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From bare peat desert to nature reserve within ten years: a review of restoration practice on Little Woolden Moss, Manchester, UK

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Abstract:

Peat-harvesting results in significant carbon emissions and complete eradication of specialised flora and fauna on lowland peatlands; recovery can be lengthy, difficult and not always successful. This review documents the techniques and procedures used to transform a bare peat-milled site into a functioning nature reserve within a decade. Site preparation, planting regimes, and methods of measuring progress are discussed, and evaluation of the site's natural capital include three descriptive essays from an initial project officer, an experienced species recorder and a long-term volunteer. The aim of the review is both to celebrate the success of the venture and to offer experience gained to other lowland bog restoration managers.

Key words:

Peatlands, restoration, ecological management, ecosystem restoration, ecosystem services, natural capital, carbon sequestration and storage, GHG, biodiversity, *Sphagnum*.

1 Introduction

1.1 Peatlands and peatland damage

Northern hemisphere peatlands in good condition are a globally important resource for climate stability and provide a myriad of ecosystem services: the wet, acidic conditions promote carbon sequestration and retention of carbon stores (CCS), flood reduction, water storage and cooling effects, and support a wealth of specialized biodiversity, cultural heritage and recreation opportunities (Joosten, 2016; Crump, 2017). Degraded peatlands are significant sources of carbon greenhouse gases (GHGs) (Evans *et al.*, 2017), and their recovery can make substantial contributions towards mitigating climate change.

CCS in peatland has been highlighted as a significant (Freeman *et al.*, 2012) and cost effective (Moxey and Moran, 2014) resource. A diverse range of technologies and techniques will be required to prevent runaway global warming and additionally to begin the process of reducing atmospheric CO_2 to safe levels by mid-century (Hawken, 2018). Peatland protection and rewetting is currently rated as #12 of the 100 currently available best solutions (Drawdown.org, 2021). Peatlands hold a disproportionately large quantity of carbon in relation to their land surface area, with the plausible and economically realistic potential to remove 42 Gigatons of atmospheric CO_2 between 2020 and 2050 under a 1.5°C global temperature rise scenario (Drawdown.org, 2021).

Peat forms in a wetland environment where organic matter production is greater than decomposition (Vitt, 2013). In sub-arctic latitudes (50°N to 70°N), which store 90% of the global total peatland carbon (Yu, 2011), *Sphagnum* is key to the process of peat formation due to its ability to manipulate the chemistry of the peatland environment (van Breemen, 1995), engineering it to be wet, acidic, anoxic, low-nutrient and antimicrobial, inhibiting decomposition and retaining the carbon stored during growth (Verhoeven and Liefveld, 1997; Freeman *et al.*, 2012). *Sphagnum* bog, in good condition, has a layered substrate profile (Ingram, 1978; Clymo and

Bryant, 2008). At the base is an impermeable mineral layer, with a variable thickness of dense, waterlogged peat overlying – the catotelm. In intact peatlands the catotelm can be up to 10 m thick, is permanently waterlogged, and consists of organic carbon built up since the end of the last ice age at a rate of approximately 1 mm per year (Keddy, 2010). The catotelm transitions into the acrotelm, a 30-50 cm thick biologically active layer with a fluctuating water table. The acrotelm is loosely packed and hydrostatically porous, containing numerous plant roots, seeds and spores and dead plant material, and merges with the photosynthetically active surface of the bog (Clymo, 1984; Price and Whitehead, 2001; Quinty and Rochefort, 2003; Lindsay, 2010). Major plant species are *Sphagnum* and other mosses, sedges and dwarf shrubs.

The majority of lowland raised bogs in the UK have been severely degraded or destroyed and lowland raised bog is a UK BAP (Biodiversity Action Plan) Priority Habitat. Only 6% remains intact across the UK, and in England only 500 ha of 37,500 ha (1.3%) remains in good condition (Maddock, 2008). 2021 is the start of the IUCN Decade of Ecosystem Restoration (IUCN, 2021) which aspires to rebuild degraded or destroyed ecosystems with the intention of gaining multiple benefits. Peatland restoration has been identified as a significant part of this process (International Organization Partners of the Ramsar Convention on Wetlands, 2019; Rouquette *et al*., 2021).

1.2 Little Woolden Moss within the Chat Moss complex

Chat Moss is an extensive area of peatland (Bragg *et al*., 1984; Hall *et al*., 1995) on the edge of Salford, Greater Manchester, UK. Prior to the industrial revolution, Daniel Defoe (Defoe, 1724-1727: 11645) described 35 square miles of impenetrable wilderness, which was bounded by Glaze Brook and what are now the M60, A580 and A57 highways (Hall *et al.*, 1995). Most of Chat Moss has since been drained and converted to farmland, and some extracted for horticultural use. However, there are scattered remnants in a near natural state, and large areas of degraded peatland could be restored if made available. A recent report (Ashby *et al*., 2021) quantified the significant monetary value of the natural capital provided by the Chat Moss area, and restoration of its degraded peatlands will bring several benefits, most significantly in CCS. The value of Chat Moss as an educational resource has also been highlighted (Lageard *et al*., 2017).

Little Woolden Moss (LWM) (107 ha) was acquired by Lancashire Wildlife Trust (LWT) in 2012, initially funded through a £1m donation from the Heritage Lottery Fund, and together with the adjoining Cadishead Moss (8 ha) forms the largest nature reserve in the Chat Moss area (Figure 1). LWM was mechanically peat-extracted, leaving a bare peat site. The restoration work started on the eastern 55 ha of LWM "Phase 1" in 2013 and proceeded to the western 42 ha of LWM "Phase 2" in 2018, after the peat extraction license expired in December 2017. Areas of heath and scrub on the perimeter of LWM total about 10 ha.

Essential factors in peatland restoration are to maintain the water table at or near the surface to reduce oxidation, seal bare peat with growing plant material to prevent loss of the remaining peat through erosion and windblow, and establish *Sphagnum* mosses to restore the acrotelm and restart peat accumulation (Joosten *et al.*, 2012; Gonzáles and Rochefort, 2014; Bonn *et al*., 2016). One solution is the 'moss layer transfer' technique, developed in Canada (Quinty and Rochefort, 2003), whereby *Sphagnum* mosses and other plant material is cut and translocated from neighbouring sites and spread at a 10:1 ratio in a 2-3 cm-thick layer to re-establish an intact plant cover. However, due to the scarcity and vulnerability of peatlands in the UK, most sites capable of being 'moss layer transfer' donor sites have SSSI designation and protection, and cannot be harvested (Caporn *et al*., 2018), so an alternative approach is required. There is a small, local source of vascular plant material on the adjoining Cadishead Moss, both turfs and seeds, for translocation, but minimal amounts of *Sphagnum* are available, as mentioned above. Therefore, plant material had to be propagated on site or purchased from specialist growers as small plug plants. As plants gradually established on the site in sufficient quantity to permit sustainable harvesting, a labour-intensive process of translocation has become possible.

