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Improving particulate carbon loss estimates in eroding peatlands through the use of terrestrial laser scanning

Grayson, R[1*]., Holden, J[1]., Jones, R.R[2]., Carle, J.A[2]., Lloyd, A[3].

[1] School of Geography, University of Leeds, Leeds, LS2 9JT

[2] Geospatial Research Ltd., Dept. of Earth Sciences, University of Durham, Durham, DH1 3LE

[3] North Pennines AONB Partnership, Weardale Business Centre, The Old Co-op Building, 1 Martin Street, Stanhope, Bishop Auckland, County Durham, DL13 2UY.

*r.grayson@leeds.ac.uk; 0113 343 3373

Abstract

Blanket bogs act as the largest terrestrial store of carbon within the UK. Unfortunately many are degraded with exacerbated erosion being common. Although considerable efforts have been made to quantify carbon fluxes across blanket bogs less attention has focussed on quantifying losses associated with erosion. Traditional approaches to measuring erosion have relied on erosion pins and sediment traps. However, both methods suffer from several problems and are unable to provide data over large areas. Terrestrial laser scanning has been used widely in geomorphology to create detailed 3D topographic maps in a range of environments. A pilot study was carried out over winter 2010-2011 to test the applicability of terrestrial laser scanning to measure erosion across a blanket bog within the North Pennines, UK. The technique was found to be superior to traditional methods providing high resolution spatial data on surface elevation change. A net increase in the peat surface height of 2.5 mm was calculated from the terrestrial laser scans between October 2010 and March 2011. This compares with a net surface lowering of 38 mm measured using pins. These results suggest that previous erosion data from peatland sites based on pin measurements ought to be treated with caution. However, several improvements are required to the laser scanning technique before it is fully implemented in peatland environments including the development of a filter to remove vegetation from the scan results, and taking account of 'mire-breathing' which can cause surface level rise and fall in peatlands. It is clear that once these factors are dealt with, regular repeated ground based laser scanning will vastly improve our understanding of the role of processes that affect the surface elevation of peatlands including the relative roles of storm events and long-term seasonal cycles, and 'roughening' of the peat surface as a result of needle-ice formation, desiccation and wind-scouring.

1. Introduction and aims

Blanket bogs cover approximately 8% of the UK (Taylor, 1983) and support a wide range of ecosystem services. Within the UK they are the largest terrestrial carbon store (Cannell et al., 1993; Cannell and Milne, 1995), supply c. 70% of all drinking water (Watts et al., 2001), and are important for grazing and game sports (Holden et al., 2007a), they also support a diverse range of flora and fauna. Blanket bog only forms under certain conditions. Within the UK the majority occurs in uplands with high annual rainfall totals (> 1000 mm), a high number of annual rainfall days (> 160 days) and low average temperatures (warmest month 9-15°C) (Lindsay et al., 1988).

At the global scale peat soils account for 30 - 50 % of all the carbon stored in soils (Holden, 2005; Limpens et al., 2008). Therefore, efforts are being made to improve our understanding of carbon dynamics in such systems (Holden, 2005; Waddington et al., 2008; Dinsmore et al., 2010; Grayson and Holden, 2011). Blanket bog erosion can result in significant export of particulate organic carbon (POC) with erosion studies in upland bogs having a long history (Bower, 1960; Bower, 1961; Bower, 1962; Radley, 1962; Tallis, 1964; Gore, 1965; Tallis, 1965). Despite 'natural' revegetation having occurred over the past few decades (Evans and Warburton, 2007; Grayson et al., 2010) large areas of bare peat remain throughout the UK Pennines, with enhanced erosion continuing at many sites (Evans and Warburton, 2005; Evans et al., 2006; Evans and Warburton, 2007).

Fluvial processes drive the majority of erosion in UK blanket bogs (Bower, 1961; Tallis, 1965), although wind erosion can also be significant (Warburton, 2003). Other erosion processes include rainsplash, desiccation of the peat surface and the impacts of frost and ice, particularly needle-ice formation and damage to gully walls as a result of freeze-thaw cycles (Imeson, 1971; Evans and Warburton, 2007). Peat, when vegetated is relatively stable (Tallis, 1998) yet widespread erosion has been observed across blanket bogs. Hypotheses forwarded to explain the onset of accelerated erosion in UK blanket bogs, include: over grazing (Evans, 1977); changes in land management, including burning and drainage (Mackay and Tallis, 1996; Holden et al., 2007b); air pollution and atmospheric deposition linked to industrialisation (Evans and Warburton, 2007).

Much of the early work examining erosion in UK peatlands estimated the total area of eroding peat and attempted to classify the type of erosion occurring (Bower, 1960; Bower, 1961; Eddy et al., 1969) with few attempts to quantify the rate of erosion. Subsequently studies have estimated erosion rates across UK blanket bogs, typically through the use of erosion pins to directly measure erosion rates (Evans et al., 2006; Evans and Warburton, 2007); while the number of studies remains relatively small observed erosion rates vary from 5.4 to 40.9 mm per year (Table 1) .

While erosion pins can provide detailed data allowing erosion rates to be calculated their use is not straightforward. Erosion pins act as a fixed datum and soil erosion rates are calculated by repeating measurements of the distance from the top of the pin to the surface through time. Therefore erosion pins need to remain stable through time to accurately calculate erosion rates (Couper et al., 2002).However they can be affected by frost heave, and surface movement resulting from wetting-drying cycles and freeze-thaw cycles (Labadz, 1988). Where a peat becomes saturated the whole of the peat can expand, while during dry periods where the water table falls, the upper peat can dry out, shrink and become desiccated. This process of expansion and contraction of the peat surface between dry and wet periods is known as ‘mire-breathing’ (Kellner and Halldin, 2002). Other problems relate to the interpolation of individual measurements of erosion at pin sites as erosion rates can vary significantly even over very small areas, this is not unique to upland peats. Erosion pins can also directly affect erosion, either increasing erosion or acting to trap eroded material (Benito et al., 1992; Couper et al., 2002) and are also a relatively intrusive measurement technique due to repeat measurements at the same site.

