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Published in:
Mires and Peat

Publication date:
2019

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Citation for published version (APA):

Sloan, T., Payne, R. J., Anderson, R., Gilbert, P., Mauquoy, D., Newton, A., & Andersen, R. (2019). Ground surface subsidence in an afforested peatland fifty years after drainage and planting. *Mires and Peat*, 23, 1-12. [06]. <https://doi.org/10.19189/MaP.2018.OMB.348>

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Ground surface subsidence in an afforested peatland fifty years after drainage and planting

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SUMMARY

In the UK, large areas of peatland were drained for forestry in the second half of the 20th century. Ground surface subsidence and diminishing depth (thickness) of the peat layer can indicate compaction of the peat and/or carbon loss, but there are few long-term datasets from afforested UK peatlands. Here we present an unprecedented 50-year time series of surface subsidence from Bad a'Cheo Forest (Caithness, Scotland). This site was initially surveyed for ground level and peat depth in 1966, prior to drainage and plantation, with repeat surveys roughly 20 and 30 years after drainage. We re-surveyed the site 50 years after initial drainage, producing a unique long-term time series to assess change since these historical studies. Significant subsidence has taken place since drainage, with an average reduction of 56.8 cm (or 13 %) in the depth of peat under forest stands. Subsidence of the peat surface was rapid in the initial phase after drainage and planting but has progressively slowed, with relatively little change between the surveys of 1996 and 2016. These results imply carbon loss but do not demonstrate it directly, as compaction of the peat is also probable. The subsidence data demonstrate that drainage followed by afforestation led to a considerable reduction in thickness of the peat layer and show how this evolved through time.

KEY WORDS: afforestation, Flow Country, peat, subsidence

INTRODUCTION

Globally, peatlands store up to 600 Gt of carbon (Yu 2011), and the fate of this large carbon stock is of considerable importance in the context of climate change (Charman *et al.* 2013). In addition, peatlands provide a wide variety of other ecosystem services including water purification and storage, cultural value and biodiversity (Littlewood *et al.* 2010). Peatlands are also managed for a variety of commercial purposes that often involve drainage, which is a key driver of carbon loss (Whitfield *et al.* 2011, Joosten *et al.* 2012).

Most UK peatlands are not naturally forested but large areas have been planted with trees. Forestry on deep peat initially presented huge challenges due to high water tables and low nutrient availability (Anderson 1997). However, development of new ploughing techniques, application of fertiliser and the introduction of North American conifer species made the afforestation of UK bogs technically possible in the second half of the 20th century (Oosthoek 2013).

Although there was doubt in some quarters as to whether a commercially viable yield could be obtained within the first rotation at many sites, the availability of generous tax incentives led to afforestation of extensive areas of deep peat (Mather & Murray 1988). Around 15 % (approximately 190,000 hectares) of the UK's deep peatlands were drained for forestry (Cannell *et al.* 1993). The practice ended only in the late 1980s, after controversy led to a change in tax law and an increase in protected areas (Stroud *et al.* 2015). The most extensive afforestation of deep peat during this period occurred in the Flow Country of northern Scotland. This is the UK's most extensive area of blanket bog, with around 400,000 ha of peat and wetlands of which around 67,000 ha (approximately 16.8 %) has been afforested (Stroud *et al.* 1987).

Drainage of a peat bog gives rise to several important processes. Primary consolidation is caused by loss of water from large pore spaces within the peat, as drainage directly removes water. Secondary compression occurs because more tightly bound

water is then gradually squeezed from the bottom layers of peat by the weight of overlying peat that is no longer supported by buoyancy. Thirdly, drainage enables oxygen to penetrate the upper catotelm, exposing the long-term carbon store to oxidative decomposition by bacteria and fungi, leading to increased production and efflux of CO₂ (Eggelsmann 1975). Water drained from the system also directly exports a large quantity of dissolved and particulate organic carbon (Freeman *et al.* 2001). If peatland is planted for forestry the peat may be further compacted over time as the weight of growing trees increases (Hobbs 1986). These processes are likely to result in subsidence of the ground surface and an increase in bulk density of the peat (Holden *et al.* 2004). While subsidence may simply reflect compaction of the peat body without carbon loss, the loss of carbon stock remains a distinct possibility. Thus, a reduction in thickness of the peat layer can be cautiously regarded as an indirect indicator that peat carbon loss may have occurred, and has been used to infer carbon loss in some previous studies (Leifeld *et al.* 2011, Hommeltenberg *et al.* 2014).

The largest quantity of data from subsidence studies on afforested peatlands originates from Fennoscandia. A survey of 273 forestry-drained peatland sites across Finland found an average of 22 cm of subsidence over 60 years, a figure low enough to suggest increased carbon storage in the system when tree biomass is included (Minkkinen & Laine 1998). Similarly, fen sites in Latvia have shown mean subsidence of 26 cm over 54 years (Lupikis & Lazdins 2017). Data from naturally open bogs, which are typically used for forestry in the UK, are rarer. On a bog in southern Norway, 70 cm of subsidence was recorded 26 years after drainage, fertilisation and establishment of naturally seeded Scots Pine (*Pinus sylvestris*) (Braekke 1987). Despite widespread recognition that subsidence is important and the relative simplicity of data collection, remarkably little long-term information has been captured on the subsidence of afforested bogs in the UK (Lindsay 2010). Indeed, the site we discuss here is, to our knowledge, the only afforested UK blanket bog for which a long-term data series exists.

