less intense processing and is there for a more practical pairing to support LiDAR based detections.

This study observed a correlation between site age and detectability, where the topographical relief of the older subsurface ruins were not detectable while the newer ruins were. LiDAR as a primary means of detecting subsurface features outside periods of drought is possible, particularly using hillshade images, but is not practical without the aid of algorithms which would use the established subsurface ruin characteristics to narrow down site candidates. No trend was observed in the type of subsurface ruins, be it either moisture shedding or retaining, this would also provide a subsequent study with the largest possible sample size. While the hill height of both features in Wales were observed to exist within a similar range (6.9-12.0 meters above local mean), a larger sample size could test detectability in other environments such as a feature on a completely flat terrain like those observed at Brú na Bóinne. Further investigation into the how long the features remain detectable is needed to support this theory further but would require a large sample size with a wide variety in ruin age.

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