Within geomorphology ground-based laser scanning using LiDAR (light detection and ranging) is increasingly being used to create high-resolution 3D maps of topography (Nagihara et al., 2004; Rosser et al., 2005; Jones et al., 2009). This technique offers a number of clear advantages over traditional techniques for measuring erosion in peatland catchments, primarily the ability to accurately measure total erosion losses across a large area of the land surface (e.g. whole gullies or peat flats) within a short period of time, but also the ability to include relatively fixed datum points within a scan to allow increased accuracy during repeat measurements. LiDAR may offer a major improvement when estimating the volume of peat lost (or gained), with a survey across a 100 m^2 site being the equivalent of measuring several million pins over the same area. Repeat measurements over time allow 3D models of erosion and deposition over time to be constructed. Therefore, the use of ground-based LiDAR to measure peat erosion and accumulation has the potential to offer a unique insight into current peat erosion rates and allow accurate measurements of the volume of peat lost (or gained) over time. The technique is also less intrusive than erosion pins as scans can be made at a distance without disturbing eroding areas.

As a pilot study this project sought to:

1. Develop a detailed 3D model of topographical changes in the peat surface over a six month period to allow an accurate estimate of the total peat volume lost through erosion.
2. Compare this estimate with measurements made using traditional methods to examine the errors associated with traditional techniques.
3. Determine the issues to be resolved when using LiDAR in peat erosion measurements.

2. Site selection and methods

The North Pennines AONB (Area of Outstanding Natural Beauty) Peatscapes project aims to conserve and enhance the peatland resource within the North Pennines, where 27% of England's blanket bog resource occurs. Severe gully erosion has been identified at the Valence Lodge Farm site, located on Harthope Moor in County Durham (54°42'28.21N 2°12'43.61W) (Fig 1); however, no quantitative erosion rate measurements have been made. Two parallel erosion surveys were carried out at Valence Lodge Farm over winter 2010/2011 to provide 'typical' baseline erosion rates across a single winter. One survey used erosion pins to measure changes in surface height which were interpolated to give erosion rates. The other used terrestrial laser scanning to produce a highly detailed 3D topographic model of erosion and accumulation.

2.1 Erosion pins

Five sets of erosion pins were installed across Valence Lodge Farm on 29/09/10 (Fig 1). Pins were constructed from 6 mm diameter stainless steel threaded rods and were 50 cm long. At each site 25 pins was manually inserted into the peat using a grid formation; pins were spaced either 50 (PS 2, 4 and 5) or 100 cm apart. All five sets were south or southeast facing with the average slope varying between 11.4° (PS5) and 34.4° (PS4) (Table 2). The actual extent of the LiDAR scan in a gully system is difficult to determine without post processing of the data. Therefore, to minimise disturbance of the peat surface, four of the pin sets were installed towards the limit of the area included in the LiDAR survey with only PS5 being installed within the main scan area to allow a direct comparison between the techniques.

The height from the top of the pin to the surface of the peat was measured on the downslope side of the pin. A dGPS survey of the site was carried out using a Leica 530 RTK GPS to identify pin movement through time; six of the pins were not measured to prevent unnecessary damage to the peat surface. Local benchmarks were measured using a feature on the nearby road to provide local fixed datum points. The site was revisited in April 2011 (08/04/11) and the height from the top of each pin to the peat surface was re-measured. A full dGPS survey was again carried out across the site. Erosion rates were calculated for each pin by subtracting the pin height measured during the second survey from the height measured during the first survey to give an erosion rate for each pin in mm. Although previous studies have ignored decreases in pin heights on slopes above 30° (Evans et al., 2006; Evans and Warburton, 2005) all data were included in this study as deposition at some sites was clearly visible across the surface and had not just occurred on the pin itself.

When using erosion pins an assumption is made that erosion/deposition measured at an individual pin is representative of the erosion or deposition occurring in the area surrounding the pin. The use of a grid of erosion pins allows the larger area to be broken down into a series of cells each with an erosion pin in the centre, therefore, the erosion rate for each cell is given as the rate measured at the pin in the centre of that cell. The area of each individual cell was calculated using equation 1.

$$\text{2D area} = \tfrac{1}{2}a \times \tfrac{1}{2}b \times \tfrac{1}{2}c \times \tfrac{1}{2}d$$

(Eqn 1)

where *a* is the distance to the next pin above, *b* is the distance to the next pin to the right, *c* is the distance to the next pin below and *d* is the distance to the next pin to the left. For pins located at the edge of the set of pins the cell area was calculated using the distance to any surrounding pins only and did not extend outwards from the edge of the set of erosion pins.

Total erosion losses for each cell were calculated by multiplying the cell's area by the erosion rate measured at the pin in the centre of that cell. The total volume of peat lost across each pin set was calculated by adding together the losses for the individual cells; this was then divided by the total area to give a volume of peat lost per m^2 to allow clear comparisons between pin sets.

2.2 Terrestrial laser scanning

Terrestrial laser scanning (ground-based LiDAR) is a surveying method in which the precise geometry of a topographic surface is measured in detail by recording the 3D position of many millions of points across the surface. The method is non-penetrative, and therefore the output of the survey is typically a "surface 3D dataset" rather than a "volumetric 3D dataset" (Jones et al., 2008).