A remaining peat depth of 2 m is estimated as the minimum needed to maintain any hydrological stability (Lindsay and Clough, 2016). However, peat depths rarely exceed 2 m on restoration sites in the UK, and average 0.5 m on LWM, although in practice the depth of peat varies between a few centimeters and 2 m, depending on the topography of the underlying glacial clay/sand (Hall *et al.,* 1995). Moreover, mechanical peat extraction necessitates deep drainage, and without hydraulic support the remaining peat collapses under its own weight and the weight of heavy machinery, resulting in loss of pore space and hydraulic conductivity (Price *et al*., 2016), and with little ability to absorb and store water. The dry, friable surface is also vulnerable to further loss. Additionally, a legacy of industrial pollution, with deposition of heavy metals, sulphur and nitrogen further complicates the peatland restoration potential in northern England, although levels are low on LWM as contamination has probably been removed through deep peat extraction (Keightley, 2015). All of the above factors contributed to making restoration of LWM highly challenging, and intensive management and a nuanced approach have proved to be essential.

The past ten years of restoration have demanded a considerable amount of time, effort and resources, both by conservation professionals and a small army of volunteers. Also, fundraising and budget expenditure have been significant, amounting to approximately another £1m over the ten years of the project to date. Water is retained on the site with an extensive network of low peat dams (bunds) which has required over a year (across the project) of contract team work to construct.

The objective of this review is to summarise the progress made on this challenging site over the first decade of the restoration process and the valuable experience gained. Individual authors have contributed summaries of different aspects of the restoration process, providing quantitative or qualitative evidence of the way this has contributed to building the natural capital of the site over the past decade.

2 Early years

When LWT bought LWM (Heritage Lottery-funded), they were faced with an enormous task (as discussed in Box 1): recovery of a bare peat-milled site with very little peat remaining, and existing peat-extraction tenure at the west end.

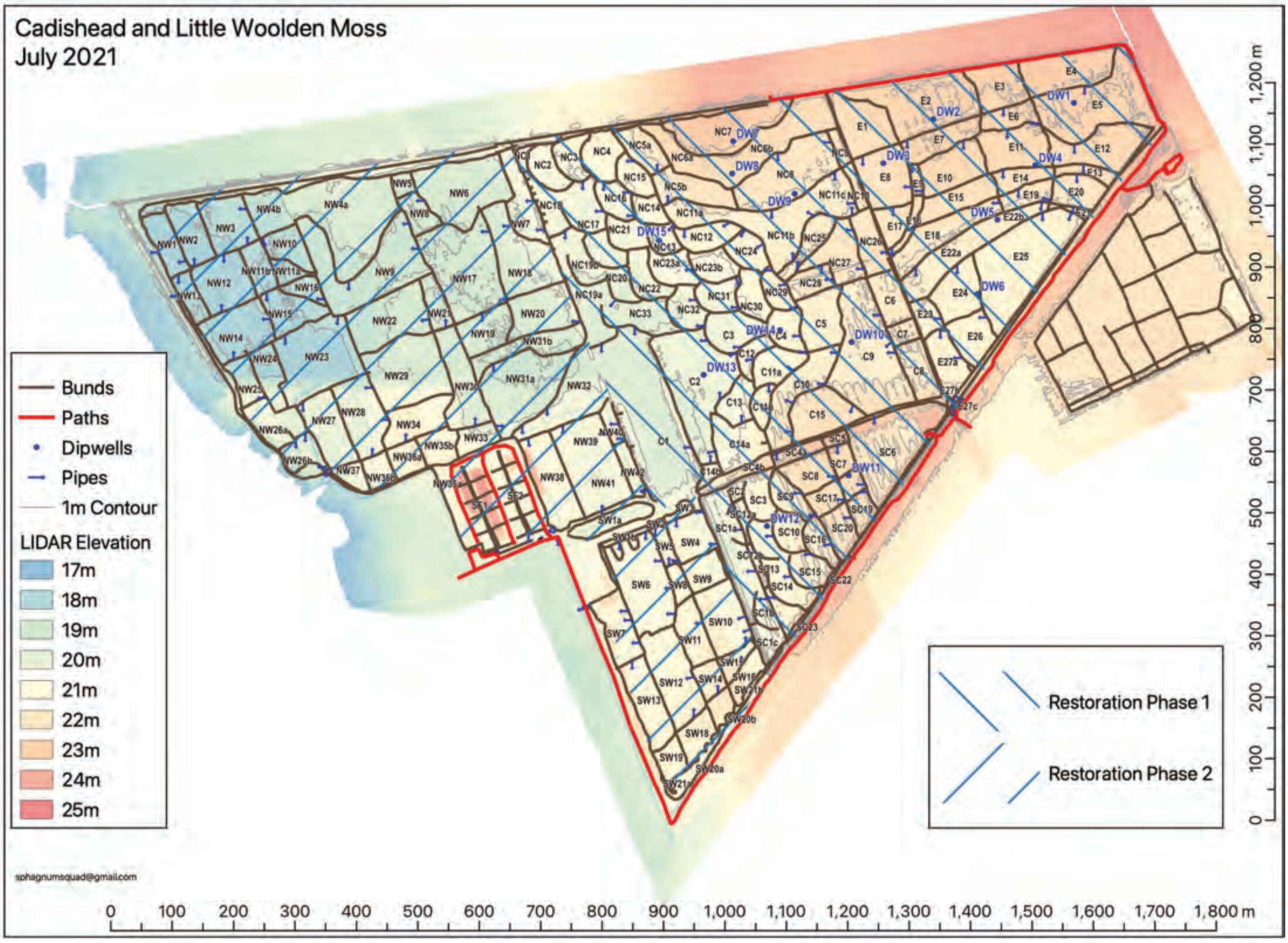

Figure 1: Cadishead and Little Woolden Moss (53.452, -2.467) site plan generated in QGIS. Phase 1 of the restoration consisting of 55 ha at the eastern end of the site has been under restoration since 2013. Cadishead Moss lies to the south and LWM Phase 2, which came under restoration in 2018, lies to the west. The site slopes westward from 24 m elevation in the northeast corner (Environment Agency open access 2019 LIDAR data), necessitating an extensive network of low peat dams (bunds) to pool water on the site. There are 15 dip wells within Phase 1, used for monitoring the water table level and individual compartments are numbered to facilitate detailed site management.

Box 1: The author of this descriptive piece was the first Chat Moss Project Officer (Chat Moss Project is now 'Lancashire Peatlands Initiative'). She initiated many of the early restoration methods, formed the first volunteer groups and started the 'Friends of Chat Moss'. Her essay is very evocative of the feel of the site, and the enormity of the job in hand, in the early years.

To step onto Little Woolden Moss for the first time in 2012 was a daunting prospect. Dark brown bare peat stretching as far as the eye could see, broken only by line after line of ruler straight drainage ditches crossing the vast expanse with regimental precision[1]. This was the Lancashire Wildlife Trust's newest nature reserve, and the job of the dedicated mossland team of the Trust to save what was left of the peat and start the gradual process of healing.