Many UK peatland forestry plantations from the 1960s and 1970s are now ready to be harvested, so decisions must be made as to whether to restock the plantations or restore them to bogs. Restoration attempts to restore bogs through tree felling and rewetting (Forestry Commission Scotland 2015, 2016). To inform decisions about which option is more appropriate, quantitative evidence for how afforestation has affected the functioning of peat bogs and the ecosystem services they provide is

required. Biodiversity and the economic value of forest plantations are important concerns, but carbon loss is a particularly important factor due to the large amount of carbon stored in these systems (Yu 2011, Billett *et al.* 2010). This study combines ground level and peat depth surveys with historical datasets, to demonstrate the effects of drainage and plantation on a blanket bog over 50 years.

METHODS

Study site

The Forestry Commission's experimental plantation at Bad a'Cheo in Rumster forest, Caithness (coordinates 58° 25' 49.3" N, 03° 25' 41.3" W) is one of the most intensively studied afforested sites within the UK. The plantation occupies around 50 ha of ombrotrophic blanket bog at an altitude of approximately 90 m a.s.l. Degree of peat decomposition within the site ranges from H3 to H8 on the von Post scale, and typically increases with depth within the catotelm. Average bulk density of the top 3 m of peat is around 0.07 g cm⁻³ in the wetter open bog areas, rising to 0.1 g cm⁻³ towards the centres of the forest stands. Bad a'Cheo was initially surveyed for ground surface level (elevation) and peat layer thickness (peat depth) in 1966. The site was subsequently drained and ploughed with a double mould board plough, then afforested in 1968 in a randomised block design as a Forestry Commission experiment. The experiment comprises blocks of Sitka spruce (*Picea sitchensis*) and lodgepole pine (*Pinus contorta*) in monoculture, plus mixed stands with the same two species planted in alternate rows. There are plough furrows around 30 cm deep across the whole site, with drainage ditches up to 1 m deep spaced at approximately 20 m intervals. The water table is close to or at the surface near the edge of the site where there has been no drainage, but is considerably lower in drained forest stands. In 1989, a second randomised block experiment was set up on the unplanted control plots of the first experiment in order to test the performance and immediate hydrological impact of then-current afforestation options (Miller *et al.* 1996, Anderson *et al.* 2000). The entire plantation was felled in 2017, prior to wind farm construction, and our study was conducted in a brief time window before this work commenced.

The Bad a'Cheo site presents a unique opportunity to assess long-term change in peat layer thickness due to subsidence over a full growth cycle, from before planting to immediately prior to felling. The site has the further advantage that it was planted

earlier than the majority of UK peatland forestry plantations, and thus offers insights into future trajectories of change elsewhere. This study combines the results of a new survey of surface elevation and peat depth with data from previous surveys conducted in 1966, 1987 and 1996, to produce a unique long-term time series. We conducted surface levelling and peat probing surveys in 2016 and 2017, respectively, immediately prior to felling of the forest. Data were collected in three phases: i) a re-survey of transects previously surveyed by Pyatt *et al.* (1992) and Shotbolt *et al.* (1998); ii) a survey of two new transects across the site margins; and iii) the first site-wide survey of peat depth since 1966.

Previous studies

Since the initial drainage and planting, several studies have been undertaken to assess the impact of forestry and drainage. The results of these previous studies provide an important long-term data resource although their re-analysis is not straightforward (see below).

Prior to planting in 1966, peat depth was measured to the nearest 0.3 m at the intersections of a square grid with spacing approximately 55 m, the ground surface was optically levelled to the nearest 0.025 m, and a map of surface contours (vertical interval 0.15 m) produced. In 1987, Pyatt *et al.* (1992) assessed the effects on the bog of conifer

planting after 20 years. Their study involved optical levelling of the ground surface along three transects (Table 1). Further surveys were completed in 1996 and are reported by Shotbolt *et al.* (1998). On that occasion the ground surface was levelled along one of the original Pyatt transects and a new short transect, as well as at 101 random points across the site, and the results were compared with ground levels estimated by interpolation between the grid points of the original site survey.

Establishing transects

Previously surveyed transects were re-located using site maps, information on starting locations, and original markers (primarily dipwells and wooden posts) along the transects. These transects are referred to by the author name and number from the original publication (e.g. 'Pyatt 1' is the first transect surveyed by Pyatt *et al.* 1992, Figure 1). Transects Pyatt 1 and Shotbolt 2 were re-located with a relatively high degree of accuracy using on-site markers, although heavy windthrow meant that only 326 m of the original 430 m of Pyatt 1 could be re-surveyed. The exact starting point and approximate route of Pyatt 2 were identified, primarily using brashed avenues through the forest stand; but as no markers were found, the route of this transect was an approximate re-creation and the sampling points could not be relocated with the same level of

Table 1. Length and measurement history of transects at Bad a'Cheo. Data collection for the current study was in 2016, when all transects surveyed contained forest stands, internal open ground and undrained bog. 1966 surveys (marked*) are based on results interpolated from the initial site survey and have not been directly measured along the transects.

| Transect name | Date established | Original length (m) | Previous survey dates | 2016 resurvey length (m) | Accuracy of resurvey to original transect line |
|---------------|------------------|---------------------|-------------------------|--------------------------|--|
| Pyatt 1 | 1987 | 430 | 1966*, 1987, 1996, 2016 | 326 | Line resurveyed, last 104 m lost to windthrow |
| Pyatt 1a | 1987 | 87 | 1966*, 1987, 1996 | NA | Transect could not be located |
| Pyatt 2 | 1987 | 326 | 1966*, 1987, 2016 | 350 | Approximate line resurveyed |
| Shotbolt 2 | 1996 | 75 | 1966*, 1996, 2016 | 70 | Line resurveyed, last 5 m lost to windthrow |
| New 1 | 2016 | NA | 1966*, 2016 | 265 | NA |
| New 2 | 2016 | NA | 1966*, 2016 | 193 | NA |

accuracy as in the other transects (Table 1). To increase coverage across the site, two further transects (New 1 and 2) were added at the southern end of the plantation (Figure 1). Like the original transects, each of these new transects spanned a length of open, undrained bog as well as forestry plantation. Some previous survey points could not be relocated or were not considered suitable for resurvey. The 101 random points of Shotbolt *et al.* (1998) were not resurveyed because detailed location records were unavailable, and one short transect from Pyatt *et al.* (1992) could not be relocated.