Scans were carried out using a Riegl LMS-Z420i terrestrial laser scanning system. This is a long range time-of-flight scanner with a typical range of up to 1000m, a maximum angular resolution of 0.004°, and acquisition rates of ca. 12,000 points per second. Such scanners currently cost around c. US $50,000–180,000 to buy but once users are trained, they are simple to use. The scanners can be hired within the UK at commercial rates of around £800–2,500 per day. The lower end is just for the hire of the equipment, while the higher end includes skilled operator(s), data acquisition, and all spatial pre-processing.). During each survey 360^{o} scans were carried out at six locations across the site, these separate scans were combined using 9 semi-permanent reference points which were included within the dGPS.

Low cloud and fog prevented an initial attempt to carry out a survey, with the moisture in the air acting to reflect the laser thus producing a false return. The site was revisited on the 05/10/2010 to carry out a complete survey; a follow-up survey was carried out on 08/04/2011. Each scan underwent a series of processing stages; first the six scans were merged and georeferenced using six of the reference points. The high precision of the LiDAR scans allowed a slight improvement in the precision of the dGPS data. The overall spatial error of the merge was <1cm. The merged scans were clipped to provide a regular edged rectangular area totalling 2655 m^2 (59 x 45 m) (Fig 1). The resultant data were filtered to remove a small number of extraneous points caused by reflection of the laser beam from airborne particles such as dust. Photographs taken during the scanning process were stitched to provide a 360^{o} image of the scan area, and combined with the LiDAR data to give a true-colour point cloud showing the 3D geometry of the topographic surface. The high precision of the LiDAR scans result in very large data files, often with redundant data (i.e. points next to each other with the same height). This redundant data was removed using an octree filter; two filters were used to produce a low (20 cm) and high (2 cm) spatial resolution dataset (2.5 million and 25,000 measurements respectively), equivalent to average point densities of approximately 940 and 9.4 measurements per m^2 respectively. The output of each LiDAR survey was an ASCII file of XYZ point locations. Each dataset was meshed to form a terrain surface within ArcGIS before being converted to a raster format to allow statistical analysis.

2.3 Site-wide erosion and carbon loss estimate

As vegetation limits susceptibility to erosion, an estimate of the area of bare and eroding peat is needed if total losses/gains for the site are to be calculated. Remote sensing techniques offer automatic identification and isolation of objects and features in aerial imagery using pixel values, but their success relies on individual features having unique values which allow them to be isolated from the wider features. The diverse nature of vegetation and features across peatlands means that complex algorithms are often required to isolate individual features (Yallop et al., 2006; Yallop and Clutterbuck, 2009; Clutterbuck and Yallop, 2010). Aerial imagery for Valence Lodge Farm indicates that bare/eroding peat areas are spatially restricted, vegetation remains similar and there are no anthropogenic features present. Therefore, a basic pixel analysis could be employed to identify eroding and bare areas.

An analysis of the spectral bands of the particular set of RGB aerial photos used in this study showed that for the blue spectral band the majority of areas of eroded/bare peat had pixel values below 15, with vegetated areas having values above 15. The blue spectral band was therefore extracted and reclassified so that pixels/cells with a value of less than 15 were coded 1 and all those above were coded 0. Fig 2 shows the original image and the reclassified image side by side to illustrate the effectiveness of the technique in identifying bare/eroded peat at this site.

The carbon content of a volume of peat differs, both with depth and between sites, for various reasons, not least due to variations in bulk density. This makes it difficult to calculate the carbon loss associated with erosion without direct measurements of the carbon content and bulk density of the peat. The carbon content of UK blanket bog peat has been found to vary between 40 and 90% (Table 3) (Milne and Brown, 1997; Frogbrook et al., 2009) being highest in the upper 15 cm (Frogbrook et al., 2009). As erosion across Valence Lodge occurs within gullies the carbon content will vary across the slope as peat from all depths is exposed and eroded. Therefore, indicative carbon loss estimates were calculated using the site-wide erosion estimate and a number of published peat carbon contents to show the potential range of carbon losses likely to result from erosion at Valence Lodge Farm.

3. Results

3.1 Erosion pins

Erosion rates varied widely between pins (Table 4), with 110 experiencing erosion and 15 experiencing deposition. The highest erosion rate of 150 mm was observed at pin 7 in PS1 and the highest deposition of 35 mm occurred at pin 20 in PS1. The largest number of pins where deposition had taken place occurred at PS2 (10 pins), while only a single pin in both PS1 and PS5 experienced deposition. Many pins exhibited little change over time; where the difference in pin height over time was less than 5 mm the angle of many of the slopes and the difficulty in measuring in exactly the same location means that measurement error may account for the changes observed.

The area of PS1 and PS3 (16 m^2) was much larger than the other three pin sets (4 m^2). Therefore, the total volume of peat lost was higher for these two pin sets; the largest loss of 0.976 m^3 occurred at PS1 (Table 5). Of the three pin sets with the smaller area (4 m^2) the largest peat loss of peat occurred at PS4 at 0.209 m^3; more than double that rate observed at PS2 and PS5. When area is taken into account, the highest the lowest erosion rates were observed at PS1 (0.061 m^3 per m^2) and PS2 (0.0146 m^3 per m^2) respectively. The mean erosion rate for all five pin sets was 0.0383 m^3 per m^2 equating to an average surface peat loss of 38.3 mm.

3.2 LiDAR

To identify surface changes through time for both the high and low resolution datasets the relevant 2011 scan raster dataset was subtracted from the 2010 scan to create two new raster datasets (diff_2010-2011_02 and diff_2010-2011_20), both of which show large changes in surface topography across the site (Fig 3); however, not all of these changes relate to erosion. Well vegetated areas are unlikely to experience significant erosion while standing water acts as a reflecting surface, and therefore both need removing. Fig 4 illustrates how vegetation impacts the LiDAR scans results, with the difference between the two scans and one of the photographs taken during the scan clearly illustrating how the presence of vegetated areas can result in apparently large changes in topography. The photographs collected during scanning were used to digitise vegetated areas and the main channels where water was present. This raster was then used to remove any vegetated areas and channels from both the diff_2010-2011_02 and diff_2010-2011_20 raster datasets to create two new raster datasets (clip_diff_20102011_02 and clip_diff_20102011_20) each showing differences in surface topography across only those areas exhibiting bare/eroding peat (Fig 5). Slope and aspect were calculated for the clipped area to allow statistical analysis of the significance of these two variables on erosion.