Bare, drained peat releases tonnes of carbon into the environment through a combination of oxidation (to carbon dioxide), run off (dissolved and particulate organic carbon) or direct sediment loss in the wind. Open and exposed with no shelter around, a site visit to the moss in those early days was sure to leave you with a fake tan of peat dust crusted around your ears, in your hair, and really anywhere else the wind could take it. The first priority for restoring the site had to be to stabilise the peat mass, by blocking the drains to raise the water table and establishing a surface cover of vegetation to keep that precious carbon locked in the ground and enable us to get on to the real business of establishing a functioning bog surface.

Whilst peat extraction continued on the western part of the site, the eastern area had been completely worked out, leaving behind an 'average minimum' of 50 cm peat. In reality, this meant some areas had no peat at all and so initial work, led by Dr Chris Miller, was focused on finding out just what peat was left to work with and then designing a complex series of compartments to try and make best use of the limited peat we had available for filling ditches and creating water retaining bunds to raise the water table.

Some vegetation did start to slowly make its way out onto the bare peat – good colonisers such as downy birch, rosebay willowherb and purple moor grass soon started popping up on bunds, with soft rush quickly taking over wet areas, particularly where the peat surface had been almost entirely lost exposing the clay layer beneath. Unfortunately, colonisation by 'proper' bog species was much slower and so a helping hand was needed to move things along. A fantastic team of volunteers worked tirelessly to plant a mix of cottongrass[2], heather and other shrubs across the site to kick start the regeneration. Handfuls of *Sphagnum cuspidatum* purloined from Cadishead Moss were chucked into anywhere that would reliably hold water, whilst trays of Sphagnum grown from fragments collected from LWTs other mossland reserves and lovingly nurtured on windowsills and in our site polytunnel, were nestled amongst sheltering vegetation that had manage to establish.

Ultimately, and ironically for Greater Manchester, water proved the greatest problem for the site. Many a time did we watch showers slip past the parched surface of the dark peat which was crying out for rainfall as it cracked and fried in the sun, only to be followed weeks (or months) later by deluges that would scour away at the delicate peat surface, taking with it tiny seedlings of plants that were just starting to get established. Our new bunds had been put in during the summer of 2013 which was largely hot and dry – ideal weather for moving a digger around on a peat site, but unfortunately not great for maintaining the condition of newly exposed peat and we soon found leaks springing up everywhere. A quirk of the underlying land surface also meant that one of the areas of deepest peat left, was also one of the lowest parts of the site, leading to a large lagoon forming[3]. It soon became a mecca for birders (and the local gull population) but wave action started to eat away at the bunds which were now being eroded from all sides.

Progress seemed slow, but for a site that started off as bare as the surface of the moon, it perhaps didn't take so long for the green springs of hope to take hold. The joy of finding Sphagnum happily growing in the southern drainage ditch for the first time, or cottongrass patches sprawling out from the small plugs planted months earlier, seemed all the sweeter because of the challenges that went into those successes. It will take some time before Little Woolden becomes a functioning lowland raised bog once more, but with its rate of progress ever increasing, and the dedicated team that look after it, the future is finally looking bright.

Elspeth Ingleby, 10th October 2021.

[1] Figure 3A. [2] Figure 5A. [3] Figure 1, compartments E23-E27.

3 Initial capital works and water level management techniques

Maintaining a high, stable water table through hydrological integrity is key to the process of restoring a degraded peatland (Joosten *et al.*, 2012; Gonzáles and Rochefort, 2014). Actions involving ditch-blocking, peat reprofiling and creation of cells by bunding were used to promote this in several stages as the site matured.

3.1 Ditch Blocks

Part of the process of peat extraction for horticulture involves large networks of drainage ditches (Gorham and Rochefort, 2003) which were mostly infilled and sometimes blocked during initial restoration work on LWM. Plastic piling dams may be used to block ditches, and have interlocking panels which provide additional, impermeable structural strength to ensure the dam does not fail or erode due to water movement. The aim is to raise water levels, prevent sub-surface flow and push water out of the ditch to the sides, thus reversing the drying effects of the ditch. They were installed in place of 'traditional' peat plugs where the ditch was large, water flows were high, on steeper gradients, or at ditch ends before they discharged into boundary ditches. These dams are usually supported by using locally borrowed peat placed behind the piling, although some may require additional strengthening by installing a fixed brace on the downstream side (wood or plastic rails/posts).

3.2 Re-profiling

Areas of post-extraction between old drainage ditches lie above the new water table, making overall rewetting very difficult. These areas are identified using surveys which include peat depth, hydrology, topography and LIDAR (Figure 1), and the correct level just above the water table level is assessed through laser-levelling (M. Champion, personal communication to M. Longden, 2020). After surveying, re-profiling is often undertaken using heavy machinery, including especially-equipped diggers and dozers, to move the excess peat to lower areas close by.

Figure 2: (A) A newly constructed bund, with shallow pools in adjacent scrapes. Credit is due to the skilled and painstaking work of the contractors, not least in employing heavy machinery on a treacherously soft surface; (B) Ply-gene installed in an old ditch line at a bund crossing point; pooled water visible uphill of the ditch block. (Images; M. Longden, A. Osborne).

3.3 Cell bunding and ply-gene sheeting

One way of restoring some hydrological function to a damaged bog, and creating localised control, is to create peat cell bunding (Schumann and Joosten, 2008) (Figure 2A). The positioning of these bunds to raise the water level has to be carefully planned to reduce water loss and movement across the site, taking into consideration the local topography and potential effects elsewhere (Gorham, 1991; Quinty and Rochefort, 2003). Bunds are created by first digging a shallow trench along the intended line of the bund, compacting the peat back into the trench, then constructing and firming a ridge on top, all ensuring a watertight seal. The bunds are constructed from the surrounding peat, particularly the higher ex-peat-extraction beds between old ditches, creating shallow scrapes – microrelief useful for later *Sphagnum* colonisation (Ferland and Rochefort, 1997). The bunds were designed to be approximately 0.4 m in height and be 0.8 m wide at the base, although height of bunds will always, to some extent, be determined by the available peat within the immediate area.

Where the bunds crossed the line of infilled ditches, the peat was removed from the old ditch until the mineral layer was reached, and a sheet of ply-gene inserted into the banks of the ditch. The ply-gene extended into the banks and the mineral layer underneath, to an extent at least half the width of the ditch. The peat was then compacted back into the ditch and the proposed bund run across its surface (Figure 2B). Overflow pipes with adjustable J-valves attached were inserted into bunds for better control of overall water levels across the site, and to prevent bunds bursting when volume was high after heavy rainfall. Systems of sluices with weirs were installed more recently, to relieve flooding from low lying compartments while maintaining permanent shallow lagoons suitable for colonisation with floating *Sphagnum cuspidatum*, the eventual aim being terrestrialisation of the open water with dense mats of *Sphagnum*.

4 Plant propagation and cover

Degraded lowland peatlands, particularly post-milling, are often left with a thin layer of poor-quality peat. Natural colonization with bog plants on an entirely bare site such as LWM is unlikely, the risk of more peat loss through wind erosion is high, and the surface is hostile to *Sphagnum* growth (Price and Whitehead, 2001; Price *et al*., 2003; Quinty and Rochefort, 2003). 'Nurse plants' have been successfully used to aid *Sphagnum* establishment, providing scaffolding and giving protection and shade from the drying effects of wind and sunshine (Grosvernier *et al*., 1997; Ferland and

Rochefort, 1997; Quinty and Rochefort, 2003; Pouliot *et al.*, 2011).

