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Version of attached file:

Accepted Version

Peer-review status of attached file:

Peer-reviewed

Citation for published item:

Kincey, M.E. and Batty, L. and Chapman, H. and Gearey, B. and Ainsworth, S. and Challis, K. (2014) 'Assessing the changing condition of industrial archaeological remains on Alston Moor, UK, using multisensor remote sensing.', *Journal of archaeological science.*, 45 . pp. 36-51.

Further information on publisher's website:

<http://dx.doi.org/10.1016/j.jas.2014.02.008>

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Assessing the changing condition of industrial archaeological remains on Alston Moor, UK, using multisensor remote sensing

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ABSTRACT

Upland environments have the potential to preserve relatively undisturbed multi-period archaeological remains due to reduced anthropogenic impacts such as intensive agriculture. However, these environments can also be extremely fragile and susceptible to alternative pressures from insensitive land-use practices and their dynamic geomorphological setting. This paper presents the results of research focusing on the interactions between industrial heritage sites and their semi-natural landscape context within the upland landscapes of Alston Moor, North Pennines, UK. Change detection using multispectral Landsat data was combined with detailed mapping from airborne lidar, aerial photographs and fieldwork to quantify the rate and nature of the changing condition of selected industrial archaeological sites. Results indicate that extensive degradation has been occurring at a number of former lead mining sites over recent decades, primarily due to fluvial erosion in the form of gullying but with slope and aeolian processes also of significance in particular locations. Soil samples taken from actively eroding areas within Fletcheras Rake, one of the earliest documented lead mines in the area, suggest that the reworking and redistribution of sediments from former mining sites are releasing heavily contaminated sediments into the wider hydrological catchment. It is argued that a more complete understanding of the complex interrelationships and linkages between archaeological sites and the semi-natural environments in which they are situated can only be achieved through the combined application of research methods employed by both the archaeological and geomorphological disciplines.

KEYWORDS

Remote sensing; uplands; industrial archaeology; change detection; geomorphological processes.

1. INTRODUCTION

The potential for archaeological remains within upland environments to survive relatively undisturbed by recent pressures such as intensive agriculture or urban development is now widely acknowledged (Tunnicliffe, 2006; Whyte and Winchester, 2004). Uplands such as the North Pennines have the potential to retain important archaeological sites as upstanding monuments or earthworks; features that would often have been destroyed through activities such as long-term intensive ploughing in corresponding lowland contexts (Coggins, 1986; Darvill, 1986a; Manby and Turnbull, 1986). The extensive peat deposits occurring within many upland environments also provide an excellent archive of palaeoenvironmental data and organic archaeological remains (Gearey et al., 2010; Simmons, 2003).

However, it has also been recognised for several decades that the archaeology within upland environments faces a diverse range of other pressures, both natural and anthropogenic, that threaten the survival of this important resource (e.g. Darvill, 1986b). Insensitive land-use practices coupled with indirect anthropogenic effects such as global climate change are impacting directly and indirectly on environments where thin soils, harsh climates and short growing seasons often predominate, making upland environments overwhelmingly dynamic and fragile. Implementing policies and management practices that maintain or improve core upland ecosystem services can therefore be particularly difficult, with the need to maintain the appropriate balance between the requirements of the direct ‘users’ of upland landscapes, whether inhabitants or periodic visitors, and associated priorities such as carbon sequestration and biodiversity (Bonn et al., 2009; Burt et al., 2002). Within this context, the need to determine practical and effective heritage management strategies is paramount.

Remote sensing has already been used effectively to investigate a wide range of environmental and anthropogenic pressures in upland landscapes, including gully erosion (Evans and Lindsay, 2010), peatland hydrology (Harris and Bryant, 2009), habitat mapping (Poulin et al., 2002), carbon fluxes (Becker et al., 2008) and the effectiveness of peatland restoration (Lowe et al., 2009). Nevertheless, there have been few studies that have attempted to specifically investigate the potential of remote sensing techniques for managing upland archaeological remains, particularly in reference to their wider semi-natural environment (cf. Kinsey and Challis, 2010).

1.1 Context to the research

This paper discusses the results of remote sensing analyses and fieldwork undertaken to assess the changing condition of industrial archaeological remains on Alston Moor in the North Pennines, UK.

Although analysis was designed to focus on the historic industrial remains of the area and so primarily medieval and post-medieval in date, many of the wider implications will equally apply to remains from other periods and site types. The condition of the archaeological resource was assessed in relation to evidence for erosion processes within the surrounding landscape, such as the presence of landforms such as gullies, debris fans and relict stream channels. Multi-temporal imagery was used to quantify the extent of change over time through an assessment of how the form and nature of the archaeological sites has altered through recent decades.

The extent and severity of erosion in upland environments is often driven by complex interrelationships between a wide range of contributing factors. The nature of the sediments and their vegetation cover provide the context against which a variety of erosion processes, including fluvial, aeolian, slope and frost are constantly acting (Burt et al., 2002; Evans and Warburton, 2010). The sensitivity of upland peatlands to change and degradation in particular is well understood (Charman, 2002; Tallis et al., 1997); with considerable research focusing specifically on peat erosion within the Pennine Chain (Bower, 1960; Evans and Warburton, 2005; Yeloff et al., 2005). The nature and severity of the erosion and its impact on the archaeological resource varies depending on the local situation and specific conditions, with landform evidence such as gullies or arcuate tears providing indirect insights into which particular geomorphological processes are dominating.

The situation in this area of the North Pennines is complicated further by the potential for these processes to cause remobilisation of metal contaminants stored in the archaeological deposits; a long-term legacy of the area's industrial heritage. The role of archaeological remains within the broader source-pathway-receptor framework for assessing land contamination is already widely acknowledged (McCaffrey et al., 2005), with such remains able to act as the source of pollutant mobilisation, the pathway linkages along which mobilisation occurs, or the receptor sites for deposited contaminants. Therefore targeted fieldwork to collect samples for testing the levels of these contaminants and their bioavailability to the wider catchment was also conducted, with the results of this analysis being considered in relation to their likely geomorphological context. The conclusions of the work are discussed in relation to this particular landscape in the UK but are equally applicable to other environments where similar anthropogenic and geomorphological factors co-exist.

The work was part of wider English Heritage research aimed at investigating the archaeological landscapes of the North Pennines Area of Outstanding Natural Beauty (AONB) (Ainsworth, 2008). This multidisciplinary research aimed to use diverse techniques including remote sensing, field survey and historic area assessments to better understand the historic environment of the area. Emphasis was

placed on recording evidence for the exploitation of mineral resources, principally lead extraction and processing, and farming; the twin practices that have historically dominated the economy of the area. The recording of these ‘miner-farmer’ industries went alongside research into the complex interplay between historic land-use practices and the surrounding semi-natural environment, with the intention being to generate an assessment of potential future impacts. This paper outlines the results of one aspect of the overall project, the use of multisensor remote sensing techniques to record and assess the condition of archaeological sites within the Alston Moor landscape (Kincey et al., 2011).

1.2 Study area

Analysis focused on a 32 km² area of Alston Moor (central NGR: NY755440), incorporating sections of the valleys of the River South Tyne to the south and the River Nent to the north, as well as a sizeable area of upland moor crossing Middle Fell and Flinty Fell; an altitudinal range of 250-670m AOD (Figure 1).

Alston Moor is located within the Northern Pennine Orefield, a geological area bounded by the faults marking the Tyne Gap and Stainmore Gap to the north and south respectively, the Pennine escarpment to the west and the former West Durham Coalfield to the east. The geology of the Alston Block consists primarily of Carboniferous age sedimentary rocks that form a series of repeating sequences of limestones, sandstones, interbedded shales and coal measures, known as the Yoredale cyclothems. Igneous intrusions into the network of faults and veins within the Carboniferous rocks resulted in the rich mineral deposits that have driven the industrial exploitation of the area, in particular lead and zinc ores and the associated gangue minerals such as fluorite and barytes (Dunham, 1990). The overall topography of the landscape developed during the last glaciation and through subsequent Holocene processes. The north- to north-east-facing valley slopes were typically covered by boulder clay as the glaciers retreated and are therefore smooth in profile, whilst the south- to south-west-facing slopes tend to have a profile consisting of stepped benches caused by the differential weathering of exposed Carboniferous strata with varying hardness characteristics (Bulman, 2004; Clarke, 2008). Soils in the area are typical of other upland environments with similar geology, comprising slowly permeable acidic loams and clays on the lower valley slopes and blanket bog peat soils on the higher fells.

The landscape is sparsely populated, with the exception of relatively small nucleated settlements at Nenthead and Garrigill, and includes fields on the lower slopes of the two valleys that have been improved with fertilisers and historically kept in constant use primarily for pasture grassland, known

locally as ‘in-bye’ land. At higher elevations the land grades into open heathland, moorland and blanket bog on the fell tops.