The average erosion/deposition rate across the scanned area was calculated for both the 2 cm and 20 cm datasets. The high (2 cm) and low (20 cm) resolution LiDAR results indicate that excluding those cells with vegetation or standing water there was a net gain in the peat surface level of 2.5 and 6.6 mm respectively. Erosion and deposition varied significantly across the scanned area (Fig 5 and 6) with erosion being highest in the northeast section of the scan area (Fig 5). A small sub dataset was extracted from this area and even here the net surface lowering was only 4.3 mm.

A direct comparison between the two techniques can be made using data from PS5. The average erosion rate for PS5 was 26.8 mm, compared with a net deposition rate of 10.8 mm calculated using LiDAR.

3.3 Site wide erosion estimate

Pixel analysis of aerial photos indicates that within the main area of actively eroding/bare peat there is 26433m^2 (35%) of eroded/bare peat and 49464 m^2 (65%) of vegetated peat (Table 6). Based on the average erosion pin rate of 38.3 mm from a single winter (27 week period), the total loss equates to 1012 m^3 of peat. Assuming erosion rates remain constant throughout the year this is equivalent to an annual loss of 72 mm or approximately 1903 m^3 of peat. As only 35% of the area is actually eroding/bare the average rate of erosion across the site was 13.0 mm over the period between surveys, again assuming a constant erosion rate this equates to 24.6 mm yr^{-1}.

The LiDAR results indicate an average increase in the peat surface of 2.5 mm between the two surveys; this suggests that there was a c. 66 m^3 deposition of peat across the site. This equates to an average site wide deposition rate of 0.87 mm or an estimated annual deposition rate of 1.6 mm yr^{-1}.

3.4 Carbon loss estimate

Indicative carbon loss estimates were calculated for Valence Lodge Farm using the data in Table 7. The erosion loss calculated from erosion pins equates to a loss of c. 41 to 93 tons C. Assuming constant erosion rates, annual losses would range from 76 to 176 t C yr $^{-1}$. However, the LiDAR results indicate a net increase in the peat mass for the survey area. If this increase is solely attributable to the accumulation of new peat this equates to a net gain of carbon of between 2.7 and 6.1 tons or a gain of between 5.1 and 11.5 t C yr^{-1}.

4. Discussion

The two techniques for measuring erosion across Valence Lodge Farm produce very different erosion rates. Between September 2010 and April 2011 the erosion pin data indicate an erosion rate of 38 mm while the higher resolution terrestrial laser scanning method indicates a net deposition of 2.5-6.6 mm. Only PS5 was completely captured by the LiDAR survey with the results from this site clearly illustrating the differences between the two techniques. Here pin data indicated a decrease in the peat surface of c. 27 mm while LiDAR data indicated an increase of c. 11 mm. The standard deviation for the changes in surface topography using the 2 cm resolution data is 13.3 mm which is still significantly lower than the erosion rates calculated using the erosion pins. Approximately 88% of the total area included in the analysis exhibited vertical change less than ± 20 mm, decreasing to 58% for ± 10 mm (Fig 6).

These measured erosion rates equate to a carbon loss of between 41 and 93 t C based on the erosion pin data but a net increase of between 5.1 and 11.5 t C based on the LiDAR method. It is improbable that there was such a large net gain of carbon over this time particularly during winter, however the LiDAR results do suggest that estimates of carbon losses associated with blanket bog erosion measured using erosion pins may be large overestimates.

The average erosion rates for each pin set are within the range of annual erosion rates observed using erosion pins at other blanket bog sites across the UK (Evans and Warburton, 2007), albeit at the higher end of the range (Table 1) and are noticeably higher than those measured at Moor House also in the North Pennines, (10.5 and 19.3 mm yr^{-1}) (Philips et al., 1981; Evans and Warburton, 2005). However, much of Moor House has been naturally revegetating since the 1970s (Grayson et al., 2010). The erosion rates measured as part of this study are rates over a six month period, and therefore annual rates may well be higher. It should be borne in mind that the winter of 2010/11 was very cold with long periods of snow and ice particularly during late November and much of December, with December 2010 being the coldest December in more than 100 years (Met Office, 2011). The spring of 2011, however, was relatively dry, particularly during March. Hence, in addition to variability in erosion during any given year there will be inter-annual variability in erosion due to weather conditions.

The precision of LiDAR scans was constrained by use of semi-permanent reflector sites, with little movement occurring over the study period. In contrast, erosion pins can be subject to a number of processes which can result in vertical and horizontal movement over time (Labadz, 1988). This movement can be reduced by driving the erosion pins into the soil underlying the peat (Evans and Warburton, 2005). However, blanket bogs are often deep (several metres). Although full dGPS surveys of the erosion pins were carried out the accuracy of these is limited both by the small head of the pins, which make it difficult to accurately place the measurement staff, and by a desire to minimise any disturbance and damage to the peat during measurement.

The extremely low temperatures observed across much of the UK in December 2010 were accompanied by significant snow and ice which can have a direct impact on erosion pins through heave processes (Labadz, 1988). The weight of snow and ice on the surface could also potentially push pins further into the peat. This may explain some of the high erosion rates observed. Cold conditions may have resulted in significant erosion on steep, less stable gully sides via freeze-thaw processes, but had little impact on shallower slopes where low winter rainfall totals may have limited the removal of any loose material. Although fluvial erosion is likely to account for the majority of erosion across Valence Lodge Farm, visible wind-blown erosion features were observed across a number of peat surfaces and many pins had peat deposits stuck to the upslope side of the pin and slight scouring on the downslope side. However, no quantitative assessment was made of how much peat was separately eroded by wind processes. This wind scouring on the downslope side of the pin may have exaggerated actual erosion rate estimates across the wider peat surface.