Sphagnum mosses are key species for northern lowland bog development (van Breemen, 1995; Rochefort, 2000) and re-introduction is seen as an essential factor in successful restoration (Rochefort *et al.*, 2003) to initiate new acrotelm development and promote long-term recovery of hydrological function and carbon accumulation and storage. Because natural sources are scarce and often protected (Caporn *et al.*, 2018), micropropagated BeadaMoss® *Sphagnum* moss products (BeadaMoss®, 2021) have been used in the restoration process on LWM, supported by *Eriophorum* spp. as nurse plants, and this has been an essential part of the restoration process.

Early plant propagation work was through collection of *Eriophorum* spp. seed from local sites, which was either scattered on site or germinated in trays and planted out. Rapid, reliable germination was achieved by first stratifying dry seed for two weeks in a domestic fridge. Early plants needed protection from grazing (Figure 5). Later, Common Cottongrass (*Eriophorum angustifolium*) turfs were translocated from the adjacent Cadishead Moss on to the east end of LWM. Initial progress was slow, particularly as personnel time was needed elsewhere on LWT-managed Chat Moss sites. Here, we describe several initiatives for site revegetation, each providing valuable experience, despite some proving more successful than others.

4.1 Translocating vascular plants

It was clear from the outset that getting a cover of vegetation on the vast expanses of bare peat would be a major priority before *Sphagnum* could be introduced, and several methods were tried. A number of curved 'greenhouse mesh' windbreaks (45 in all), held in place by metal rods, were established (1 m tall, around areas of approx. 5 m x 3 m in size) in bare peat areas on the prevailing windward side to protect planting from wind-drying (seen in Figure 6A). Turfs of *Eriophorum angustifolium* and *Eriophorum vaginatum* (Hare's-tail Cottongrass), harvested from nearby patches of established vegetation, were planted, stimulating more growth at the donor site as well as introducing mature vegetation into bare peat areas. High winds tore the windbreak material and bent the rods so they were removed within 2 years, but the plants established well. Overall, the turfs (planted March 2016) had grown by 503±466% after 6-7 months, and by 891±638% after 18 months, with more rapid growth in areas with greater surface moisture. It is now impossible to identify the windbreak areas as there is continuous *Eriophorum* spp. cover across this whole area. In hindsight, the transplanted vegetation would probably have survived without windbreaks, although they provided well-defined monitoring points.

Approximately 13,000 *Eriophorum* spp. turfs have been translocated by hand using spades and wheelbarrows from in-situ donor sites to nearby bare peat areas, readying the site for *Sphagnum* transplanting within this foundation vegetation. Subsequently, *Eriophorum angustifolium* and *Eriophorum vaginatum* plug plants have been purchased by LWT in very large quantities (approximately 200,000 to date) and planted by a combination of volunteers and contractors into the majority of the site, where conditions allow. Plug plants have been uprooted by foraging geese on the edge of water bodies, and have not survived in very dry areas of the site, so mature turfs of vegetation prove more successful in these areas.

4.2 Sphagnum propagation and proliferation

Sphagnum was regularly collected in small amounts from existing site locations (where allowed), cut into fragments and placed on peat (from the site) in seed trays, then grown on under cover until well-established, before being transferred into *Eriophorum angustifolium* areas in suitable locations at the east end of the site. A larger amount of *Sphagnum* was also collected, with permission, from a neighbouring site on Chat Moss, cut as before and scattered amongst newly planted *Eriophorum angustifolium* to create a large lawn of continuous *Sphagnum*, primarily as a nursery for future use. Additionally, there were large supplies of both *Sphagnum cuspidatum* (an aquatic species) and *Sphagnum fimbriatum* on the adjacent Cadishead Moss and these (within the 10% guide) were harvested and introduced across LWM. *Sphagnum cuspidatum* was distributed in handfuls into open water areas whereas *Sphagnum fimbriatum* was planted initially under *Eriophorum angustifolium* in the windbreaks described above in fist-sized clumps, leaving only the green top 5 cm above the peat surface. Subsequently, clumps of *Sphagnum* were carefully drawn from well-established hummocks and re-planted within *Eriophorum angustifolium* elsewhere on the site, as in the windbreaks. All of these methods have contributed to getting pockets of *Sphagnum* growing across the site, from where they can proliferate. *Sphagnum cuspidatum* in particular has spread exponentially in all wet areas, transforming the open pools across the site (Figure 3B), and also proving remarkably resilient after prolonged dry periods when pools have completely dried up.

BeadaGel™ is a BeadaMoss® product of *Sphagnum* mixed-species strands suspended in gel solution, and application was an innovative initiative in the early stages of restoration. BeadaGel™ was applied by volunteers to the peat surface under existing vegetation across the site, using backpack mounted pump dispensers. Unfortunately, the site was not ready for this material and, sadly, there is very little evidence of any surviving *Sphagnum*. This demonstrates that small trials need conducting on site before investing resources into large applications.

Latterly, very large numbers (almost 100,000 to date) of BeadaMoss® *Sphagnum* mixed-species plugs have been purchased and planted within vascular plant cover in suitable (i.e., moisture-retaining) areas of the site, where they have established well, and over time will develop into the acrotelm necessary for retention of moisture and carbon stocks, and subsequent peat accumulation.

4.3 Scrub control

Scrub (*Betula* spp. particularly) can be a persistent problem on lowland peatlands (Campbell and Rochefort, 2003; Alonso *et al*., 2012), particularly on degraded sites. Scrub further lowers the water table by impeding rainfall from reaching the peat surface (Zając *et al*., 2018) and through leaf transpiration (Fay and Lavoie, 2009). Nutrients are added through deciduous leaf fall, encouraging growth of non-bog species which outcompete slower-growing bog plants (Money and Wheeler, 1999; Zając *et al*., 2018). Many volunteer hours have been spent clearing scrub. Cutting and painting the stumps with herbicide to prevent re-growth has proved to be more efficient and less destructive on the establishing moss carpet than lifting entire root balls. The material removed has been useful in creating wave-breaks in larger water areas (seen in Figure 3B) to both reduce bund erosion and retain *Sphagnum cuspidatum in situ*.

4.4 Managing water levels, monitoring conditions and prioritising work

Successful planting relies on the right site conditions, and managing water levels is key if the site is to reach its intended lowland bog status. The 28 km of bunds creating 167 sealed compartments across Phase 1 and Phase 2 (by 2021), and linked by water-flow pipes, have made a huge difference to the site's ability to retain water at efficient levels. Controlling the lateral movement of water between these compartments to achieve optimum levels throughout needs fine-tuning and monitoring. The site is now holding far more water in the right places but there are still many compartments where levels are too low or too variable.

Volunteers have worked on monitoring site progress and identifying priorities, including vegetation surveys, establishing trial plots to monitor planted *Sphagnum* growth and spread, *Juncus effusus* and scrub control, use of Coir materials to stabilize bunds and retain aquatic *Sphagnum*, monthly dipwell monitoring (Figure 4 and 5.1 below), and carried out an extensive survey of all compartments in early 2021 to monitor species abundance and prioritise future work.