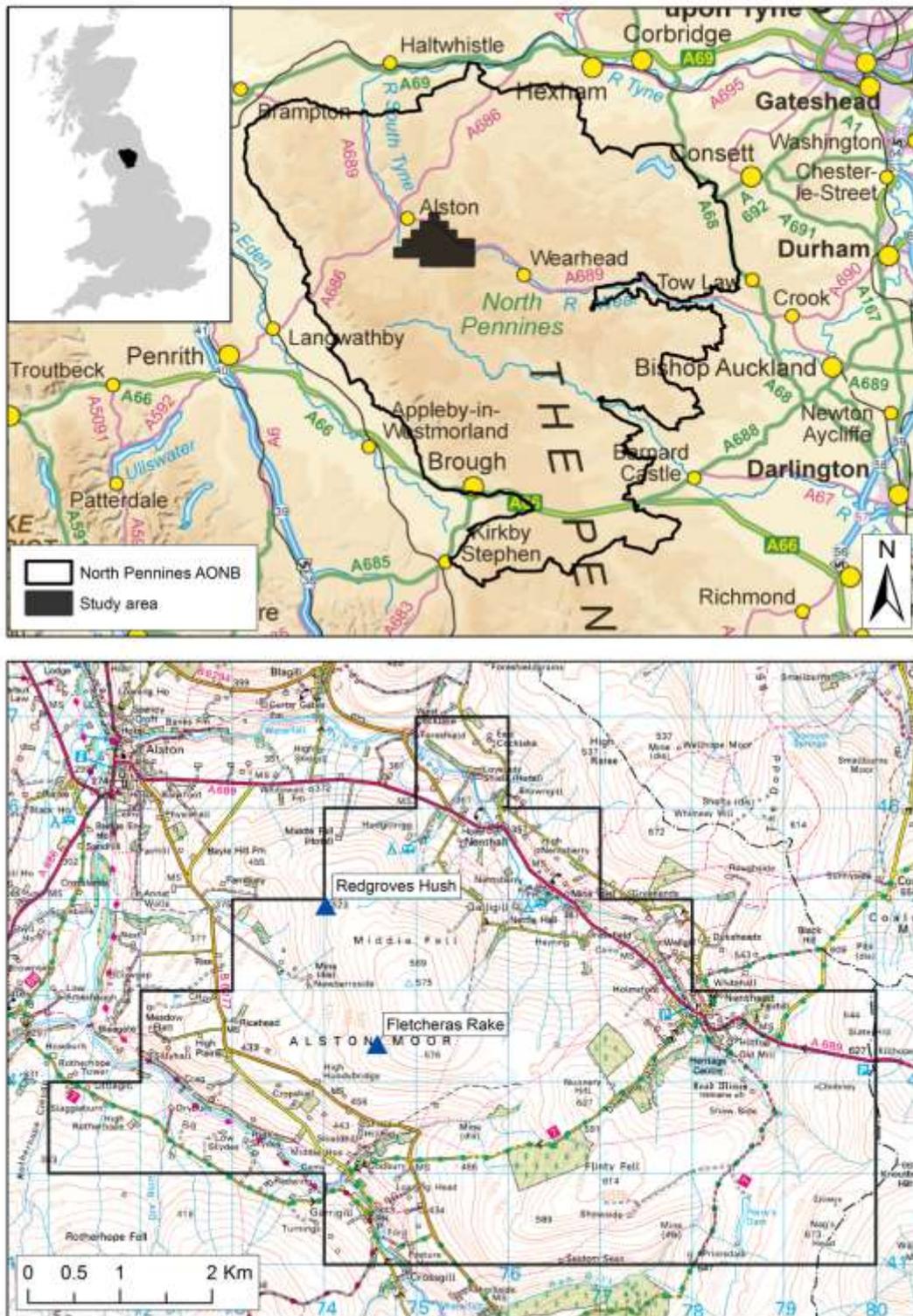


Figure 1. Location of study area (Map data © Crown Copyright / database right 2012. An Ordnance Survey / EDINA supplied service)

The archaeological mapping covered the entire study area but with two locations selected for more detailed analyses in order to better characterise detailed process interactions and patterns of change: the surface lead workings and hush at Redgroves (NY734448) (Figure 2) and the lead workings at the Scheduled Monument site of Fletcheras Rake (NY745434) (Figure 3). The main workings at Redgroves were opencast along Redgroves Hush, an artificial ravine caused by the repeated discharge of water from an upstream reservoir in order to clear overburden from surface mineral veins, although with later subterranean workings also accessed from Natrass Level to the west of the hush. The surface workings at Redgroves cover an area of approximately 0.19km², of which 0.025km² relates to the main hush itself. The veins here were leased sometime prior to 1737 and continued to be worked until the late 1860s, primarily for lead ore but with some additional limited zinc extraction (Dunham, 1990; Fairbairn, 1993). Fletcheras Rake extends over 0.23km² and is one of the earliest documented lead working sites on Alston Moor, with the vein being granted to the Duke of Gloucester in 1475 but probably already being worked prior to that date. Large spreads of mine tailings along Fletcheras Rake are thought to date from this period, with later subterranean workings documented between 1736 and 1873 (Fairbairn, 1993).

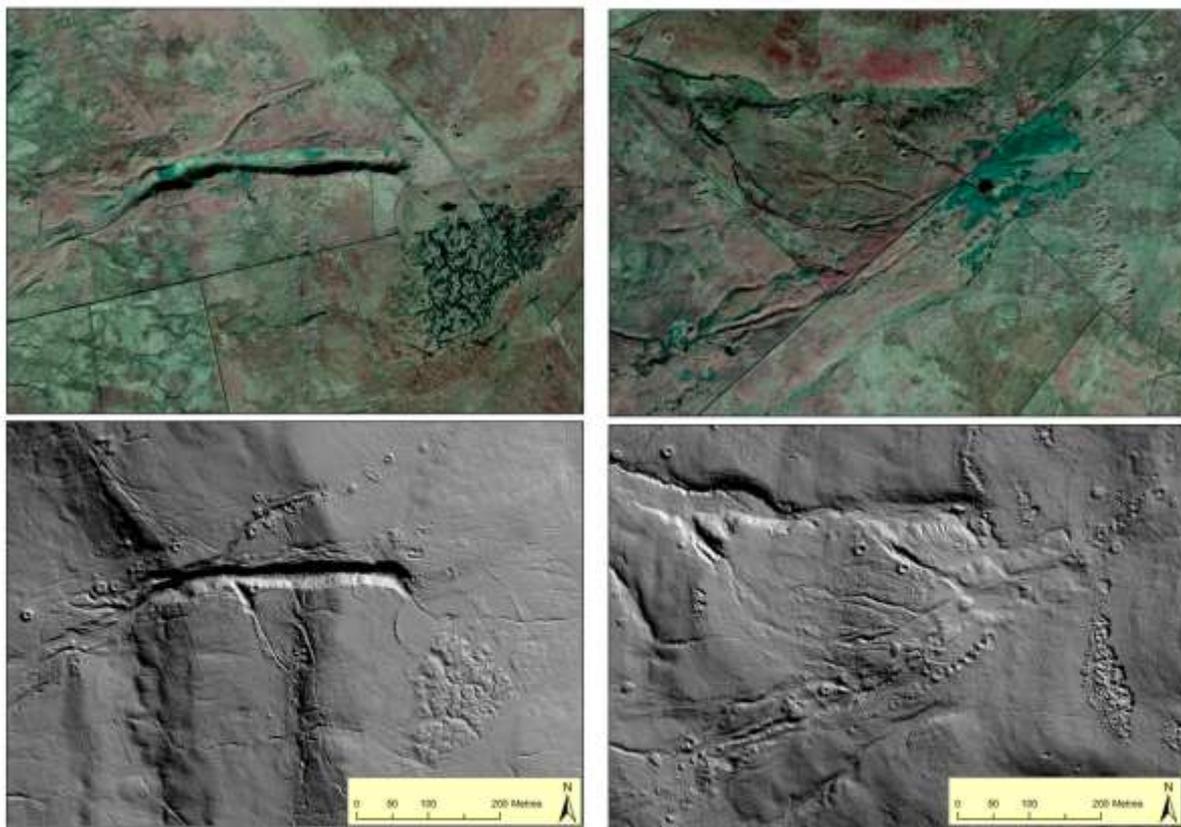


Figure 2. (left) Colour-infrared aerial photograph (top) and hillshaded airborne lidar image (bottom) showing industrial features at Redgroves Hush (Photography © English Heritage)

Figure 3. (right) Colour-infrared aerial photograph (top) and hillshaded airborne lidar image (bottom) showing industrial features at Fletcheras Rake (Photography © English Heritage)

The main objectives of this study were:

- (i) to use airborne remote sensing to generate a baseline record of the industrial archaeology of Alston Moor.
- (ii) to use multi-temporal satellite imagery to assess patterns of change to selected archaeological sites.
- (iii) to test the significance of these changes through targeted fieldwork at a single site, including soil sampling and lab analysis for metal contaminants.
- (iv) to use the results of the research to better understand the interactions between geomorphological processes and archaeological sites in upland environments.

2. DATA AND METHODS

2.1 Archaeological mapping

To establish a baseline archaeological record against which to assess issues of threat and change, a rapid mapping exercise was conducted across the entire 32km² study area based on analysis of a range of airborne remote sensing data. The recording was limited to areas of industrial heritage as this was the primary focus of this aspect of the research, and was designed to supplement the much more detailed mapping carried out by the English Heritage aerial survey (Oakey et al., 2012) and field investigation teams. Archaeological mapping was carried out within ArcGIS with identified features digitised as vector polygons and with relevant attributes being recorded as associated tabular information. Features indicative of active erosion, such as pronounced gullies, were digitised to a separate layer in order to provide a point-in-time assessment of landscape condition. The primary data used for mapping were airborne lidar data, colour and colour-infrared aerial photographs and airborne hyperspectral imagery, all collected and pre-processed by Infoterra Global Ltd (Table 1).

Table 1. Airborne remote sensing data sets used for the archaeological mapping

| Data set | Sensor | Acquisition date(s) | Ground resolution (m) | Spectral resolution (nm) | Image processing / analysis methods |
|----------------|---------------------------|---------------------|------------------------|--------------------------|---|
| Airborne Lidar | Optech ALTM Gemini 167 | 24/10/08 | 0.5 (for gridded data) | - | Hillshade PCA (Devereux et al., 2007) |
| | | 27/10/08 | | | Slope / Curvature (Kennelly, 2008) |
| | | | | | Local Relief Models (LRM) (Hesse, 2010) |
| | | | | | Solar Insolation Models |

| | | | | | |
|--------------------------------------|--|----------|-----|----------------------------|---|
| RGB / CIR aerial photographs | Vexcel Imaging UltraCam X (7.2µm pixels) | 12/04/09 | 0.2 | Panchromatic (415-675) | Orthorectification / Colour-stretching (Mather, 2006) |
| | | | | Blue (410-50) | |
| | | | | Green (490- 630) | |
| | | | | Red (585-680) | |
| | | | | Near Infrared (685-910) | |
| Airborne hyperspectral imagery | Specim AISA Eagle | 22/05/10 | 1 | 34 bands | True-colour composites |
| | | 04/06/10 | | (397 – 1001 range) | False-colour composites Vegetation indices (NDVI / TNDVI) (Lillesand et al., 2008) |

2.2 Multi-temporal change detection

Multispectral satellite data in the form of archived Landsat imagery for five epochs between 1977 and 2006 were used for multi-temporal change detection analyses. Data were downloaded as orthorectified TIF files from the Global Land Cover Facility (GLCF) hosted at the University of Maryland (Table 2). The individual bands were all resampled to a 30 metre pixel size in order to match the spatial resolution of the majority of the Landsat bands from each epoch. The MSS Landsat 2 data from 1977 was, however, of a much lower spatial resolution (79m) and although resampled to a 30m pixel size for analysis purposes proved noticeably less valuable for detailed site-scale analyses. The bands from each individual epoch were then stacked within Erdas Imagine to create five separate multiband composite images.