Needle-ice formation within the upper peat layers during cold conditions can result in changes to the peat surface which could explain the increase in the peat surface identified by the LiDAR survey. Surface changes in a Canadian bog have been linked to needle-ice, with consolidation after melting resulting in bog-surface lowering (Campbell et al., 2002). It is possible that at Valence Lodge Farm any subsidence linked to consolidation after melting had not fully occurred, resulting in the surface being elevated relative to measurements made prior to winter. Alternatively, expansion of needle-ice during formation at or just below the peat surface results in the breakup of the peat, forming loose individual and aggregated peat particles on the peat surface. These individual particles are likely to be less well consolidated and have a higher volume per mass unit compared to peat not subject to needle-ice erosion. The effect on the peat surface would be a ‘roughening’ of the loose aggregates as larger voids are likely to occur between each aggregate than would be the case in an intact peat surface. This ‘roughening’ would be seen as an increase in the peat surface despite no actual deposition and no overall increase in the peat mass. Desiccation of the peat surface after long dry periods results in the peat surface drying and cracking, again resulting in loose particles and aggregates on the peat surface. While not particularly warm, the early months of 2011 were characterised by low rainfall totals and possible desiccation of the peat surface. This may also suggest that ‘mire-breathing’ (Kellner and Halldin, 2002) where the whole peat expands under wet conditions is unlikely to be the cause of the increased surface levels observed in the LiDAR scans – although this is a factor which should be accounted for in future LiDAR studies. The most likely explanation of the apparent increase in peat surface elevation over the winter is that both winter needle-ice formation and desiccation of the peat in spring resulted in the presence of loose particles and aggregates on the surface of the peat leading to a ’roughening’ of the peat surface, but with little being removed due to the lack of rainfall.

This pilot exercise suggests caution must be taken when interpreting erosion rates based on both erosion pins and LiDAR in peatland sites. However, the effectiveness of the LiDAR scanning technique for measuring potential erosion losses in the long-term is clear as long as seasonal surface roughening effects, vegetation change and mire-breathing are accounted for.

5. Conclusions and recommendations

This pilot study demonstrated that use of LiDAR offers considerable potential for measuring erosion rates on peatlands. Terrestrial LiDAR reduces the need to interpolate results between pins and removes any potential impacts of pins on erosion processes as well as any damage caused during installation and repeated pin measurements. It provides high resolution spatial data on erosion and deposition through time. In addition the study emphasises the need for great caution when interpreting or upscaling erosion pin measurements across study sites as results from the two techniques were very different.

Despite having overcome a number of problems associated with the application of LiDAR to measure erosion in blanket bogs further research is needed. The following would significantly enhance the application of the terrestrial laser scanning technique in blanket bogs:

1. The development of a filter to remove any vegetation from the scan data and allow the peat surface to be mapped would offer real advantages and greatly improve erosion and deposition measurements across blanket bogs, particularly in transition zones where vegetation cover is patchy or changing. Similar methods have previously been developed for aerial LiDAR data (James et al., 2006).

2. Once reference markers have been installed and the scan locations identified, repeat scans can be carried out relatively quickly enabling erosion measurements at a range of timescales. Regular LiDAR surveys offer the ability to examine changes through time including changes to surface roughness caused by frost action or desiccation and changes to surface height due to mire breathing. The high precision of the LiDAR technique and the large number of individual measurements (> 1 million points per m^2) means that with the right controls the LiDAR technique could greatly improve our understanding of the above processes. Thus regular surveys using LiDAR would allow:

- Quantification of the effects of roughness processes on peat surface levels and enable these processes to be accounted for so that actual erosion or deposition rates can be calculated more effectively over longer time periods.
- The opportunity to calculate erosion rates at various temporal scales such as changes due to individual storm events and changes over weeks, months, seasonally, annually and in the longer-term.
- The importance of different peat erosion processes to be identified which would improve understanding of the spatial nature of erosion processes in peatlands which impact landform development.

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Table 1: Peat erosion rates for England and Wales calculated using erosion pins, from Evans and Warburton (2007).

Location	Context	Period (Years)	Surface Retreat Rate (mm yr^{-1})	Reference
Moor House, N. Pennines	Gully walls	4	19.3	(Evans and Warburton, 2005)
Plynlimon	Hagg Faces	5	30.0	(Robinson and Newson, 1986)
Snake Pass, S Pennines	Gully walls	1	7.8	(Philips et al., 1981)
Moor House, N Pennines.	Gully walls	1	10.5	(Philips et al., 1981)
Holme Moss, S Pennines	Low angled peat margin	2	33.5	(Tallis and Yalden, 1983)
Holme Moss, S Pennines	Peat Margin	1	73.8	(Philips et al., 1981)
Harrop Moss, Pennines	Bare peat surface	7	13.2	(Anderson et al., 1997)
Snake Pass, S Pennines	Peat margin	1	5.4	(Philips et al., 1981)
Mid Wales	Ditch walls	1.4	23.4	(Francis and Taylor, 1989)
North York Moors,	Low angled bare peat surfaces	2	40.9	(Imeson, 1974)
S Pennines	Low angled flats	1	18.4 – 24.2	(Anderson, 1986)
Cabin Clough, S Pennines	Low angled eroded face	2	18.5	(Tallis and Yalden, 1983)
Doctors Gate, S Pennines	Low angled eroded face	2	9.6	(Tallis and Yalden, 1983)
Plynlimon, Wales	Peat faces	2	16.0	(Francis, 1990)
Forest of Bowland	Summit Peat	1	20.4	(Mackay, 1993)

Table 2: Site details for each set of erosion pins including the spacing used, total area, average, maximum and minimum slope across the set of pins and the average aspect and orientation of the set of pins.