5 Monitoring restoration progress

Several techniques have been used to monitor restoration progress, guide ongoing work and also provide useful information to funders and encouragement for team members during the past decade of activity.

Figure 3: Progress on the east end of LWM. (A) 2012, bare peat with open drainage ditches running north-south; (B) 2021, over 90% vegetation cover with pools successfully colonised with Sphagnum cuspidatum (bright green), which reduces evaporation from the open water (black); bunding visible, and a dry hedge running north-south breaking up the large central pool. (Images: Google Earth).

5.1 Water table monitoring

Water table is of fundamental importance to bog plant establishment and carbon balance of peatlands (Evans *et al.*, 2017). Monitoring in Phase 1 has been undertaken with an array of 15 dipwells, fully installed by 2015. Dipwells were randomly sited within each major compartment and measured monthly (Figure 4). The water level is unstable, changing rapidly according to recent rainfall but has steadily increased over the monitoring period. Statistical analysis was performed in R v.4.0.4 (R Core Team, 2021) using R Studio v.1.4.1106 (RStudio Team, 2021) in order to test the hypothesis that "Water Table Depth" has improved during the course of the restoration work ("Date"). Linear regression of dipwell data shows that Date significantly predicts Water Table Depth (F: 19.92 on 1 and 940 DF, Adj R^2=0.020, p<0.001). Date significantly predicts improvement in the problematic summer Water Table (F: 7.80 on 1 and 252 DF, Adj R^2=0.026, p=0.006) and autumn Water Table (F: 23.06 on 1 and 223 DF, Adj R^2=0.090, p<0.001). Other seasonal trends did not achieve statistical significance. Dipwells 7 and 15 are frequent outliers in the earlier part of the series, probably due to their relatively elevated local topography (see LIDAR elevation contours in Figure 1).

5.2 Photography

Geo-tagged photographic time-sampling (Lindsay *et al.*, 2019) documents encouraging changes in vegetation cover, with large areas of near confluent *Eriophorum angustifolium* and *Eriophorum vaginatum* cover now established (Figures 5 and 6).

5.3 Remote sensing

Remote sensing data was acquired using publicly available satellite images from the Earth Explorer website of the USGS (United States Geological Survey). Landsat 8 images were available from 2013 onwards, enabling data to be collected retrospectively as suggested by Lindsay *et al.* (2019), in order to produce a time series of the Phase 1 restoration. Surface Reflectance (SR) series images, which had been pre-corrected for atmospheric reflectance (Vermote *et al.*, 2016) were downloaded, allowing a calibrated series of images to be constructed (Figure 7). Spectral bands were processed in QGIS v.3.16.5 (Development Team, 2020) to produce Normalized Difference Vegetation Index (NDVI) (Rouse *et al.*, 1974) map layers in order to quantify green vegetation cover. Images captured in mid-late summer were selected in order to coincide with peak vegetation

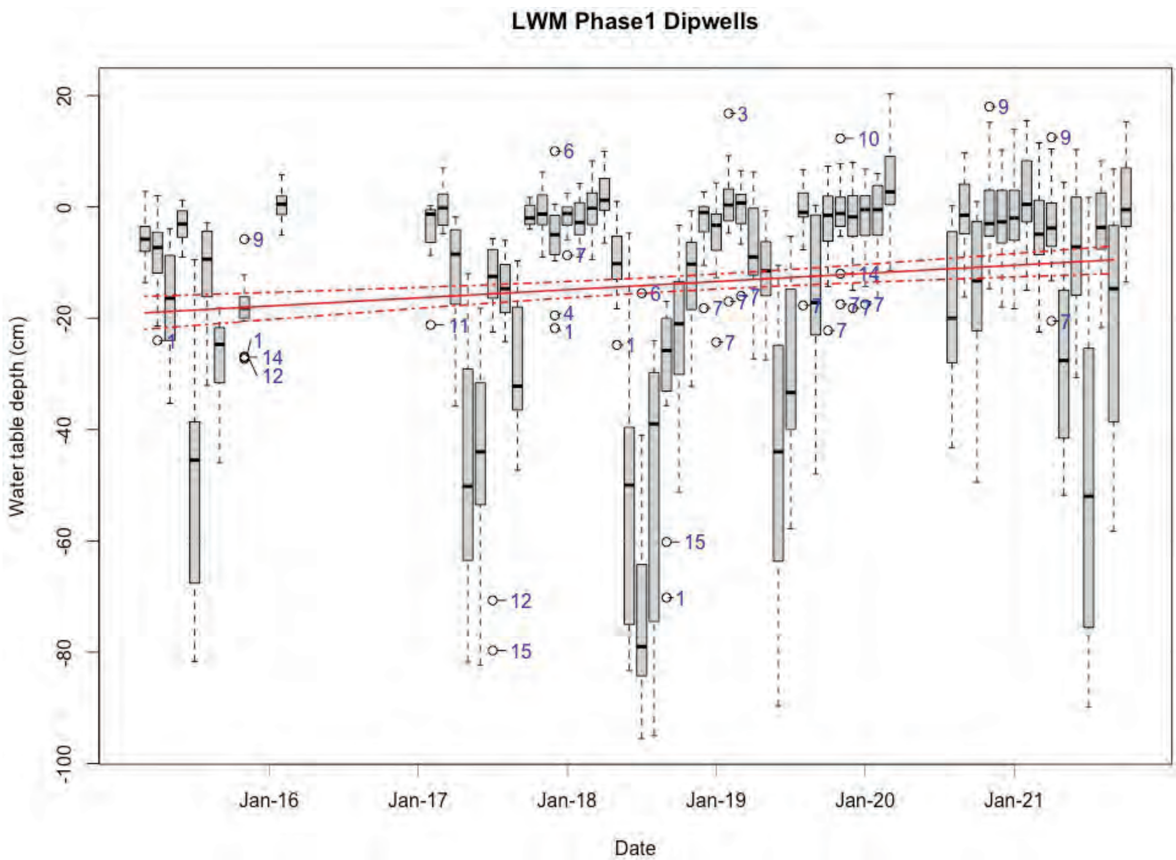

Figure 4: The box plot shows the range of water table depths below the peat surface. The regression line (red) and confidence limits (red dashes) confirm significant overall improvement. Dipwell outliers (blue) become less frequent after the last phase of bunding was completed in late 2019.