Table 2. GLCF Landsat data sets utilised in change detection analyses

| GLCF ID | WRS notation | Satellite | Sensor | Acquisition date | Year | Spatial resolution (m) |
|---------|--------------------------|-----------|--------|-----------------------|------|------------------------|
| 232-128 | WRS-1, Path 219, Row 022 | Landsat 2 | MSS | 27 th May | 1977 | 79 |
| 205-964 | WRS-2, Path 204, Row 022 | Landsat 5 | TM | 14 th May | 1988 | 30 |
| 205-932 | WRS-2, Path 203, Row 022 | Landsat 5 | TM | 18 th May | 1992 | 30 |
| 214-703 | WRS-2, Path 204, Row 022 | Landsat 7 | ETM+ | 7 th May | 2000 | 30 (Band 8 = 15) |
| 223-235 | WRS-2, Path 203, Row 022 | Landsat 5 | TM | 10 th June | 2006 | 30 |

Landsat data were processed to produce true- and false-colour composites, the Normalised Difference Vegetation Index (NDVI) and the brightness, greenness and wetness outputs of the Tasseled Cap transformation (Campbell, 2006; Crist and Cicone, 1984; Lillesand et al., 2008). The resulting images were visually analysed for gross landscape features such as substantial areas of mining waste, as well as being compared with the higher spatial resolution lidar and spectral data. In order to quantify any temporal variation the change detection methodology established by Barlindhaug et al., (2007) was applied, involving the image differencing of NDVI outputs from each data epoch to provide summary rasters displaying changes in biomass and vegetation cover.

Landsat data were selected due to their similar within-year date (May-June) in order to ensure that the change detection analysis would reflect longer term trends rather than short term phenological variation. However, this approach is based on the assumption that the weather in the months preceding the acquisition dates is broadly comparable. In order to test this assumption more thoroughly historic climate data for the closest available UK Met Office station were obtained and analysed (Newton Rigg, Cumbria, NY493308). The rainfall and temperature data from the years corresponding with the Landsat imagery were tabulated to allow comparison of the weather in the months preceding the satellite acquisition dates.

2.3 Field sampling and laboratory analysis

Fieldwork focused on a programme of vegetation survey and soil sampling at a single site (Fletcheras Rake), aimed at providing data relating to species variation and metal contamination levels that could then be cross-referenced with the results of the remote sensing analysis (Figure 4).

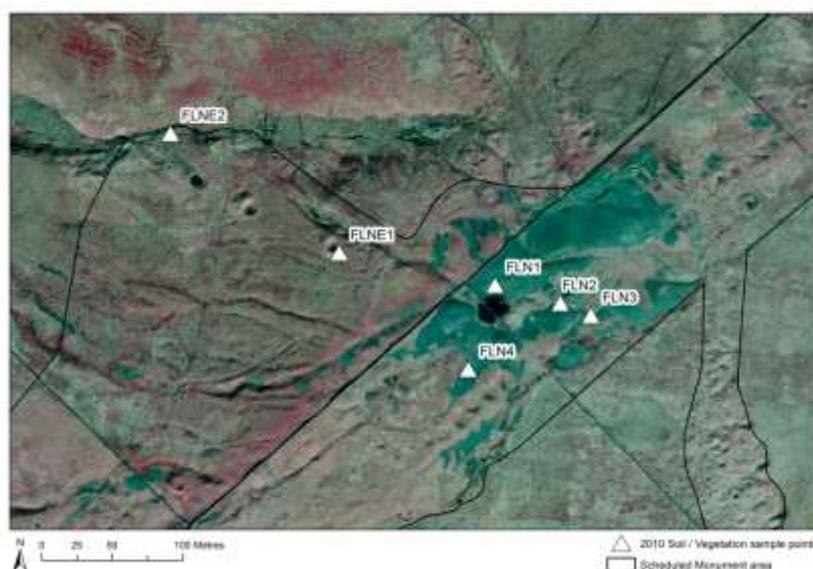


Figure 4. Location of soil samples taken at Fletcheras Rake (Photography © English Heritage)

The aim of the vegetation survey was to establish whether there were distinct vegetation communities at this field site and in particular to determine whether there were metallophyte communities present. A metallophyte is a species that can tolerate elevated metal concentrations within soils and can range from those that are obligate metallophytes (those that depend upon high concentrations of particular metals), facultative metallophytes (those species that can occur on non-metalliferous soils but a specialised ecotype is dependent upon the presence of metals) and accompanying metal tolerant species (Baker et al., 2010; Lambinon and Auquier, 1963). The survey was carried out according to National Vegetation Classification Guidelines (Rodwell, 2006).

Soil sampling focused on two areas of Fletcheras Rake containing representative vegetation and land cover characteristics, with three replicate samples taken at each of six sample locations in order to account for variability. Samples were removed using a 50cm core and divided into 10cm sections to provide an assessment of variation in metal concentrations down the soil profile. Laboratory analysis involved the determination of pseudototal metal concentrations in dried soil using the aqua regia method, and BCR sequential extraction to determine metal content of different geochemical fractions within the soil (Margui et al., 2004). A sub sample of each soil section was left un-dried (fresh) and the novel technique of Diffusive Gradient in Thin-Films (DGT) was applied to measure the metal flux which gives a more accurate measure of the bioavailable fraction of metals. All extracts from the above techniques were analysed using atomic absorption spectroscopy for Fe, Mn, Cu, Zn, Co, Cr, Ni and Pb.

3. RESULTS

3.1 Baseline archaeological record

The rapid mapping identified 1193 features or areas of probable industrial heritage within the study area, suggesting an approximate spatial density of c. 37 extant surface sites per square kilometre (Figure 5). By far the most commonly recorded archaeological features (>80%) were the shafts and shaft mounds associated with historic mineral extraction industries, principally lead mining. The shafts and their surrounding spoil heaps can be identified in long rows following the mineral seams that criss-cross the majority of the study area, with particularly high densities south of Bentyfield Mine and to the south and southwest of Nenthead. Additional features relating to the extractive aspect of historic mineral industries were identified in the form of areas of open face extraction (the small-scale working of a mineral vein exposed in crag or outcrop) and a relatively large number of levels, the surface entrances to the subterranean mining operations. The mapping also recorded numerous examples of the later stages of lead working, including the remains of former dressing floors at Whitesyke Mine, the abundant spoil heaps surrounding the former smelt mill at Nenthead and the

almost kilometre long flue leading southeast from this location to Killhope Cross. The water management features relating to the mining activities were another dominant aspect of the industrial archaeology of the landscape, including drainage channels to remove water from mine levels and the extensive networks of leats, dams and reservoirs used to supply the various needs of the extraction, processing and smelting stages of the mining workflow. Other minerals were worked in the Alston area but it is likely that the majority of these remains relate primarily to the extensive lead mining that dominated the area from at least the 17th Century onwards (Bulman, 2004; Forbes et al., 2003; Turnbull, 2008).

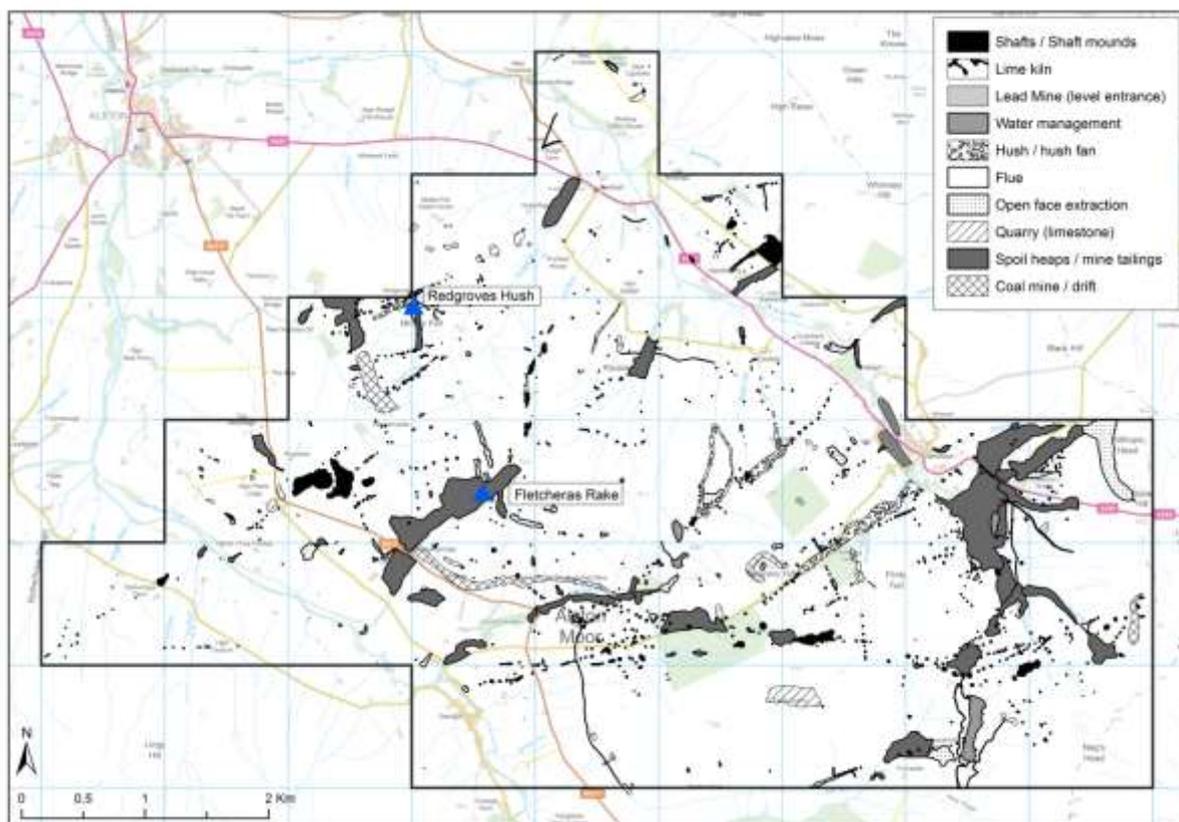


Figure 5. Distribution of mapped industrial sites, displayed by broad site type category (Map data © Crown Copyright / database right 2012. An Ordnance Survey / EDINA supplied service)