Pin Set	Pin Spacing (m)	Area	Average Slope (degrees)	Max Slope (degrees)	Min Slope (degrees)	Average Aspect (degrees)	Orientation
1	1	16	18.00	32.75	0.04	170	S
2	0.5	4	17.88	49.13	5.44	172	S
3	1	16	28.63	40.27	16.32	179	S
4	0.5	4	34.36	52.52	21.62	152	SE
5	0.5	4	11.35	17.79	1.51	174	S

Table 3: Carbon content per m^3 of blanket bog peat within the UK from Milne and Brown (1997) and Frogbrook et al. (2009)

Reference	Site Location	Depth (cm)	kg C m^3
Milne and Brown (1997)	Scotland		47
Frogbrook et al. (2009)	Wales	0-15	79.59
Frogbrook et al. (2009)	Wales	15-30	60.57
Frogbrook et al. (2009)	Wales	50-65	40.08
Frogbrook et al. (2009)	Scotland	0-15	92.2
Frogbrook et al. (2009)	Scotland	15-30	68.6
Frogbrook et al. (2009)	Scotland	50-65	58.02

Table 4: Heights from peat surface to top of pin measured for each pin during surveys 1 and 2 and the difference between the two heights; negative numbers indicate erosion and positive numbers deposition.

Pin	**Set 1**			**Set 2**			**Set 3**			**Set 4**			**Set 5**		
	1st	2nd	**+/-**	1st	2nd	**+/-**	1st	2nd	**+/-**	1st	2nd	**+/-**	1st	2nd	**+/-**
1	15	35	**-20**	56	37	**+19**	58	66	**-8**	80	129	**-49**	68	140	**-72**
2	50	100	**-50**	100	108	**-8**	39	56	**-17**	49	150	**-101**	58	75	**-17**
3	62	143	**-81**	69	65	**+4**	35	85	**-50**	88	160	**-72**	70	100	**-30**
4	60	169	**-109**	53	74	**-21**	45	57	**-12**	66	81	**-15**	109	155	**-46**
5	54	170	**-116**	34	110	**-76**	60	156	**-96**	265	264	**+1**	70	93	**-23**
6	71	104	**-33**	48	60	**-12**	56	154	**-98**	193	266	**-73**	39	46	**-7**
7	35	185	**-150**	60	59	**+1**	104	168	**-64**	68	128	**-60**	56	74	**-18**
8	48	148	**-100**	75	82	**-7**	92	128	**-36**	51	75	**-24**	37	61	**-24**
9	43	90	**-47**	50	46	**+4**	69	125	**-56**	65	165	**-100**	53	44	**+9**
10	43	66	**-23**	43	35	**+8**	85	92	**-7**	85	86	**-1**	49	79	**-30**
11	49	69	**-20**	65	62	**+3**	35	42	**-7**	59	60	**-1**	50	63	**-13**
12	33	159	**-126**	35	43	**-8**	48	60	**-12**	30	120	**-90**	66	79	**-13**
13	44	66	**-22**	55	49	**+6**	40	58	**-18**	67	166	**-99**	60	93	**-33**
14	68	110	**-42**	28	28	**0**	35	45	**-10**	49	95	**-46**	74	102	**-28**
15	40	89	**-49**	85	137	**-52**	43	64	**-21**	93	110	**-17**	62	71	**-9**
16	95	130	**-35**	45	79	**-34**	50	103	**-53**	36	50	**-14**	34	46	**-12**
17	47	107	**-60**	30	84	**-54**	50	173	**-123**	50	75	**-25**	65	70	**-5**
18	47	132	**-85**	54	96	**-42**	55	109	**-54**	62	150	**-88**	64	81	**-17**
19	50	73	**-23**	64	70	**-6**	60	115	**-55**	40	90	**-50**	39	49	**-10**
20	35	0	**+35**	48	38	**+10**	74	45	**+29**	72	81	**-9**	60	115	**-55**
21	33	63	**-30**	29	17	**+12**	57	53	**+4**	40	60	**-20**	65	110	**-45**
22	115	127	**-12**	88	104	**-16**	50	83	**-33**	50	130	**-80**	54	102	**-48**
23	40	124	**-84**	50	96	**-46**	105	135	**-30**	32	136	**-104**	43	117	**-74**
24	30	103	**-73**	27	91	**-64**	60	121	**-61**	23	11	**+12**	28	48	**-20**
25	48	98	**-50**	49	59	**-10**	55	154	**-99**	44	48	**-4**	35	64	**-29**

Table 5: Erosion rates for each set of erosion pins, including the average change in surface height, the total volume of peat lost and the erosion rate for 29/10/10 to 8/4/11

Pin Set	Total volume loss (m^3)	Erosion Rate (m^3 per m^2)
1	0.976	0.0610
2	0.058	0.0146
3	0.658	0.0411
4	0.209	0.0523
5	0.090	0.0226
Mean		0.0383
Median		0.0411

Table 6: Results from the pixel analysis to identify bare/eroded areas of peat, including the total number of cells classed as eroded/bare or vegetated and the total area of each across the area outlined in red in Figure 2.