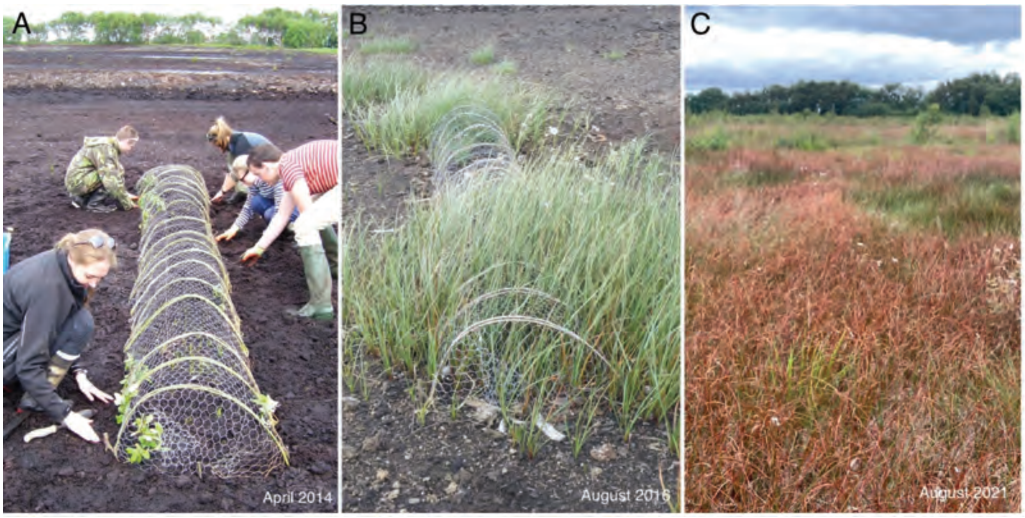

Figure 5: Looking East across compartment E13 (Figure 1). (A) 2014, early in the restoration, volunteers planting E. angustifolium *plugs under wire mesh; (B) 2016, rapid rhizomatous spread of* E. angustifolium *on bare peat; (C) 2021, confluent ground cover mainly with* E. angustifolium*. (Images: A. Keightley).*

biomass (Rafique, 2019). Shape files were imported into R for statistical analysis in order to test the hypothesis that NDVI has improved during the course of the restoration work. Linear regression of pixel data demonstrated that Date significantly predicts NDVI (F: 1486 on 1 and 5653 DF, Adj R^2=0.208, p< 0.001). This series of Landsat 8 images (Figure 7) documents progress on the ground, borne out by the photo series in Figures 5 and 6. Seeds and plug pants were slow to establish, but progress over the past three years has been increasingly rapid. There are still patches of bare peat, even in well vegetated areas, which are more apparent viewed from above (Figures 3 and 7), than in photographs taken at ground level (Figures 5 and 6).

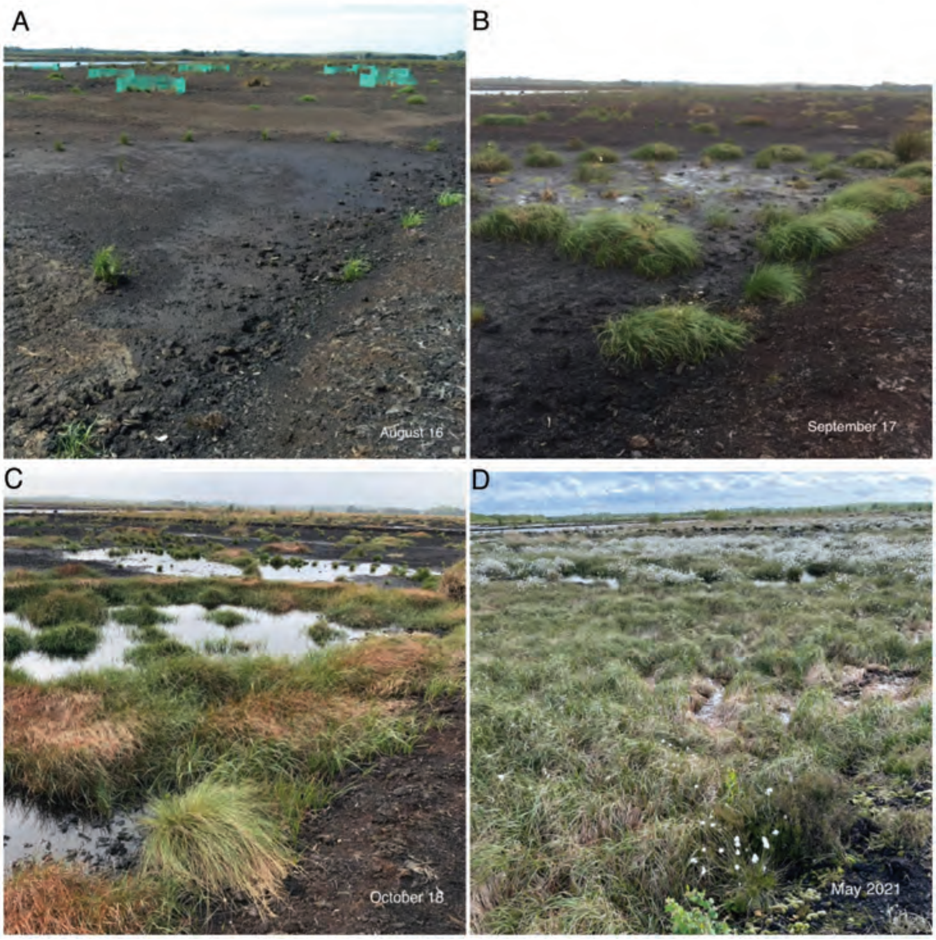

Figure 6: Looking Southwest across compartment E11, from the bund adjacent to the pipe running out of E6 (Figure 1). (A) 2016, small turfs of E. angustifolium *transplanted into a wet depression in an old ditch line; the mesh windbreaks in the background were planted with cottongrass turfs in an effort to establish ground cover, which was proving difficult 4 years into the project; (B) 2017, rapid growth of the transplanted turfs, in favorable growing conditions; (C) 2018,* E. angustifolium *clumps now becoming confluent, and spreading onto the bund (right); (D) 2021, near confluent ground cover, ripe 'bog cotton' visible on* E. vaginatum *is an important seed resource, driving the restoration process forwards. (Images: A. Osborne).*