3.2 Rates and patterns of change at selected archaeological sites within the overall study area

Across the entire study area the change detection between the 1977-1988, and the 1988-1992 images indicates general areas of decreasing vegetation health along the valley bottoms (decreased NDVI values) but with broader areas of increasing vegetation vigour (increased NDVI values) along the valley sides and fell tops. However, examination of the change detection results involving the Landsat imagery from 2000 highlighted a problem. Although the NDVI image for 2000 showed a similar overall distribution of vegetation vigour to the images from other epochs, the change detection results for both the 1992-2000 and 2000-2006 periods show very different patterns. The 1992-2000 image

indicates that the vast majority of the study area experienced a significant overall decrease in NDVI values, while the 2000-2006 change detection image showed the opposite situation with the entire area indicating a notable increase in NDVI values.

Examination of the corresponding climate data explained these results, indicating that there was a general overall trend towards higher temperatures and increased rainfall in the early months of the sample years between 1977 and 2006, but with a notable sharp decrease in the temperature averages for the two months prior to the 2000 acquisition date (Figure 6). The rainfall data also suggested that the rainfall average for the early months of 2000 was appreciably lower than those for 1992 and 2006. These data suggest that the 2000 satellite image was taken at a time when the preceding weather in the region had been notably colder and drier than in the months leading up to the other image acquisitions. It is therefore likely that the marked difference in change detection results when using the 2000 data relates to phenological changes caused by short term climate trends. There is also the potential for the access and farming restrictions resulting from the Foot and Mouth outbreak of 2001 to have impacted on the land cover characteristics and derived NDVI values between the 2000 and 2006 data sets. These factors were taken into account during the detailed analysis of Redgroves Hush and Fletcheras Rake.

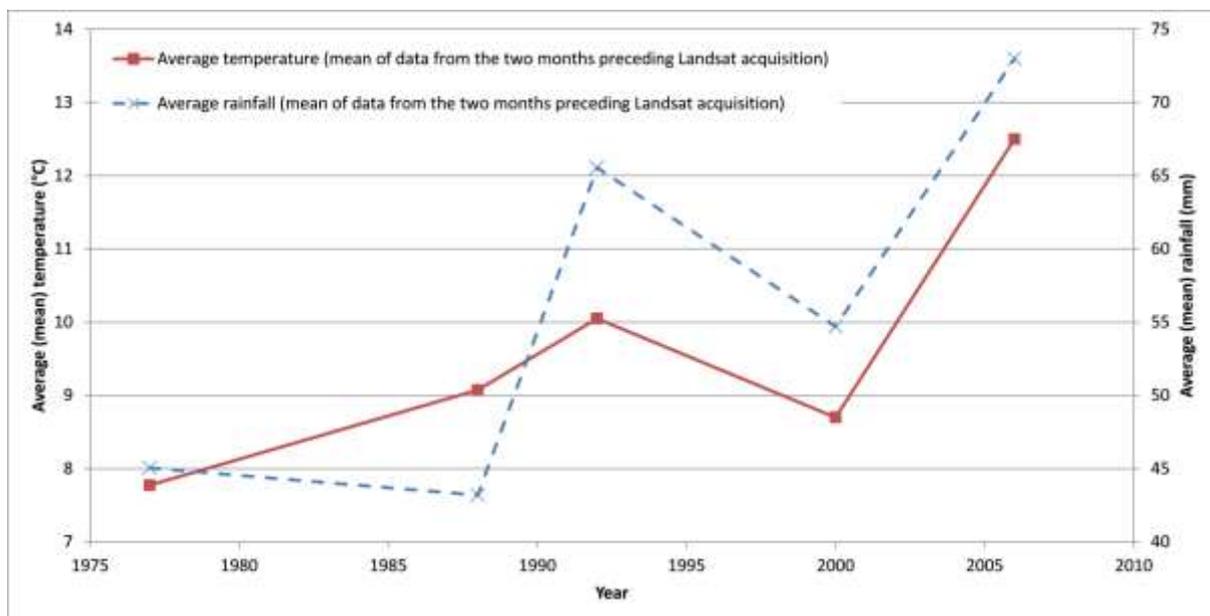


Figure 6. Graph showing mean temperature and rainfall values for the two months preceding the Landsat acquisition dates used in the change detection analyses. Data are for the closest Met Office monitoring station at Newton Rigg, Cumbria (NY493308) and were obtained from <http://www.metoffice.gov.uk/climate/uk/stationdata/>.

3.2.1 Redgroves Hush

The mapping from the airborne lidar and aerial photographs indicated an area of relatively severe gully erosion in the peat deposits at the eastern end of Redgroves Hush (Figure 2). This gully erosion covers an area of 0.04km² and hydrological modelling using the airborne lidar data suggests that the gullies are directly linked with a system of leats feeding into a dam at the upslope (eastern) end of the hush. Visual inspection of the multi-temporal Landsat data from each of the different epochs was able to discern both the hush and this area of erosion, particularly when using a SWIR false colour composite of bands 7-4-2 (Figure 7). However, although detectable, the clarity of the archaeological features on the lower spatial resolution 1977 MSS imagery was noticeably reduced and the majority of the change detection analyses focused on the later 1988 to 2006 data.

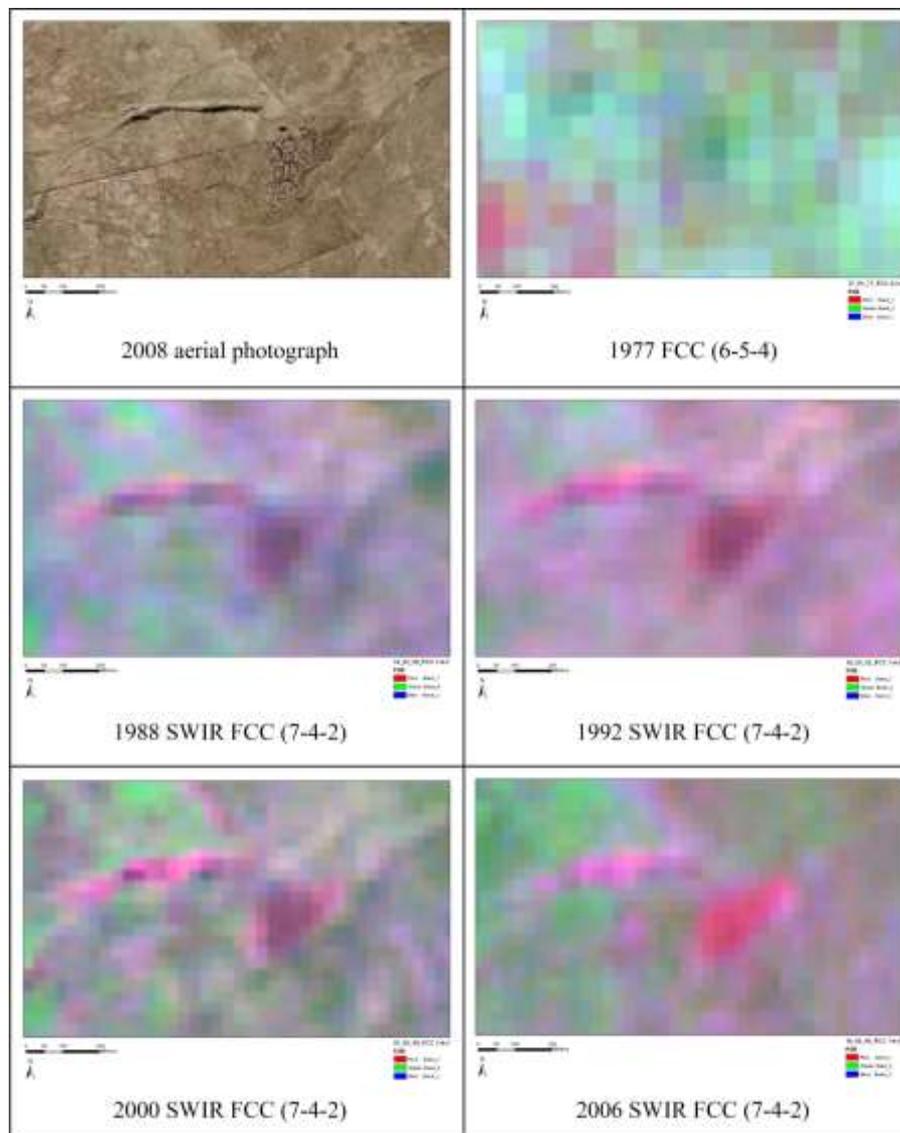


Figure 7. Landsat images for Redgroves Hush showing SWIR (7-4-2) false colour composites (Landsat data from GLCF; Photography © English Heritage)

Although visual examination of the Landsat data suggests that the erosion at the eastern end of Redgroves Hush has been present since at least the late 1970s, the pixel-based NDVI change detection of the same area indicates that it may actually be relatively stable (Table 3; Figure 8). The NDVI values for the core of the eroded area increase steadily between 1988 and 2006 from 0.25 to 0.35. These low positive NDVI values reflect areas of relatively unhealthy or sparse vegetation but their increase does suggest that the general vegetation vigour is improving. However, it is also apparent from the 1988-2006 change detection data that there are areas of decreasing NDVI values around the periphery of the main erosion core. Taken together these results suggest that the core of the gullying area is relatively stable or possibly even re-vegetating, but its spatial extent is probably increasing around the periphery (Clement, 2005).