During the initial survey in 1966, five metal pipes were drilled into the mineral layer underlying the peat at the corners of the site and used as benchmarks for the original ground level surveys. These markers were relocated, their locations were recorded using DGPS (Trimble, R8 GNSS/R6/5800), and they were again used as benchmarks for this study. As the DGPS system could not be used accurately under the forest canopy, only open bog sections were recorded and the remaining points were derived by interpolation.

Measuring ground elevation

Ground elevation was surveyed along the previously established transects (Pyatt *et al.* 1992, Shotbolt *et al.*

1998), and along the two newly-established transects. Previous surveys were carried out with optical levels, so similar equipment (Level Mark, AL10-32) was used for repeat measurements in this study. On the original transects the sampling intervals of the 1987 and 1996 surveys were reproduced, which gave 10 m intervals in the open bog and narrower more erratically spaced intervals in the forest stands (typically 1.0–0.3 m). In the new transects, open bog was surveyed at intervals of 5–10 m depending on the variability of the microtopography, and at 0.5 m resolution under the forest stand to capture the increased variability of these ploughed areas. The locations of sampling points along the transects on open bog were again recorded accurately using DGPS.

Measuring peat depth

Peat depth was surveyed along all the ground elevation transects, as above. In addition, we undertook a site-wide re-survey of peat depth for the first time since 1966. This survey was conducted along nine new transects established in 2017 (Figure 1, Table 2) and recorded at 5 m or 10 m intervals (Figure 1). Coring established that basal peat directly overlies sand, clay and rock in the site,

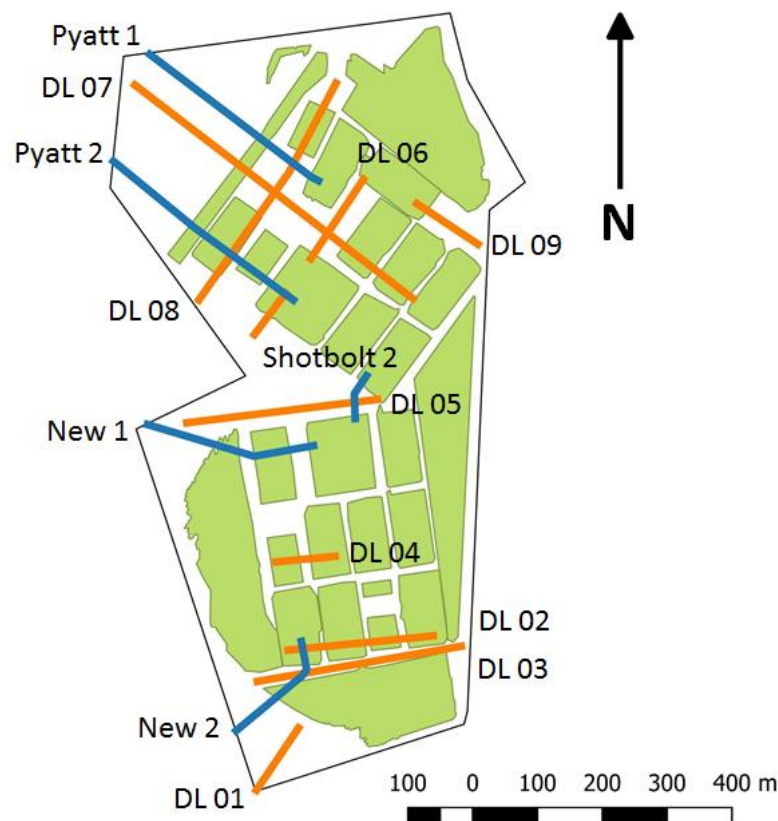


Figure 1. Bad a'Cheo peat depth and elevation survey locations. Blue lines indicate transects surveyed for ground elevation and peat depth. Orange lines indicate transects surveyed for depth only.

so peat depth was measured by inserting a sectional peat probe into the ground until it made contact with the substratum. Due to limited availability of the DGPS equipment and its unsuitability for use across a large forestry plantation, a GPS (Garmin, GPSmap 62s) was used to mark transect locations for later plotting against the 1966 depths.

Data analysis

In order to compare ground levels and peat depths between the various surveys, digital data were required so that interpolated values from before drainage and planting (1966 survey) could be compared with subsequent data gathered over the following fifty years.

Most of the raw data from the original 1966 surveys have been lost. Notebooks containing original elevation or peat depth measurements could not be located in Forestry Commission archives, meaning that a single paper survey map produced from these measurements was the only remaining data source. Scans of original notebooks from the more recent Pyatt *et al.* (1992) study were available, along with raw data from Shotbolt *et al.* (1998) in the form of an appendix to Shotbolt's thesis (Shotbolt 1997). These disparate data needed to be digitised and combined for reanalysis.