	No. of Cells	Cell Size (m^2)	Total Area		% of Area
			m^2	Hectares	
Eroded/bare	857426	0.030828	26433	2.64	34.83
Vegetated	1604505	0.030828	49464	4.95	65.17
Total			75897	7.59	100.00

Table 7: Indicative carbon loss/gain estimates due to blanket bog erosion/deposition at Valence Lodge Farm based on the erosion pin and LiDAR survey results and peat carbon content estimates from Milne and Brown (1997) and Frogbrook et al. (2009)

Reference	kg C m^3	C loss/gains from Valence Lodge (tons)	
		Erosion Pins	LiDAR
Milne and Brown (1997)	47	-47.6	+8.7
Frogbrook et al. (2009)	79.6	-80.6	+14.7
Frogbrook et al. (2009)	60.6	-61.3	+11.2
Frogbrook et al. (2009)	40.1	-40.6	+7.4
Frogbrook et al. (2009)	92.2	-93.3	+17.1
Frogbrook et al. (2009)	68.6	-69.5	+12.7
Frogbrook et al. (2009)	58.0	-58.8	+10.7

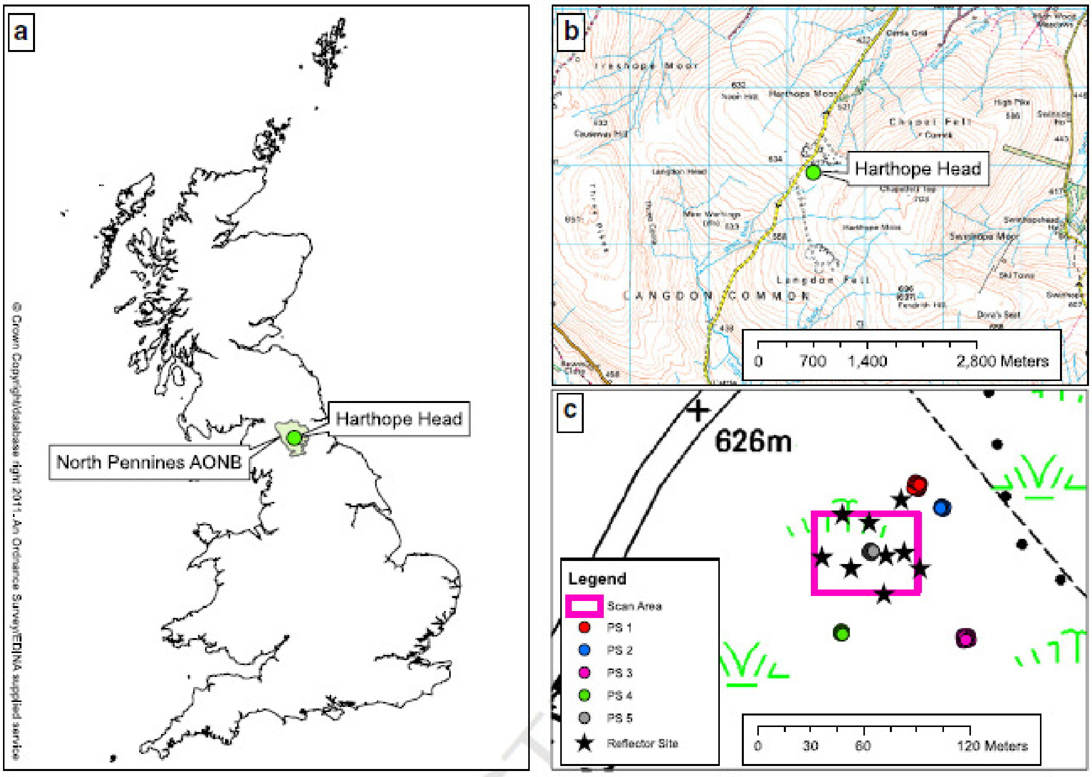

Fig. 1. Map showing the position of Valence Lodge Farm within the North Pennines AONB and the UK (a) and locally on Harthope Moor (b) and a detailed site map (c) showing the location of each set of erosion pins, the total LiDAR scan and the position of the reflector sites used during the LiDAR survey.

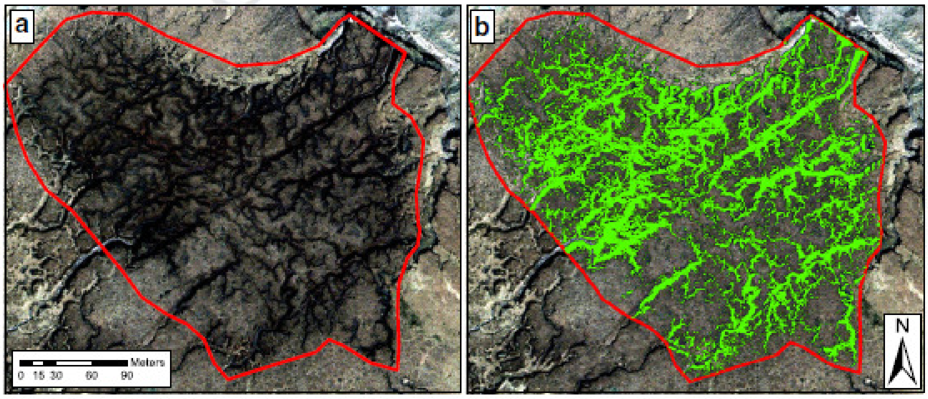

Fig 2. aerial image (a) showing the extent of bare and eroded peat across Harthope Head, the red outline shows the main area of erosion and the results of the pixel analysis (b) used to categorise bare/eroding areas of peat across the site, green shows those cells identified as bare/eroding.