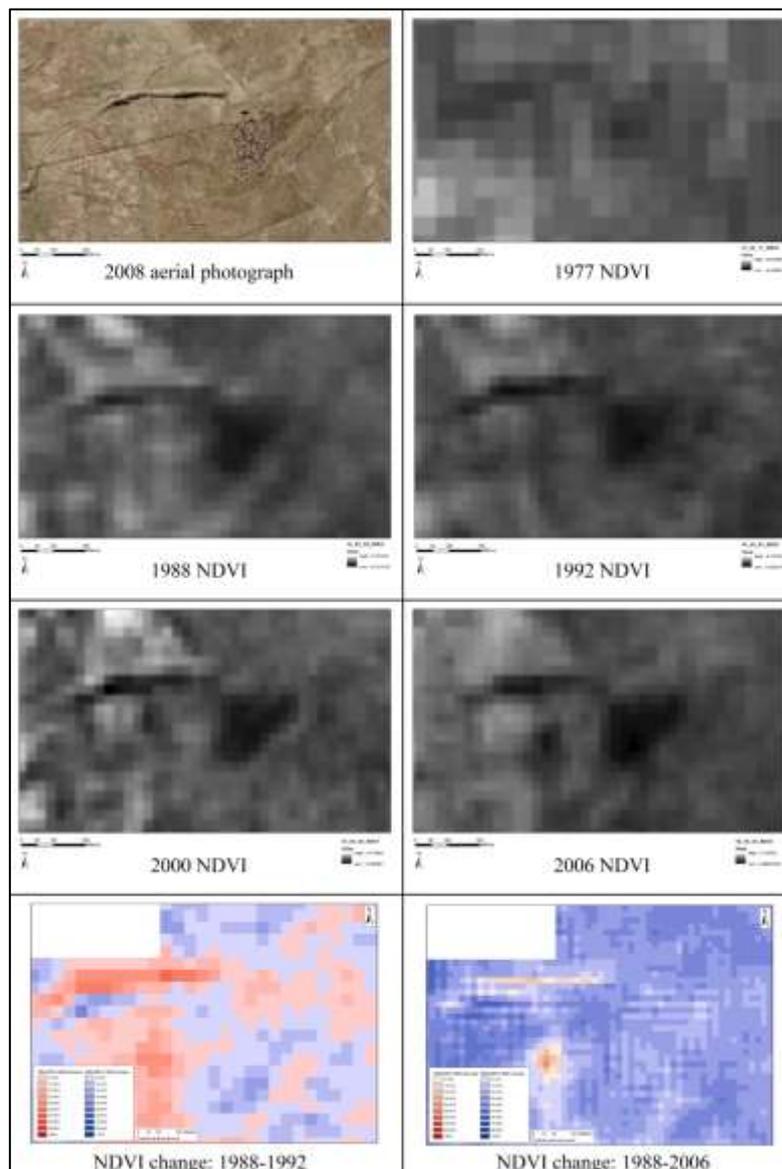


Figure 8. Landsat data for Redgroves Hush showing single epoch NDVI images and NDVI change results (Landsat data from GLCF; Photography © English Heritage)

In contrast, the main section of Redgroves Hush itself shows a marked decrease in NDVI values between 1988 and 2006, indicating that the vegetation cover along this abandoned mining feature has decreased in spatial extent and vigour. Field inspection suggests that this is likely the result of soil creep, rilling and shallow landsliding along the slopes of the hush itself. This situation is compounded by an additional area displaying a noticeable decrease in NDVI values located to the south of the hush and the west of the main erosion area. This area corresponds with what appears from the 2008 aerial photographs and field walkover to be relatively sparse vegetation cover and some additional minor surface erosion in the form of shallow gullying and downslope sediment movement through water and wind action.

Table 3. NDVI statistics for Redgroves Hush (note the decreased values for 2000)

| Year | Count | Minimum | Maximum | Sum | Mean | Standard |
|------|-------|-----------|----------|-------------|----------|-----------|
| | | | | | | Deviation |
| 1977 | 3160 | 0.209302 | 0.461078 | 944.944764 | 0.299033 | 0.040982 |
| 1988 | 3160 | 0.266667 | 0.536 | 1283.150609 | 0.40606 | 0.043205 |
| 1992 | 3160 | 0.274725 | 0.529412 | 1276.415819 | 0.403929 | 0.03613 |
| 2000 | 3160 | -0.081967 | 0.333333 | 440.435205 | 0.139378 | 0.049534 |
| 2006 | 3160 | 0.34 | 0.635135 | 1610.334538 | 0.5096 | 0.048861 |

3.2.2 Fletcheras Rake

In addition to recording the complex surface workings at Fletcheras Rake, mapping using the airborne lidar and spectral data highlighted the presence of large areas of un-vegetated mining waste at the centre of the Scheduled Monument area (i.e. the area that is deemed of national importance and therefore under statutory government protection) (Figure 3). With no vegetation cover to stabilise the relatively loose matrix of spoil this site has the potential for widespread erosion and was therefore selected for the more detailed analysis. Visual inspection of the multi-temporal Landsat imagery proved capable of differentiating the un-vegetated mining waste from the surrounding grassland, with both the SWIR colour composite and the greenness index of the Tasseled Cap transform proving particularly useful (Figure 9). Although the lower resolution of the 1977 MSS data again means that quantitative comparisons using this imagery for site-scale analyses have to be treated with some caution, the main features at Fletcheras could still be detected in imagery from this date.

Approximate measurement of what is interpreted as bare ground on the Landsat data suggests that the SW-NE long axis of the mining waste has increased from 460m in 1988 to 540m in 2006. Detailed measurements taken from imagery with this spatial resolution (15m-30m) have to be treated with caution but comparison with contemporary historic aerial photography suggests that the values derived from the Landsat data are broadly correct. No historic aerial photographs were available for the 1988 – 2000 epochs but a long axis measurement of 490m taken from the 1977 Landsat data approximates an equivalent measurement of 452m from an aerial photograph taken in 1976, albeit within the potential error margins present when using satellite data with a spatial resolution of 79m. A similar check using the later imagery provided a measurement of 528m using a higher resolution aerial photograph from 2008 that compares well to the equivalent measurement of 540m from the 2006 Landsat data. These comparative measurements taken from broadly contemporary Landsat imagery and aerial photographs indicate that such satellite data can be used for the approximate quantitative assessment of archaeological site change, at least within the constraints of the spatial resolution of the Landsat data. The key value here is that good spatial and temporal coverage of historic aerial photography is not always available, particularly in remote upland areas. The excellent spatial coverage of Landsat data and its frequent temporal revisit rate means that it provides a valuable alternative for such assessments in areas where aerial photographic coverage is poor.

The NDVI change detection analysis at Fletcheras Rake supports the results of the visual inspection (Table 4; Figure 10). Each of the NDVI images record the main area of un-vegetated mining waste as a region of markedly lower NDVI values ranging between 0.13 and 0.27. The NDVI change detection image comparing the 1988 and 2006 data indicates that the majority of the pixels in the central areas have decreased in value by between 0-30%, with some areas decreasing by as much as 50-60%. These results clearly suggest that the core area of mining waste at Fletcheras has experienced a decrease in vegetation cover or vigour during this period. Shallow gullies identified during the field survey suggest that this may be the dominant erosion process occurring at this site, although with the exposed nature of the site and lack of stabilising vegetation, the movement of exposed spoil through wind erosion processes is also likely.

Of additional concern is the presence of an elongated area of decreased NDVI values visible extending in a southwest direction from the core of the site, recorded through both the visual and NDVI change detection analysis. Through comparison with the 2008 aerial photographs it is apparent that these decreased NDVI values correspond with the location of pronounced northeast-southwest gullies extending downslope from the centre of the Scheduled Monument. It appears likely that this response in the change detection data is due to the fluvial erosion and redistribution of mining waste from the core of the site along these gullies and the covering under debris fans or subsequent erosion

of the minimal vegetation in these downslope areas. This conclusion was supported by the field walkover survey, with evidence for clearly defined incised gullies that are eroding through areas of vegetated mining waste.