A high-resolution scan of the 1966 survey map was produced (Figure 2). GPS and DGPS data including corner points and benchmark locations, peat depth survey transect locations (GPS) and ground level transect locations (DGPS) were uploaded to QGIS (version 2.14.21, 'Essen'). Where tree cover had prevented accurate use of DGPS, missing survey points were added to the transect lines at the intervals at which they had been surveyed.

Using the benchmarks and additional corner points, the 1966 survey was georeferenced to the transect data. The contour lines of the 1966 survey were digitised and assigned elevation values converted to metres. These levels were used to produce an interpolated map of projected ground levels in 1966, using inverse distance weighting on a grid of 100 × 100 cells. Depth was also interpolated using inverse distance weighting from the 1966 map values, using the grid of survey points converted to metres and rendered in a grid of 100 × 100 cells.

Differences between interpolated values for the 1966 survey were tested to determine the change in elevation and peat depth since planting. Transects were divided and analysed separately in three classes based on the likely hydrological impact of plantation, namely: forest, undrained bog and internal open ground (IOG). In this way, measurements in areas of

Table 2. Description of additional transects added for depth surveys. 'Undrained bog' refers to areas extending from the edge of the plantation, where the hydrological impact of drainage will be diminished. 'IOG' refers to Internal Open Ground areas between forest stands which have not been drained for plantation, but may be impacted by the hydrological changes caused by nearby trees.

| Name | Length (m) | Number of points | Areas covered |
|------------|------------|------------------|----------------------------------|
| DL 01 | 110 | 11 | undrained bog |
| DL 02 | 320 | 33 | IOG |
| DL 03 | 250 | 26 | forest stand |
| DL 04 | 100 | 11 | forest stand |
| DL 05 | 300 | 61 | IOG |
| DL 06 | 230 | 46 | IOG, forest stand |
| DL 07 | 550 | 55 | undrained bog, IOG, forest stand |
| DL 08 | 400 | 41 | IOG, forest stand |
| DL 09 | 120 | 13 | IOG, forest stand |
| Pyatt 1 | 326 | 36 | Undrained bog, IOG, forest stand |
| Pyatt 2 | 350 | 33 | Undrained bog, IOG, forest stand |
| Shotbolt 2 | 70 | 16 | Undrained bog, IOG, forest stand |
| New 1 | 265 | 26 | Undrained bog, IOG, forest stand |
| New 2 | 193 | 17 | Undrained bog, IOG, forest stand |

undrained bog at the margins of the site (farther away from forestry) were separated from measurements taken in rides (narrow strips of unplanted ground separating blocks of forest) and on larger areas of internal open ground between the drained, planted blocks. This classification scheme differs slightly from the one used in some previous work on the site by Pyatt *et al.* (1992), which distinguished between unplanted bog > 10 m from trees, unplanted rides within 10 m of trees, and unplanted plot and ride 10–40 m from trees. Our reclassification aimed to simplify the categories and discard those with small numbers of data points.

Measured elevations were then compared with the previous Pyatt *et al.* (1992) and Shotbolt *et al.* (1998) measurements to determine the extent of subsidence over the final twenty years of the fifty-year forest rotation. During exploration of the notebooks containing data from previous surveys, it became apparent that while data for Pyatt 1 and Shotbolt 2 were usable, those for Pyatt 2 were unusable because benchmark data had been lost.

In each instance, Wilcoxon signed rank tests were used to compare pairs of measurements taken at the different sampling times (e.g. 1966, 2016 etc.) at each point (IBM SPSS Version 24).

RESULTS

Data quality and limitations

Before considering the results of this study, some possible sources of error should be acknowledged. Error during levelling surveys was found to average 4 cm, a figure comparable to previous surveys and relatively minor considering the difficulty of using optical levels on soft and wet peat surfaces. Shotbolt (1997) identified possible instrument errors in the 1987 measurements of the Pyatt 1 transect, on the basis that they suggested an improbable rise in ground surface level over the IOG section after afforestation. The difficulty of using levelling equipment on very soft bog surfaces means that the risk of recording error is high, and the marked disparity between the 1987 and both the 1996 and the 2016 recordings suggest possible problems with the 1987 survey across the IOG.

Ground elevation

Widespread and significant changes were found to have occurred across the site as a response to drainage and afforestation. Ground elevation was compared between the unplanted site in 1966 and the mature plantation in 2016 (Figure 3). Generally,