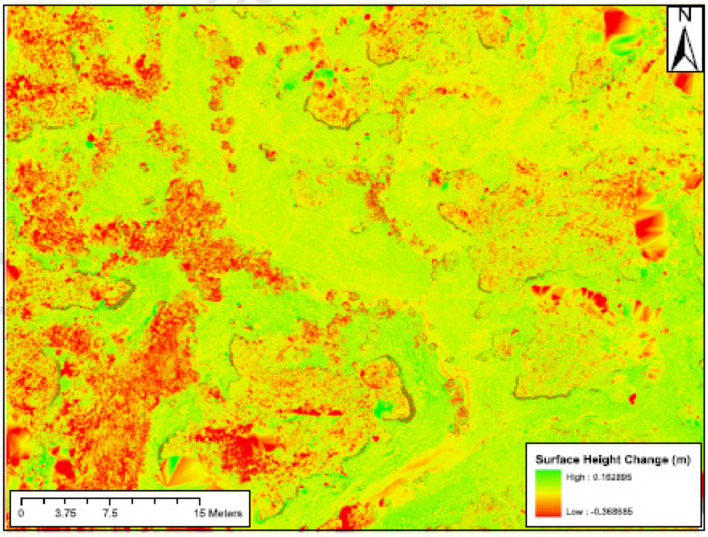

Fig. 3. Raster dataset showing changes in the peat surface height between October 2010 and April 2011 across the clipped LiDAR scan area at 2 cm resolution. Location of the survey area is shown in Fig. 1.

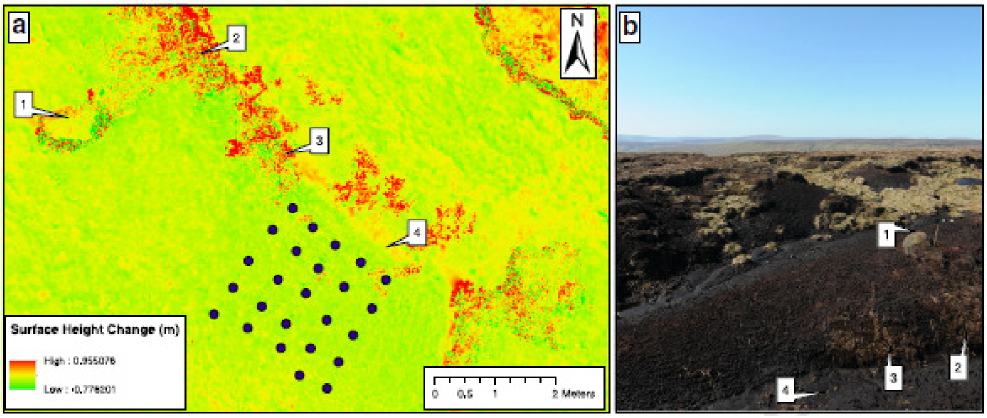

Fig 4. Impacts of vegetation shown in (a) the diff_2011-2011 raster dataset and (b) photograph. Annotations A and D show areas of vegetation and how these appear in the diff_2010-2011 raster dataset. Blue circles show pin locations for pin set 5.

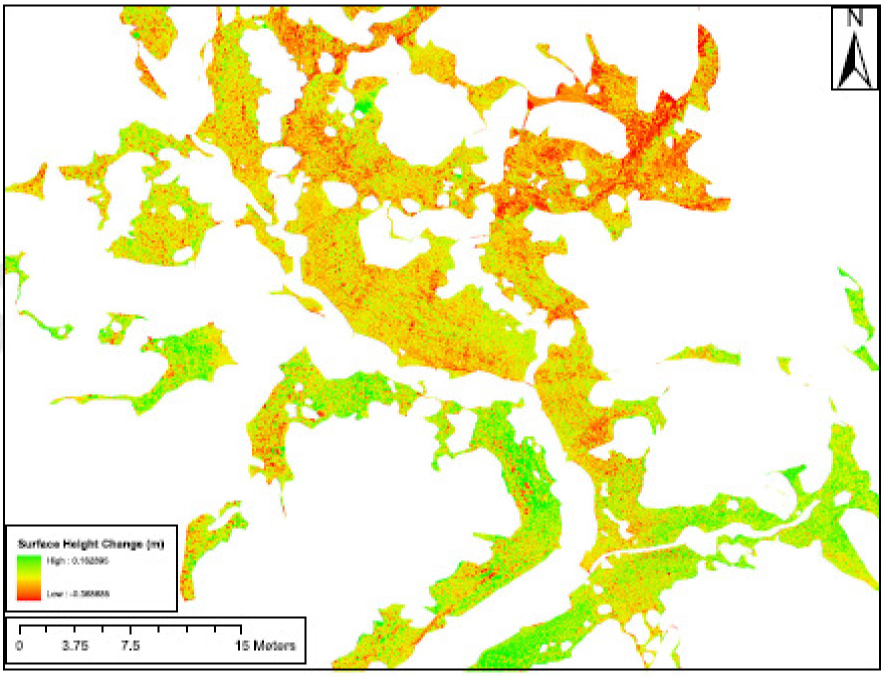

Fig 5. Raster dataset (2cm resolution) showing changes in the peat surface height between October 2010 and April 2011 limited to only those areas which are bare or eroded.

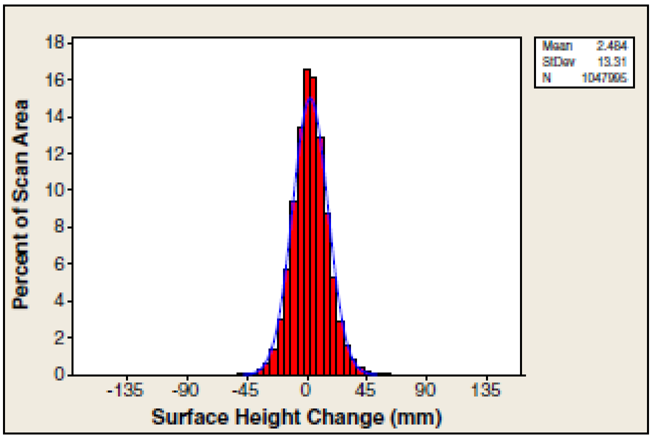

Fig. 6. Frequency distribution of surface height changes measured using the 2 cm resolution LiDAR data for Harthope Head.