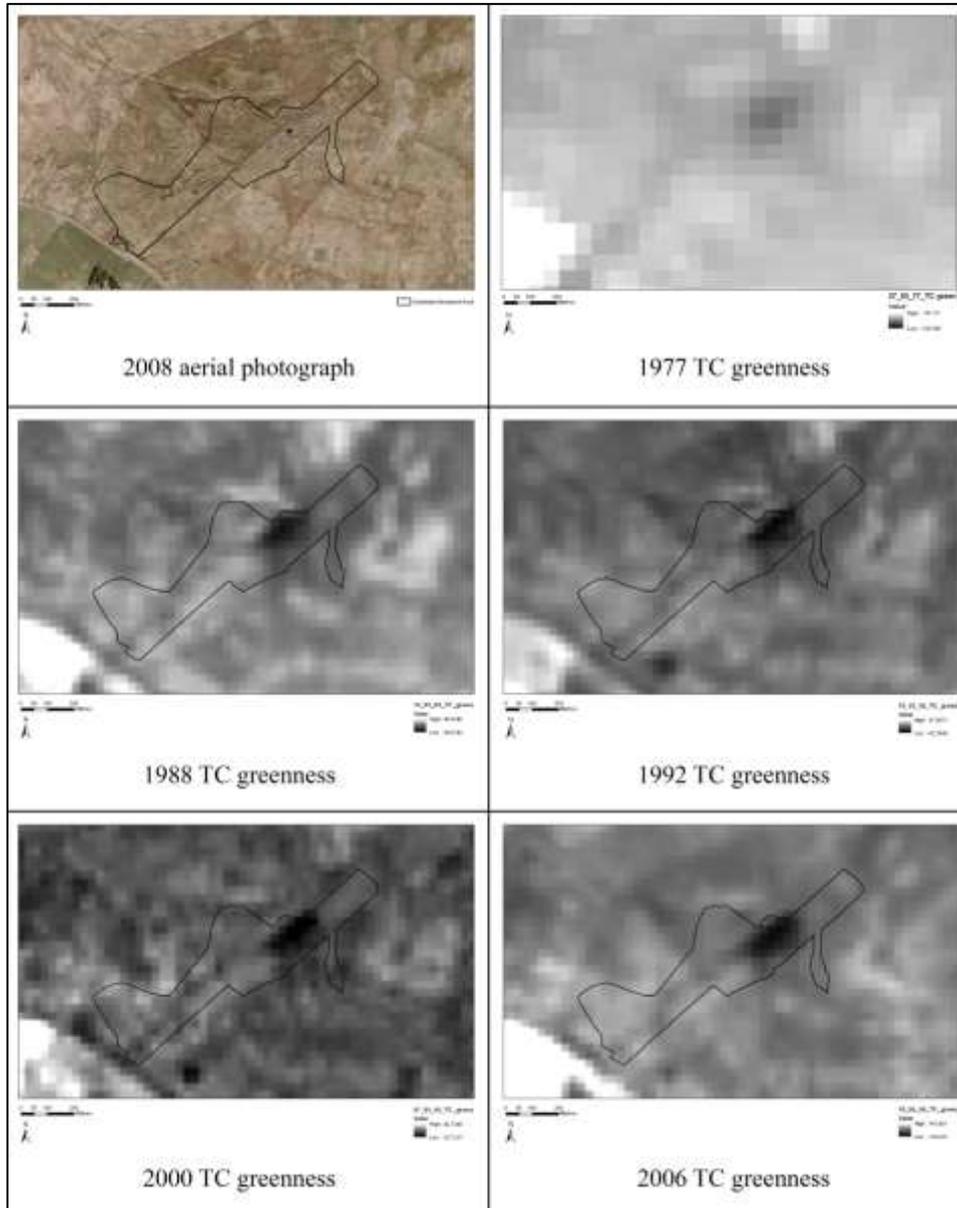


Figure 9. Landsat images for Fletcheras Rake showing Tasseled Cap greenness index. The black polygon outline indicates the area designated as a nationally important Scheduled Monument and therefore under statutory government protection (Landsat data from GLCF; Photography © English Heritage)

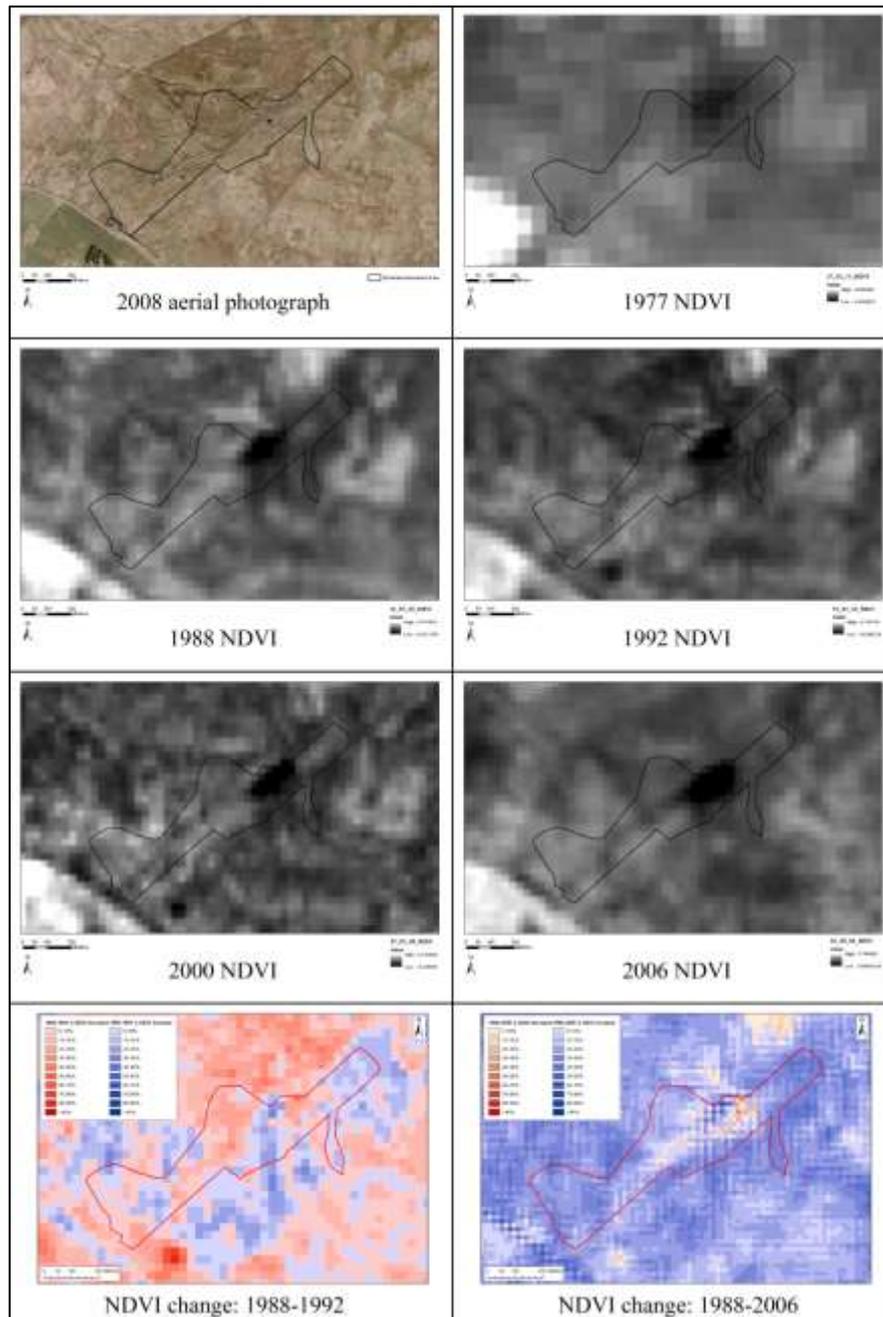


Figure 10. Landsat data for Fletcheras Rake showing single epoch NDVI images and NDVI change results. The black polygon outline indicates the area designated as a nationally important Scheduled Monument and therefore under statutory government protection (Landsat data from GLCF; Photography © English Heritage)

Table 4. NDVI statistics for Fletcheras Rake (note the decreased values for 2000)

| Year | Count | Minimum | Maximum | Sum | Mean | Std Dev |
|-------------|--------------|----------------|----------------|-------------|-------------|----------------|
| 1977 | 7866 | 0.148936 | 0.595745 | 2569.738121 | 0.326689 | 0.061456 |
| 1988 | 7866 | 0.102564 | 0.714286 | 3497.713805 | 0.444662 | 0.069948 |
| 1992 | 7866 | 0.103448 | 0.675676 | 3394.222415 | 0.431506 | 0.063468 |
| 2000 | 7866 | -0.263158 | 0.5 | 1157.809208 | 0.147192 | 0.076672 |
| 2006 | 7866 | 0.137255 | 0.777778 | 4289.33464 | 0.545301 | 0.068832 |

3.3 Field sampling and soils analysis (Fletcheras Rake)

The vegetation communities at Fletcheras Rake are typical of an upland heath or upland dry grassland with no evidence of metallophyte communities. In contrast, lead concentrations from each of the six soil sample locations are extremely high and exceed all suggested guidelines (SGV and ICRCL) (Table 5; Figures 4, 11 and 12). This is of significant concern in terms of environmental risk, particularly in those areas where there is the potential for access by livestock. Sequential extraction showed that a significant proportion of this lead is in the exchangeable fraction and therefore potentially available for uptake by organisms or movement through the landscape. The DGT values for lead from the northern area of Fletcheras Rake confirm that Pb is available for uptake and therefore constitutes a significant environmental risk for the area. The remaining metals that were measured fell within the normal ranges for soils and therefore do not pose a risk to the environment.

From comparison of the mapping and soil analysis it was evident that the vegetation communities did not accurately reflect the underlying soil chemistry but instead were strongly influenced by the elevation at which the community was located. However it is also clear that the farming activity within the area has significantly affected the vegetation community. On areas of spoil which might have been expected to support metallophyte communities, there is a thick grass sward which is most likely due to the input of fertilisers from livestock. On areas that are either isolated from livestock or have limited access and have the appropriate open habitat, metal tolerant species are present, but these are isolated and extremely limited in extent. This finding has important implications for the use of vegetation mapping alone to identify areas of metal contamination, reaffirming the view that the distribution of metallophyte communities cannot be used as a simple predictor of soil chemistry.