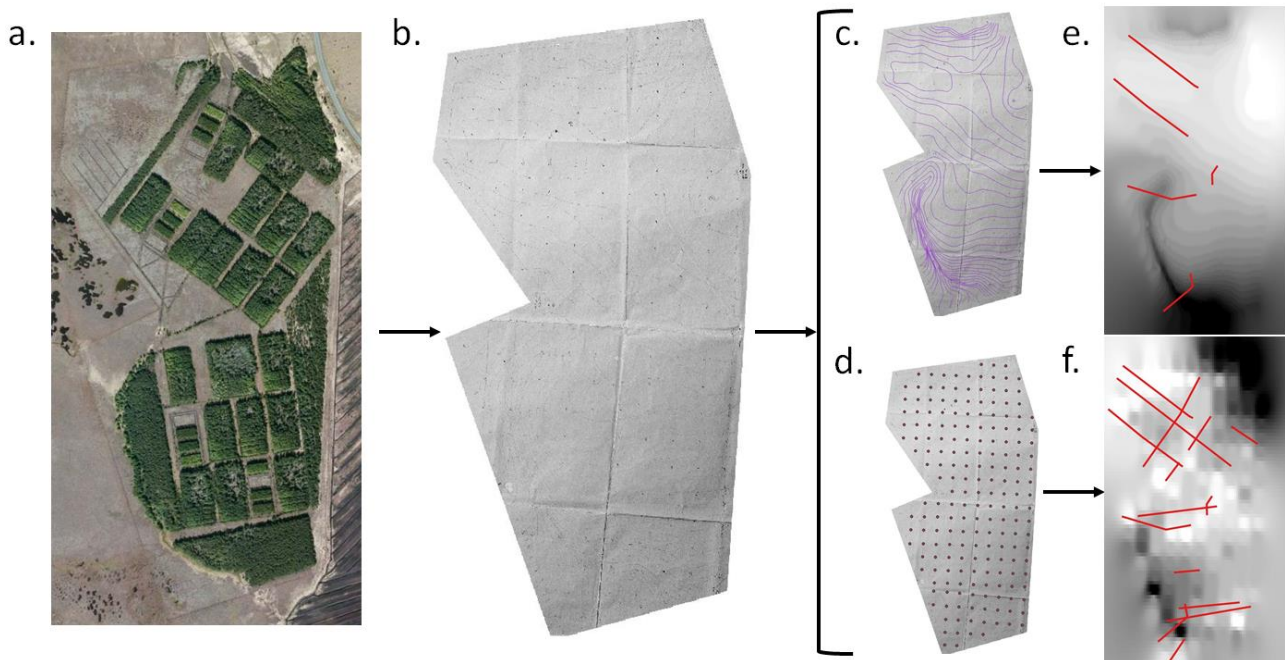


Figure 2. Data from Bad a'Cheo (a) were georeferenced to the 1966 Bad a'Cheo survey map (b). The values from the 1966 survey were used to determine likely surface elevation and peat depth. Contour lines (c) and peat depths (d) were digitised and interpolated in GIS to generate elevation and depth maps from which data for each of the transect sampling points could be extracted. Darker areas represent (e) lower elevation and (f) shallower peat, respectively.

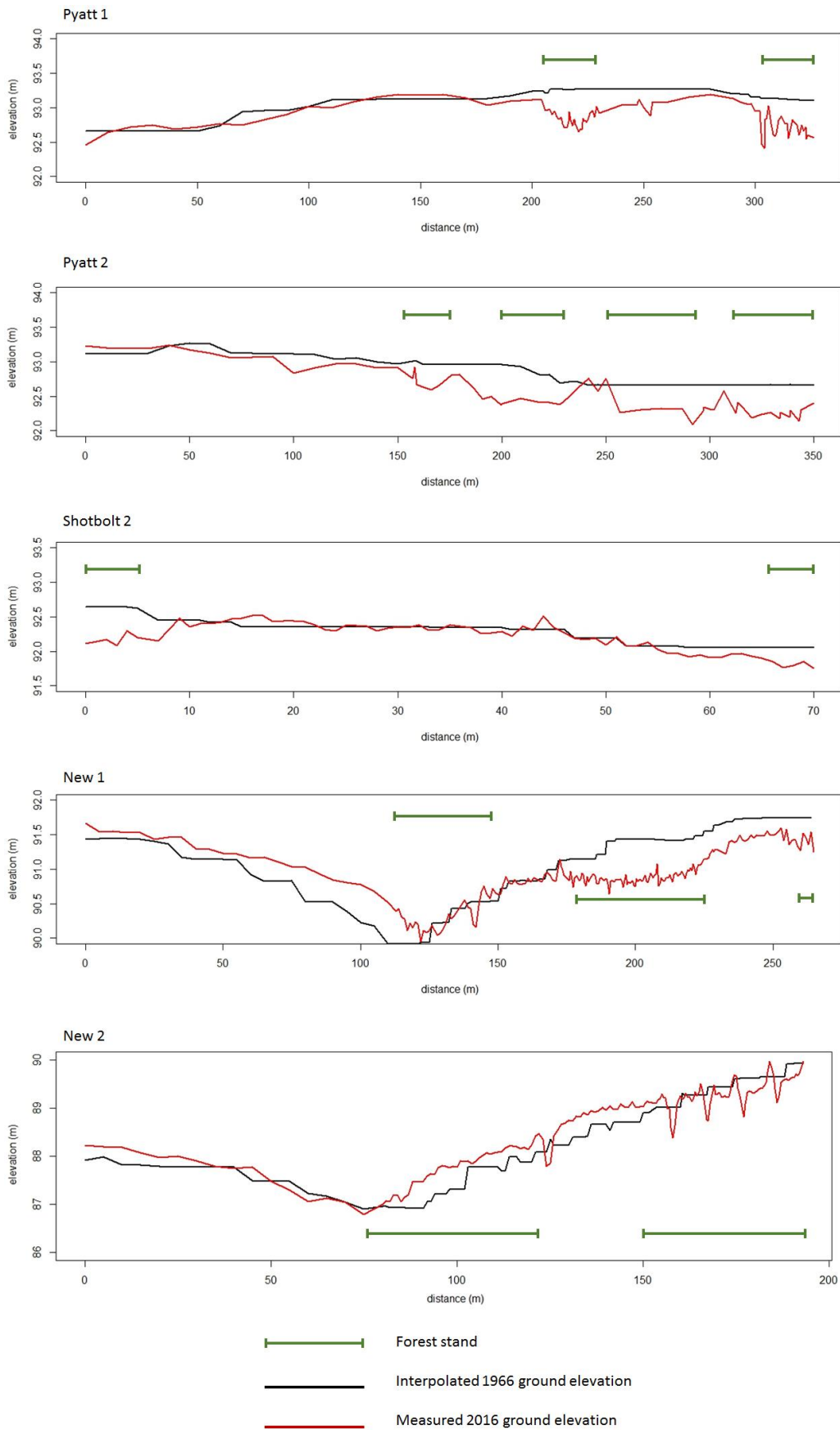


Figure 3. Ground surface elevation across Pyatt 1, Pyatt 2, Shotbolt 2, New 1 and New 2. The black lines indicate 1966 interpolated elevations and the red lines 2016 survey results. Green bars indicate the positions of forest stands.