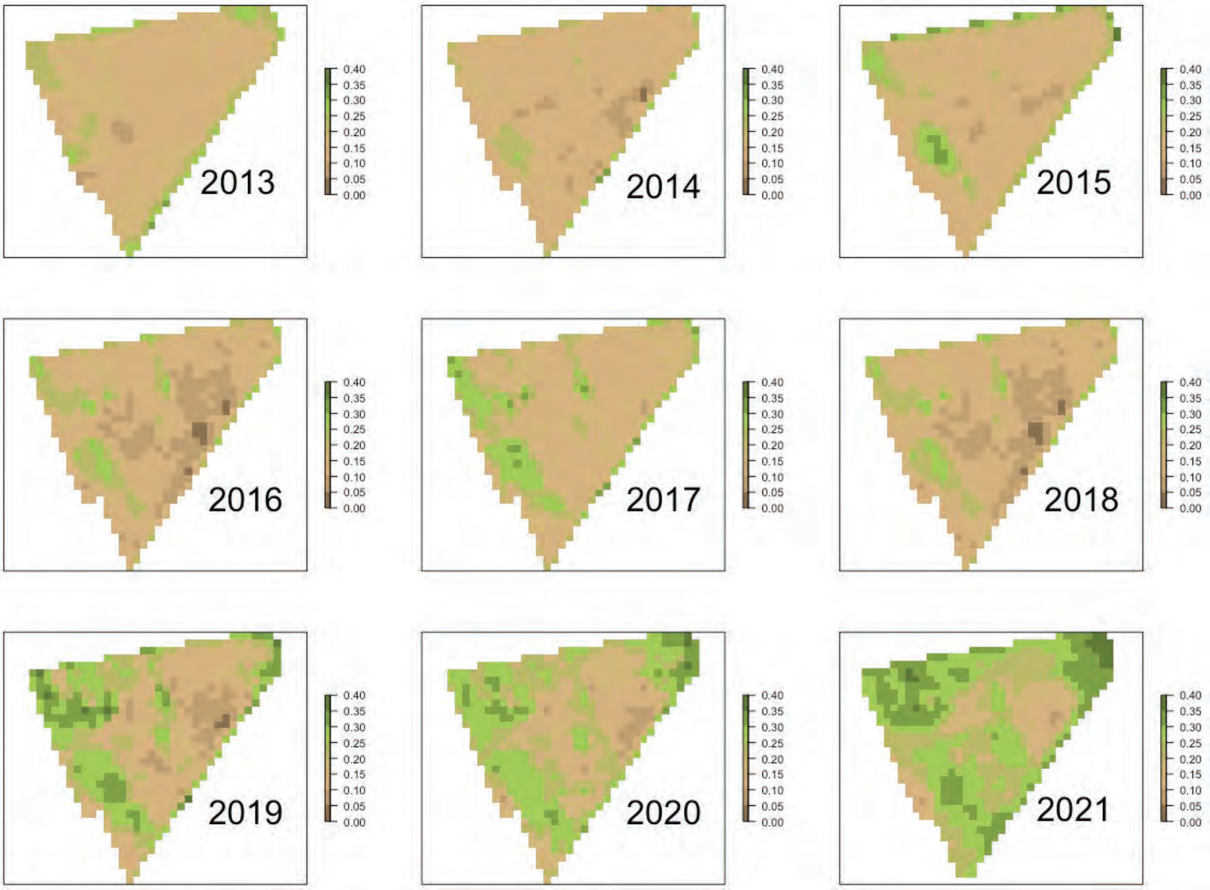

Figure 7: NDVI series for LWM Phase 1, generated from Landsat 8 satellite images (30m pixel). There has been rapid increase in green vegetation cover over the past three years, coinciding with the last phase of bunding work which was completed in late 2019. Moderate NDVI values of 0.2-0.3 typically equate with scrub/grassland (Weier and Herring, 2000) – the highest pixel values in these images are in the 0.35-0.37 range (dark green). (Images courtesy of USGS).

6 Carbon greenhouse gas (CGHG) sequestration

A study by Manchester Metropolitan University (MMU) on Cadishead Moss, a recovering cut-over site owned by LWT on the south border of LWM, examined CGHG flux over a two-year period on stands of *Eriophorum angustifolium* with and without *Sphagnum* moss (BeadaMoss® origin) with control plots of bare peat (Keightley, 2020). There was continual CGHG emission from bare peat (337±73 gCO_{2e} m^{-2} yr^{-1}) and increasing CO_2 uptake with increasing vegetation density and *Sphagnum* cover (-15±422 to 592±501.99 gCO_{2e} m^{-2} yr^{-1} i.e., small emission to large uptake) in the first year of study. Methane emissions were higher in plots of mature vegetation, but not enough to turn the site into an overall source of CGHGs and small compared to other studies (e.g., those of Beyer and Höper (2015) and Evans *et al.* (2016). The second year of study included a long period of drought, which reduced photosynthesis rates and consequently reduced CO_2 uptake, although there was still a small net CGHG uptake. The study also found residual evidence of long-term peat degradation on Cadishead Moss, leaving the site hydrologically unstable and more vulnerable to drought-related climate change. However, early intervention with planting of cottongrasses, and particularly *Sphagnum* to retain peat surface moisture, is likely to deliver good outcomes for site recovery and CGHG uptake in the future. The study had some influence in the decision to make widescale planting with cottongrasses and the introduction of BeadaMoss® *Sphagnum* priorities for restoration on LWM. Further studies by MMU, as part of the Interreg NW Europe funded Care Peat project (Care Peat, 2021) showed that widescale planting of cottongrasses delivered a very high uptake of CO_2 in the establishment phase when plants were young and vigorous, despite bare peat gaps between plants in the very early stages. Studies are continuing to measure the change in CO_2 uptake as the plants mature, and will further inform restoration techniques on Little Woolden Moss.

7 Biodiversity

To date, relatively little work has been carried out on species recording on LWM, mainly because it was initially devoid of wildlife, although the situation is transforming rapidly with the increase in primary production, not only of vegetative plant growth, but also nectar, insects and other primary food resources.

A spider survey conducted in 2018 at the eastern end of LWM documented 19 species, including 8 bog indicator species (Burkmar, 2018). There was a surprising abundance of spiders (also an abundance of small insect prey – notably springtails; verbal report) which the author commented could explain why the site had become important for breeding waders only 6 years into the restoration (as discussed in Box 2). Willow tit (*Poecile montanus*), a UK BAP priority species (JNCC, 2007), has also been recorded in a newly planted shelter belt.

*Figure 8: Illustrations of a recovering ecosystem. (A) Curlew (*Numenius arquata*), Britain's largest wader has successfully fledged young on the site; (B) Yellow wagtail (*Motacilla flava*) foraging sawfly larvae on willow scrub; (C) Lapwing (*Vanellus vanellus*) group; (D)* V. vanellus *chick, evidence of successful breeding; (E) Hobby (*Falco Subbuteo*) predator; and prey (F) Banded demoiselle (*Calopteryx splendens*) female. (Images: D. Steel).*

Surveying during the summer of 2021 recorded 14 butterfly species, and moth trapping over four nights between May and August recorded 35 species of macro-moth with a maximum abundance of 79 individuals. A bat survey noted common pipistrelle (*Pipistrellus pipistrellus)*, soprano pipistrelle (*Pipistrellus pygmaeus*), noctule (*Nyctalus noctule*) and brown long-eared bat (*Plecotus auratus*). Bog Bush Cricket (*Metrioptera brachyptera*), a rare and localised invertebrate (Maddock, 2008), has been recorded on heathland areas of Phase1 (Figure 1). The acid tolerant palmate newt (*Lissotriton helveticus)* has also been noted.

Box 2: The author of this descriptive piece has a lifelong association with bird recording on Chat Moss and conducts weekly bird walks around the mosslands – narrator[1], writer, early riser, observer, recorder, photographer[2]. This essay summarises the biodiversity of two highly visible species groups, and also captures the value of the natural capital of LWM for inspiring and delighting visitors.

August 2012, the LWT purchase date for the site. Prior to 2012, I personally feel, I should refer as Year Null – for all I can offer by way of wildlife observations on the Little Woolden Moss section is, to me, summed up in this observation.

Dragonfly recently emerged and on the wing from the Cadishead Moss section of the reserve would take to the air in search of mates and places to eventually oviposit their eggs and soon enter the airspace of a virtually null and barren landscape of bare and vegetation-devoid milled peat. Some drainage ditches, which were multitudinous across the site (all the better to dry out the peat for milling), did hold some vegetation to which some dragonfly could alight upon – but in truth these were negligible with respect to the number of dragonfly on the wing. To me, seeing this lack of habitat ensured that perhaps generations of dragonfly had been denied the opportunity to sustain previous numbers and were as a consequence in decline[3].