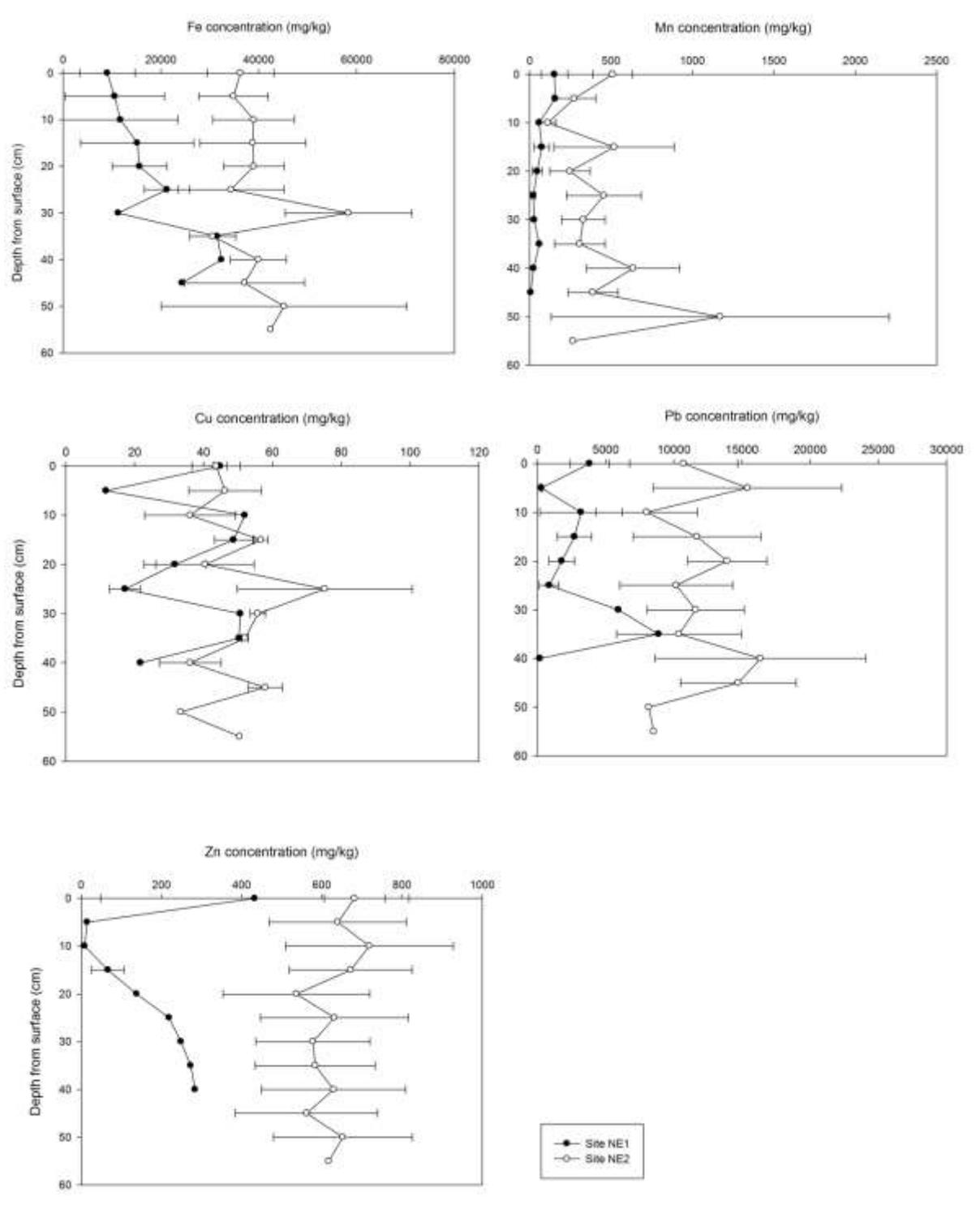


Figure 11. Total metal concentrations in soil profiles from Fletcheras mine samples NE1 and NE2, taken from vegetated areas of short grass species *M. caerulea* and *P. schreberi*

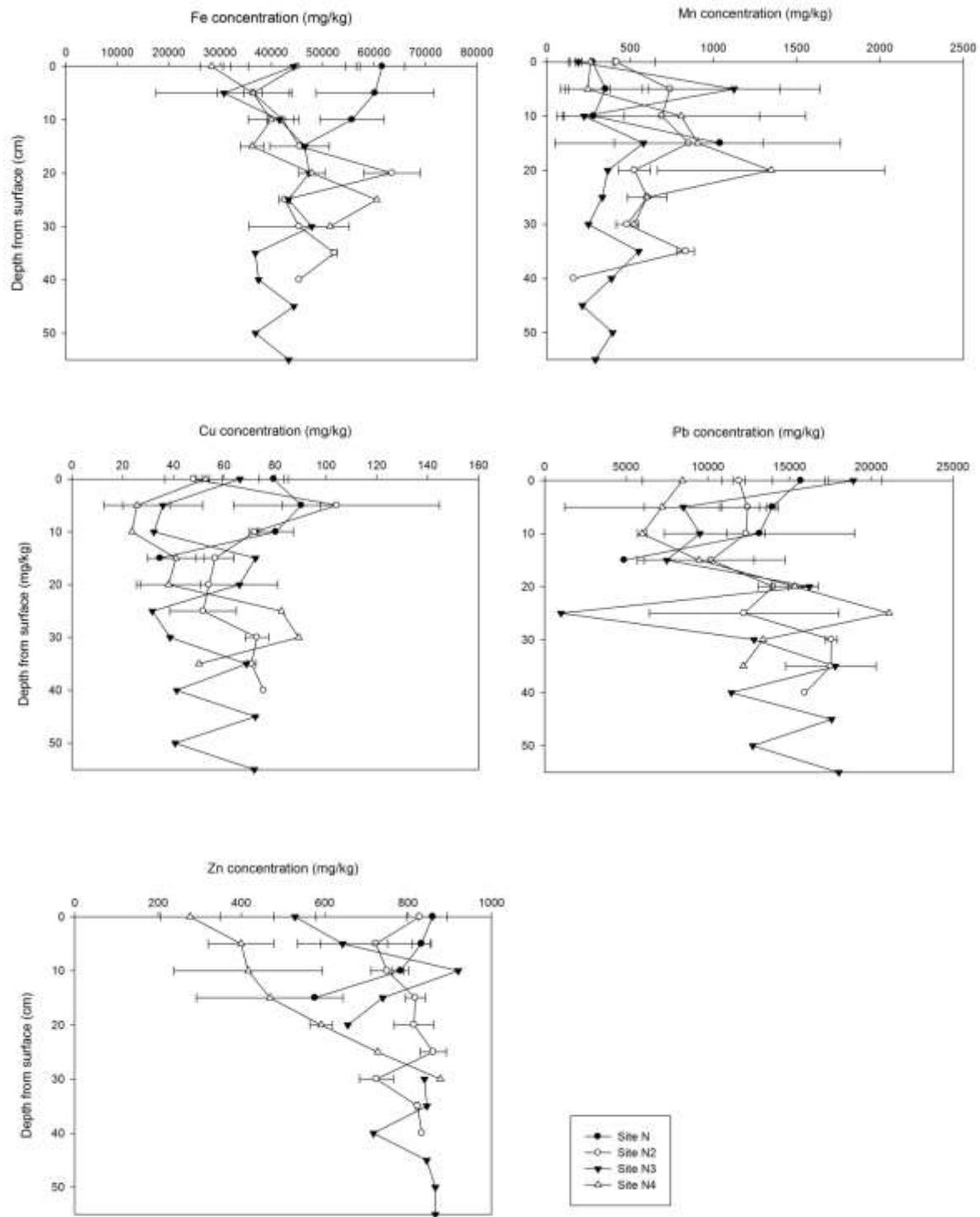


Figure 12. Total metal concentrations in soil profiles from Fletcheras mine samples N1-N4, taken from a bare, unvegetated spoil heap (N1) and partially vegetated spoil heaps (N2-N4)

Table 5. ICRL Interdepartmental Committee on the Redevelopment of Contaminated Land guideline values for restoration of metalliferous mining sites (ICRL, 1990) compared with sampled values from Fletcheras Rake

| | Trigger Value (mg/kg air dry weight) | Maximum concentration for grazing (mg/kg air dry weight) | Fletcheras Rake concentrations (range in mg/kg air dry weight) |
|--------|---|---|---|
| Zinc | 1000 | 3000 | Barely detectable - 870 |
| Copper | 250 | 500 | 12 - 104 |
| Lead | 300 | 500 | 192 - 20303 |

4. DISCUSSION

4.1 Landscape scale condition of industrial heritage on Alston Moor

The density and variety of archaeological features identified through the aerial mapping clearly demonstrates the significance of the industrial heritage resource on Alston Moor. However, the subsequent erosion mapping and change detection analyses also sharply highlight the potential fragility of these remains. The mapping revealed numerous sites at which evidence for landforms indicating direct erosion could be found, including the gullies extending through the western side of Fletcheras Rake and the presence of similar gully features across the processing floors at Whitesike and Bentyfield mines. Examples suggestive of indirect coupling between geomorphological erosion processes and archaeological remains were equally apparent. The spatial linkage between the gully erosion east of Redgroves Hush and the system of leats feeding into the upper end of the hush suggests that the historic anthropogenic alteration of the local hydrology at this site may have caused, or at least exacerbated, the erosion of the peat. A similar situation was noted in a number of other locations throughout the study area, associated with historic and more recent alterations to the upland hydrology. For example, the extensive gullying occurring on Flinty Fell appears to be directly associated with the network of 20th century drainage grips dissecting the landscape in this area (Figure 13). Although it is not clear from the remotely sensed data whether the grips were cut to flow into pre-existing gully features or whether the gullying is being caused by the gripping, what is apparent is that anthropogenic alterations to the landscape are inextricably linked with the ongoing fluvial erosion.

The potential for ongoing or future fluvial erosion at a high proportion of the archaeological sites mapped across the entire study area can also be demonstrated by assessing the location of these sites in relation to the local stream pattern. The hydrological drainage network was modelled in ArcGIS using a 5m resolution digital terrain model, with the output being a vector layer representing the

stream locations and with stream order as an associated tabular attribute. Analysis of this drainage network demonstrates that 175 mapped industrial features are in direct spatial contact with a stream of second order or higher, representing 14.7% of all recorded archaeological features. A total of 315 archaeological features (26.4% of the total mapped) are within just 10m of a stream of second order or higher. When the first order streams are included in the analysis these figures increase to 333 features (27.9%) in direct contact with a stream and 601 features (50.4%) within just a 10m distance.