drainage and planting led to a significant fall in ground elevation in all but one (New 2) of the forested sections of the transects, with average subsidence of up to 44.9 cm observed in afforested areas (Table 3). Most transects showed no significant change in ground elevation in the undrained bog sections of the transect, except for New 1 which was significantly higher than the 1966 interpolation (Table 3). Most IOG sections showed a highly significant drop in ground elevation since 1966, except for Shotbolt 2 which was unchanged ($n = 60$, $Z = -1.966$, $P = 0.490$) and New 2 which showed significantly higher elevation ($n = 27$, $Z = -3.772$, $P < 0.001$) (Table 3). An average reduction in ground elevation of 22.1 cm (35.7 cm if New 2 is excluded) was observed across the afforested portions of the site, with an average drop of 7.6 cm in IOG and a rise of 6.5 cm in undrained bog (Figure 4).

Where intermediate surveys were available, the ground levels from 1987 and 1996 were compared to the most recent data. In Pyatt 1, ground elevation did not change significantly between 1996 and 2016 in either the undrained bog ($n = 25$, $Z = -0.525$, $P = 0.600$) or the forest sections ($n = 45$, $Z = -1.801$, $P = 0.072$). A significant rise in ground level, on average 14.8 cm, had taken place in the IOG sections ($n = 31$, $Z = -2.274$, $P = 0.023$). Significant ground level subsidence since 1987 was found in both the IOG ($n = 9$, $Z = -2.666$, $P = 0.008$) and undrained bog sections ($n = 22$, $Z = -2.419$, $P = 0.016$) with an average fall of 21.3 cm and 5.4 cm, respectively. Data from 1987 suggests a rise in elevation in the IOG following afforestation; a finding which is surprising and calls into question the accuracy of the 1987 measurements, as previously highlighted by Shotbolt *et al.* (1998) (see above). There were insufficient data

Table 3. Results of Wilcoxon signed rank tests to determine change in elevation between 1966 interpolations and 2016 survey, with the average mean change in ground level between 1966 and 2016. The non-forested area is further divided into ‘undrained bog’ (extending from the edge of the plantation, where the hydrological impact of drainage will be diminished) and ‘internal open ground’ (IOG; between forest stands which have not been drained for plantation but may be influenced by nearby hydrological changes). N refers to number of points, Z is the test statistic, P is the significance, and GL refers to ground level.

| Transect | Undrained bog | | | | Internal open ground | | | | Forest stand | | | |
|------------|---------------|--------|--------|----------------|----------------------|--------|--------|----------------|--------------|--------|--------|----------------|
| | N | Z | P | GL change (cm) | N | Z | P | GL change (cm) | N | Z | P | GL change (cm) |
| Pyatt 1 | 25 | -1.951 | 0.051 | -5.08 | 32 | -4.937 | <0.001 | -28.67 | 46 | -5.905 | <0.001 | -44.9 |
| Pyatt 2 | 17 | -1.728 | 0.084 | -6.47 | 13 | -2.691 | 0.007 | -23.1 | 31 | -4.860 | <0.001 | -37.9 |
| Shotbolt 2 | NA | NA | NA | NA | 60 | -1.966 | 0.490 | -2.26 | 10 | -2.803 | 0.005 | -39.2 |
| New 1 | 23 | -4.197 | <0.001 | +25.9 | 53 | -5.219 | <0.001 | -16.4 | 148 | -9.152 | <0.001 | -32.5 |
| New 2 | 15 | -1.931 | 0.053 | +10.9 | 27 | -3.772 | <0.001 | +30.1 | 126 | -1.090 | 0.276 | +3.24 |

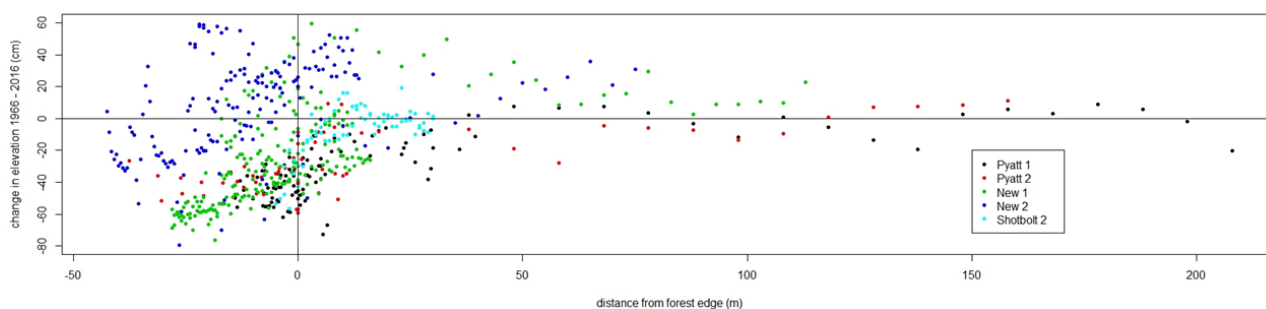


Figure 4. Change in ground elevation (cm) between interpolated 1966 points and measured 2016 plots, based on distance from plantation edge. Negative distance values reflect sampling points within the forest stand.

points to analyse changes in Pyatt 1 between 1987 and 2016.

The Shotbolt 2 transect showed no significant change under forest stands since 1996 ($n = 10$, $Z = -1.786$, $P = 0.074$) but a significant fall across the IOG ($n = 60$, $Z = -2.075$, $P = 0.038$) of 0.9 cm on average.

Peat depth

Mean peat depth under forest plantations decreased significantly between 1966 and 2016/17 ($n = 121$, $Z = -8.646$, $P < 0.001$). Peat depth of IOG also decreased significantly ($n = 193$, $Z = -4.820$, $P < 0.001$) while external undrained bog peat was not significantly changed ($n = 111$, $Z = -1.015$, $P = 0.310$). This represented an average peat depth loss of 56.7 cm (13 %) in forest stands, 24.7 cm (5.5 %) in IOG and 3.1 cm (0.6 %) in undrained bog (Figure 5). Average peat depth dropped from 435.3 cm to 378.6 cm in afforested areas, from 446.7 cm to 422.0 cm in IOG and from 475.1 cm to 472.0 cm in undrained bog. Overall, measuring peat depth indicated more extreme subsidence relative to the interpolated 1966 values than did measurements of ground elevation. Peat depth measurements showed average reductions in peat depth 9.6 cm, 17.1 cm and 34.6 cm greater than indicated by the

ground elevation measurements in undrained bog, IOG and forest stands, respectively.

DISCUSSION

Comparison of interpolated undrained ground levels and peat depths with repeat measurements 50 years after the drainage and afforestation of Bad a'Cheo reveals large changes. Significant reductions in both peat depth and ground elevation are observed under afforested areas. This subsidence and reduction in peat depth is also seen throughout the IOG, even though these areas have not been directly drained. This suggests that afforestation affects the areas of peat surrounding plantations, which may be important in estimating carbon loss and hydrological change in peatland forestry plantations.

The mean subsidence in afforested transects is of similar order of magnitude to the limited pool of other datasets for bogs, for instance the 70 cm of subsidence recorded by Braekke (1987). The average reduction in peat depth of 56.7 cm under afforested areas is larger than has been observed in peatland drainage areas, which comprise the bulk of the studies, and underlines the need for more data from afforested UK bogs.

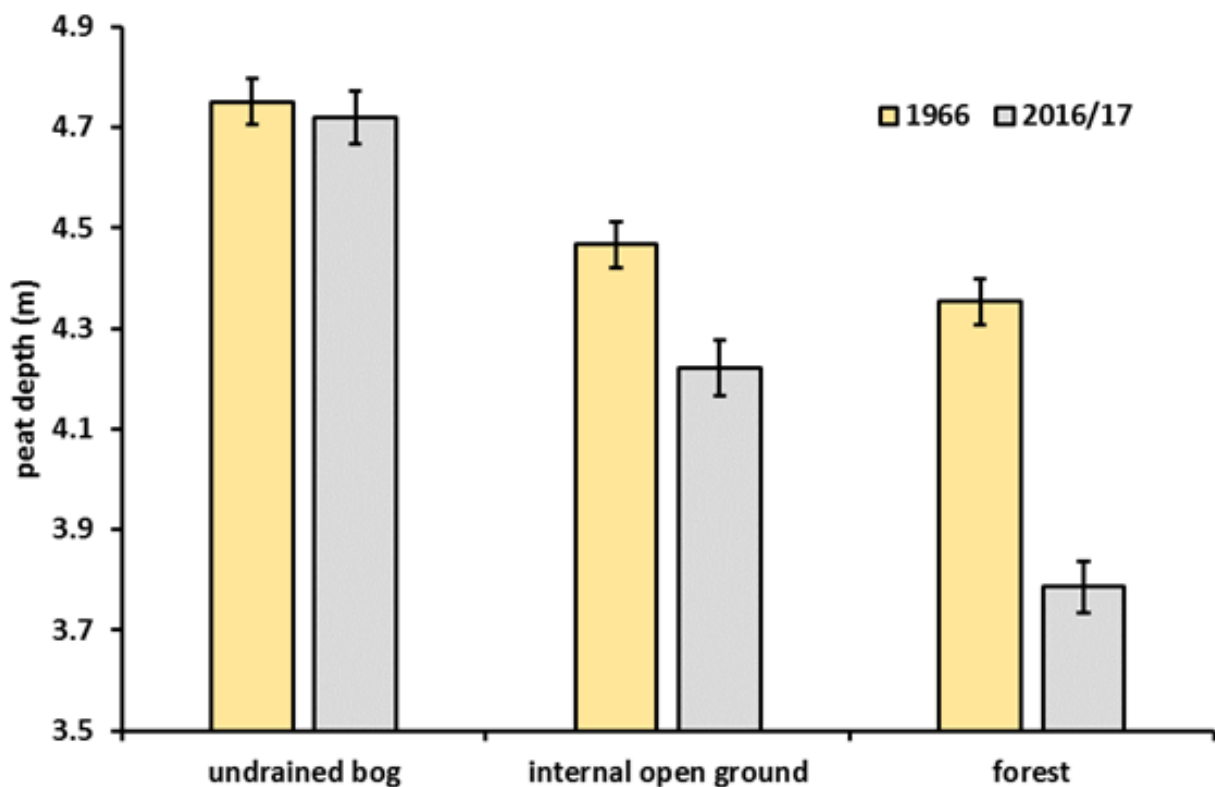


Figure 5. Mean peat depth across Bad a'Cheo: 1966 interpolated values and 2016/17 measurements, with standard error.