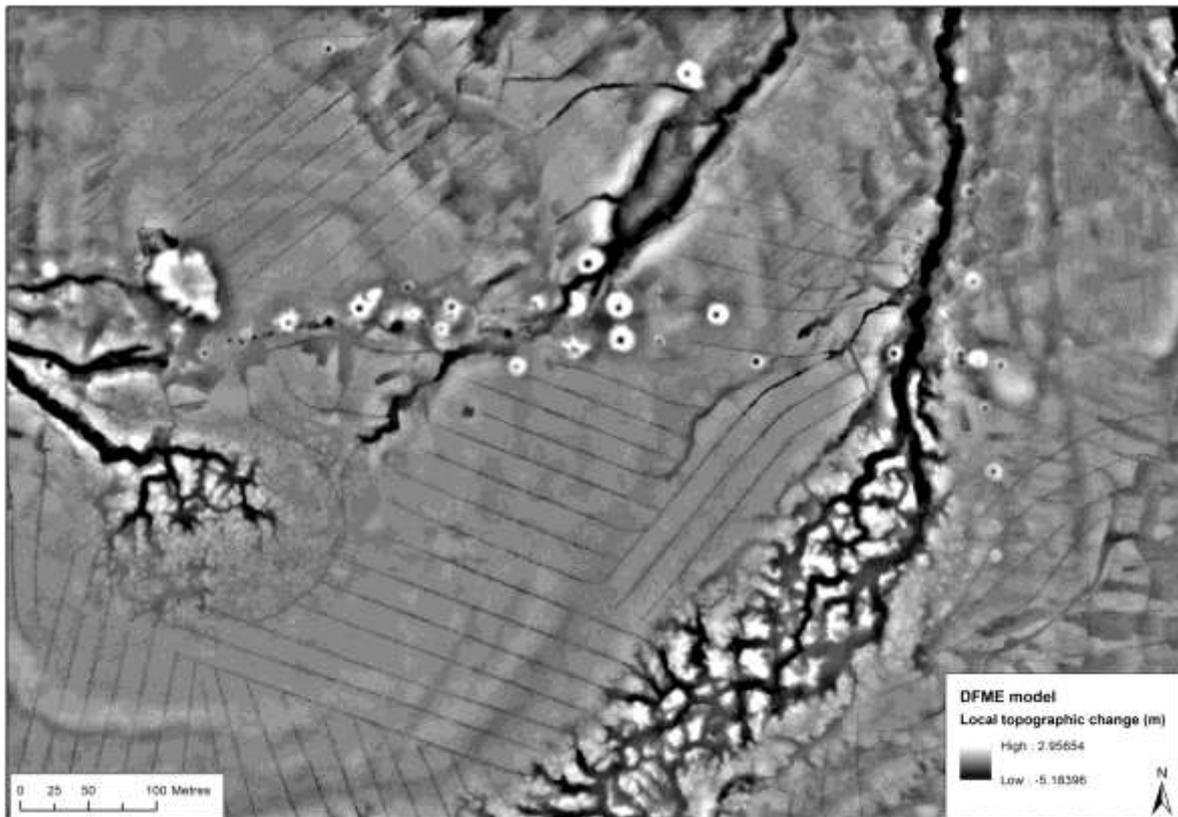


Figure 13. Difference from Mean Elevation (DFME) model produced from airborne lidar data, showing complex spatial relationships between peat gullies, 20th century drainage grips and industrial archaeological remains on Flinty Fell (Lidar data © English Heritage)

The proximity of an archaeological feature to a modelled drainage channel is not necessarily a direct indicator of active erosion but does highlight one potential factor that could be contributing to the erosion of important heritage sites. It is also worth noting that many of the other potentially destabilising surface characteristics present at Redgroves Hush and Fletcheras Rake, such as a lack of vegetation cover, steep slope angles and gullying, are visible at many of the other sites mapped as part of this study. Importantly this includes a number of the other Scheduled Monuments in the area, including the lead mines at Whitesike and Bentyfield and the extensive lead/zinc workings around

Nenthead. The threats caused by surface erosion at Whitesike and Bentyfield have already been recognised and determined to be of high enough risk that recent attempts have been made by English Heritage and the North Pennines AONB to assess their condition and stabilise them from further degradation. Similarly, a monitoring programme has been put in place by the Coal Authority to assess the erosion of some of the spoil heaps in the Nenthead mining complex. However, this present study suggests that the erosion of the industrial archaeological remains on Alston Moor is potentially far more widespread than just these individual sites.

The detailed change detection analyses at both Redgroves Hush and Fletcheras Rake suggest that the extent of erosion at these two sites has certainly changed during the last c. 35 years. Although the NDVI change detection results display marked heterogeneity across the archaeological remains, significant trends have been detected. At Redgroves Hush the main area of peat gullying appears relatively stable but the vegetation cover on the hush itself does appear to have decreased, potentially exposing the site to further future erosion. Similarly, the spatial extent of bare, unvegetated spoil at the Fletcheras site has increased markedly between 1977 and 2006, mainly in a southwesterly direction along pronounced gullies. This same pattern of reworking of archaeological deposits and their movement downstream from their original location was also identified at both Whitesike and Bentyfield Mines, where significant areas of unvegetated bare spoil are located close to steep valley sides. Although fluvial processes have been identified at both field sites it is also likely that both slope and aeolian processes are playing a significant role in the erosion of the archaeology of the area. The fieldwork identified evidence for soil creep, rilling and shallow landslides on the slopes of Redgroves Hush and probable wind transport on the exposed spoil heaps at Fletcheras Rake.

4.2 Significance of change for wider landscape

The significance of the ongoing interaction between the industrial archaeology of Alston Moor and the erosion of the landscape through natural processes lies in its implications for both heritage management priorities and natural ecology. With archaeological sites being actively damaged through erosion there is the real risk that elements of important industrial heritage will be lost. The industrial sites in question often contain complex and multi-period remains, with erosion not just damaging waste spoil heaps but also a multitude of other associated features. Furthermore, although this research has focused on industrial heritage it is important to remember that upland environments are often excellent preservers of archaeological remains from a wide range of site types and periods. This preservation has largely been due to relatively low anthropogenic pressure in these environments in modern times but the continued survival of the resource is in the balance. Natural erosion processes, such as the widespread gullying that is occurring throughout the Alston landscape, have the potential

to not just damage upstanding archaeological remains but to also alter the sub-surface burial environment and therefore affect levels of *in situ* preservation, as well as less tangible resources such as the palaeoenvironmental archive that can be provided by intact peat deposits.

The localised relationship between geomorphology and archaeology has been demonstrated elsewhere to be one of the key drivers behind the release and redistribution of previously stored lead contaminants in non-peat soils in both the UK and beyond (Hudson-Edwards et al., 2008; Hürkamp et al., 2009; Macklin et al., 2006; Rowan et al., 1995). The results of this research into the Alston landscape indicate that there is a similar relationship with high contamination levels associated with historic land-use practices. The relative concentrations within and between the sites are heterogeneous and therefore the potential for redistribution is likely to depend upon both the local archaeological and geomorphological context, although the limited sample size in this study prevents us from making a conclusive statement regarding this.

Extensive erosion of archaeological deposits on abandoned lead mining sites was shown to be actively occurring at a number of locations. Where this erosion corresponds with soils containing high levels of metal contaminants, as was demonstrated at Fletcheras Rake, the implications are significant. Lead concentrations from all of the six soil samples taken from Fletcheras Rake exceeded current guideline values but equally importantly, they were all located within the area indicated by the NDVI change detection analysis as becoming less vegetated through time. With the results suggesting that mine tailings from this central area are being redistributed downslope along pronounced gullies the conclusion has to be that the lead contaminants are also being mobilised. The erosion of industrial archaeological remains and the release of metal contaminants into the wider landscape should be a matter of real concern, not just for archaeologists and ecologists but also for surrounding communities, with the potential for such contaminants to reach important infrastructure elements such as water supplies and agricultural land (Johnston et al., 2008; McCaffrey et al., 2005).

5. CONCLUSIONS

This research has demonstrated that multisensor remote sensing techniques have the potential to significantly increase our understanding of the interrelationships between archaeological sites, landscape change and the geomorphological context occurring in upland environments, especially when combined with field-based mapping and soil sampling. Industrial archaeological sites in the Alston area are clearly at risk of continued erosion from natural processes, particularly surface run-off and slope instability. However, it is also apparent that this relationship is far from one sided; with

damage to former mining sites potentially releasing high levels of harmful metal contaminants into the wider catchment and therefore impacting negatively back onto the natural environment.

The focus of this study was primarily on providing a landscape-scale assessment of the archaeological resource within this area of the North Pennines and to this end it can be deemed a success.

Nevertheless, the results have demonstrated that the coupling effect between historic land-use practices and natural processes is extremely complex and far more locally variable than the spatial and temporal resolution of this project has been able to adequately define. In particular, the work has established that the relationship between surface vegetation community and the levels of heavy metals in the underlying soils is not as straightforward as initially presumed, with the important resulting conclusion being that vegetation mapping alone cannot be used as a direct indicator of metal contamination on former mine sites. It is only through further detailed combined consideration of the archaeological, geomorphological and modern land-use context of a site that we will obtain a more complete understanding of the interaction between the various processes at work.

ACKNOWLEDGEMENTS

This research was funded by English Heritage as part of their wider ‘Miner-Farmer Landscapes of the North Pennines Area of Outstanding Natural Beauty’ project. The overall Miner-Farmer research was project managed by Stewart Ainsworth. The authors extend their thanks to the numerous other staff in the English Heritage Archaeological Survey and Investigation teams who have given of their time and advice, especially Dave Went and Yvonne Boutwood. Paul Leadbitter and Andy Lloyd of the North Pennines AONB Partnership kindly provided relevant digital data and assisted with fieldwork access. The landowners of the focus area are thanked for access permissions. The authors are grateful to Dr Jeff Warburton and two anonymous reviewers who provided helpful comments on an earlier draft of this paper.

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