Analysis suggested a significantly lower elevation and reduced peat depth since 1966 in both afforested peat and IOG. The extent of the subsidence and reduction in peat depth suggests large changes in the density and volume of peat, possibly accompanied by a loss of carbon. The lowering of the water table likely to have been associated with the subsidence reported here may have led to changes in other peat soil properties and features such as peat cracking, which can make restoration more difficult (Holden *et al.* 2004). While the strongest subsidence and loss of peat depth occur soon after planting in the drained forest stands, we also find that the effects of drainage and afforestation have spread to the adjoining areas of peat, with peat significantly shallower than the 1966 interpolation in the IOG. The continuing subsidence across the IOG in Shotbolt 2 suggests that in some areas the impacts of afforestation on adjoining open peatland reported by Shotbolt *et al.* (1998) may continue over the life of the plantation.

In the Pyatt *et al.* (1992) study of the site, subsidence had been found to taper away 10–20 m from the edges of the forest plots, with the water table remaining unchanged beyond 20 m away. The lateral extent of the influence of subsidence at fifty years since afforestation is more in line with the 40 m observed by Shotbolt *et al.* (1998) after 30 years (Figure 4). This may represent the full extent to which surrounding bog is affected by drainage and plantation, achieved after roughly 30 years, although this figure has been disputed elsewhere as an under-estimation by up to 40 m (Lindsay 2010). Other factors, such as poor maintenance of drains, may also have played a part in limiting the spread of subsidence.

In the external undrained bog, subsidence in the Pyatt 1 transect was close to being significant (Table 3). This may be a result of how sections of the transect were designated as “external undrained bog”. We have used a loose definition which designates any section of transect at the edge of a stand, not enclosed on any other sides, as undrained bog. While this categorisation was ultimately felt to be best way to differentiate types of bog, earlier studies on the site have suggested that an alternative approach which differentiates bog adjacent to plantations may also be valid (Shotbolt *et al.* 1998, Lindsay 2010).

New 2 exhibited some unusual changes. While the undrained bog and forest stand were not significantly changed, the IOG surface was significantly higher than in 1966. Errors in the original survey map or in the interpolation may be a factor, especially as the transect has some of the steepest gradients on the site. Much of the forest stand in this section is shelter belt (an area on plantation edges designed to protect the

main forest stands from high winds), which was planted on ploughed ground but without any drains, thus differing from normal commercial stands. A lack of proper drainage would have meant that the water table remained relatively high, reducing consolidation and compression of the peat.

In the forest stands, no significant difference was found between the intermediate (1987 and 1996) and recent measurements. This suggests that the bulk of subsidence is related to initial drainage and planting, with relatively little change thereafter. More mixed results occurred in comparisons between 1996 and 2016 in the IOG sections of Pyatt 1 and Shotbolt 2, with the former increasing in elevation and the latter decreasing. This confusing picture, which contradicts the otherwise strong effects shown in the comparisons between 1966 and 2016, may be due to the difficulty of relocating the transects on the site. While the discovery of some markers allowed these transects to be recreated closely, the high variation in microtopography could mean that a location error of even a few cm could lead to a very different elevation from the original sampling point. For this reason, these recreated transects are perhaps not as useful as the data extrapolated from the 1966 survey maps.

As with other studies examining long term subsidence, the quality of old datasets will determine the reliability of conclusions. While this analysis used GIS techniques to interpolate data from the 1966 survey, replacing work that had been done by hand in previous studies, problems remain. The original survey used relief lines to map the ground surface, but these data would be too coarse to show small scale changes in ground topography. Peat depth can be even more variable; the 55 m × 55 m resolution of the original survey is insufficiently high to capture fine-scale variability, nor does it provide information on accrued errors revealed by back-sighting during levelling. Thus, it cannot reflect the original microtopography of the site. This may be reflected in the few improbable instances of larger peat accumulation since 1966 suggested by Figure 4. Such difficulties in interpolation may also explain the differences in subsidence indicated by the measurements of ground elevation and peat depth. However, considering the limitations of the older datasets available, this study represents the most thorough analysis possible. Other previous study sites on the bog were not re-surveyed. In particular, an investigation of subsidence across the forest rides between plantation blocks by Anderson *et al.* (1992) could not be repeated due to tree encroachment into these areas.

Felling of the forest began in March 2017. This left a short time window for a campaign of data

collection on the site. As a result, no account was taken of seasonal variation in ground levels driven by Mooratmung ('bog breathing'), although the effect is unlikely to be significant here.

Bad a'Cheo has been monitored for over 50 years, and has been the subject of studies focusing on many aspects of peat bog afforestation (Ray & Schweizer 1994, Miller *et al.* 1996, Anderson *et al.* 2000). The site has been managed and records maintained by the Forestry Commission, and the archives of raw data were invaluable in completing this research. Other long-term experiments of this type are rare, and whenever they are undertaken it is vital that all data are properly archived and made accessible so that future use can be made of these invaluable resources.

The large subsidence and changes to the depth of peat on the site suggest that carbon may have been lost from the system. There may have been related changes in the functioning and character of the bog, which may impede restoration. Work to quantify the exact nature of these changes is required, as this site may differ from the well reported Fennoscandian drained peatland forests which often require less drainage.

ACKNOWLEDGEMENTS

Assistance in the field was provided by Rebecca McKenzie and Gearoid Murphy. Thanks for advice on GIS given by Francesca Falcini, and comments on the manuscript from Roland Gehrels. Thanks to Innes Miller, Forest Enterprise Scotland and RWE/Innogy for site access. This work was funded by the Leverhulme Trust through grant RPG-2015-162.

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Submitted 31 Mar 2018, revision 08 Oct 2018
 Editor: Bartłomiej Głina

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