Birds simply overflew the site save for the Cadishead Moss section which since earlier in the century had started to recover from incursions upon it by one mechanised peat extractor whose operations, whilst ultimately unsuccessful, were slowly depleting the site of its wildlife and peat.

The positive years then began and now Cadishead Moss/Little Woolden Moss combined nature reserves have a shared increasing population of birds/dragonflies and much else in the natural world.

The reserve now shares many species with an upland Peat Bog, and as such has attracted breeding Meadow Pipit and Curlew, both of which were generally thwarted by the peat extraction years, with their breeding attempts ending in failure. Looking at my records for breeding birds on the site since restoration both species have now found success (although the Curlew being in UK-wide serious decline succeeds less well than the Meadow Pipit, which year on year grows from strength to strength).

The strenuous and sustained effort in habitat restoration to regain an inland raised peat bog has worked, from my records for this site's breeding birds, which reads as follows (birds with an * indicate breeding on the site since the restoration work began in 2012): Canada Goose*, Water Rail*, Moorhen, Oystercatcher*, Little Ringed Plover*, Lapwing*, Black-Headed Gull*, Woodpigeon, Nightjar*, Skylark*, Meadow Pipit*, Pied Wagtail*, Yellow Wagtail*, Dunnock, Robin, Song Thrush, Blackbird, Garden Warbler*, Blackcap*, Common Whitethroat*, Sedge Warbler*, Grasshopper Warbler*, Reed Warbler*, Willow Warbler, Wren, Willow Tit, Long-Tailed Tit, Magpie, Jay, Carrion Crow, Chaffinch, Linnet, Redpoll, Goldfinch, Reed Bunting.

The site is now offering an opportunity for feeding/resting on migration, due to the vastly increased vegetation, all of which has created that seedbed of life … insects … attracting: Arial feeders (Swift, Swallow, Sand Martin, House Martin); passage migrants pausing to feed whilst on migration (Avocet, Stone Curlew, Ringed Plover, Grey Plover, Golden Plover, Knot, Sanderling, Turnstone, Dunlin, Little Stint, Wood Sandpiper, Green Sandpiper, Common Sandpiper, Redshank, Spotted Redshank, Greenshank, Black-Tailed Godwit, Whimbrel, Ruff); winter visitors (Common Snipe, Jack snipe, Short-eared Owl); raptors drawn to hunt over the site due to the increased prey (Red Kite, Marsh Harrier, Hen Harrier, Hobby, Peregrine, Merlin, Buzzard, Kestrel, Sparrowhawk, Barn Owl).

Pink-footed Geese, instead of simply overflying the site on their migration, now pause and even stay due to the attractiveness of the site for their resting/roosting/preening needs.

With respect to the dragonfly numbers on the site, I can give no greater example than that on the Little Woolden Moss area of the reserve their numbers have risen to such an extent that this summer there have been up to four Hobby taking dragonfly on the wing, day after day for quite a long period in early summer and even to 07/09/21 I noted one taking dragonfly.

My recording of dragonfly for the Carbon Landscape Citizen Science project offers good numbers of: Banded Demoiselle, Emerald Damselfly, Azure Damselfly, Common Blue Damselfly, Blue-tailed Damselfly, Migrant Hawker, Southern Hawker, Brown Hawker, Four-spotted Chaser, Black-tailed Skimmer, Black Darter.

Year Null, with respect to wildlife, has been spectacularly transformed by the LWT and its dedicated Volunteers in 10 years … a mere 10 years … to nothing short of a wildlife Ark of Life, which has come to symbolise this Nature Reserve … where there is life there is hope … where there is denuded lowland raised Peat Bogs there is a beacon of light carried by the LWT.

Dave Steel, 8th September 2021.

[1] Figure 9C. [2] Figure 8. [3] The inhospitable territory probably functioning as an ecological sink or trap, resulting in decline in insect abundance (Hallmann *et al.*, 2017).

8 Volunteering; Social and Natural Capital

It is challenging to put a monetary value on, or even clearly define, the true value of goodwill and the donation of hours and days of time by individuals and communities to enhancing natural capital and biodiversity (Costanza, 2003; Pretty and Smith, 2004).

From LWT records (Table 1) kept for the duration of the restoration until September 2021, nearly 13,000 volunteer hours have currently been accrued. At the current National Living Wage this time has a value of £123,000, although many volunteers bring specialist skills to the project beyond simply providing a willing pair of hands. Moreover, the 'donation-

Table 1: Number of individual volunteers and hours donated during the restoration of LWM to date. The total time recorded is 12,966 hours (up to September 2021) by registered volunteers, excluding activity by 'guests' on organized events. (Data courtesy of LWT).

Year	2013	2014	2015	2016	2017	2018	2019	2020	2021
Volunteer hours	1036	1615	941	1190	2088	1907	1578	1107	1504
Volunteer numbers	23	40	56	62	47	59	39	15	29

Box 3: The author of this descriptive piece is a long-term volunteer – retired local solicitor, survivor, gardener, stoic, optimist, grandfather. His essay captures the spirit of the LWM volunteers.

A volunteer on Little Woolden Moss.

There is something about volunteering in retirement that captures the soul. A feeling that one is putting back into society an element taken from it during a working life. Hence my initiation into the Wildlife Trust, first at Wigan Flashes, then Astley Moss and latterly at Little Woolden Moss.

The first impression of Little Woolden is its sheer size. A vast oasis bog hidden close to suburbia. There is a buzz inside as you turn off Glazebrook Lane and bump and jolt along the pitted track to the meeting point by the container. Pulling on the essential wellingtons you meet your companions for the day as you sign in. Some are as constant as the Northern Star, others transitory but all united in seeking fulfilment in what nature has to offer. The team leaders spell out the day's labours amid good hearted banter and soon the wheelbarrows squeak away with their laden tools. A host of different tasks have beckoned over the years that vary with the seasons.

Winter can be punitive on the Moss[1]. On one memorable occasion our group were caught in a storm where we stood in a line with our backs to the onslaught as the wind swept the hail in horizontal gusts across the landscape. Six layers of clothing kept out the bitter chill and a wee drop of brandy in the coffee at lunch can lift the spirits. Much of the winter months are spent cutting down that arch enemy of the Moss – birch. You cannot win but at least force a draw. It is everywhere, but makes super dead hedges[2]. Those across a lagoon are especially challenging as one steps gingerly ahead step-by-step to test the water depth.

Spring finally arrives and the Moss is a sea of white from our planted cottongrass. *Sphagnum* has spread in many of the pools, trapping carbon within, while elsewhere lapwings[3] patrol their territories and the haunting call of the curlew[4] pervades the silence. The coming months see volunteers hard at work planting cross-leaved heath and bog rosemary, maintaining the essential bunds to access the site and keeping the pathways clear.

The reward is to behold a transformation of a ravaged and denuded expanse of peat into a living vibrant landscape with areas full of butterflies, darters and dragonflies.

Heather comes into its own in autumn with its gentle purple hues whilst earnest searches begin for that other villain of the piece – Himalayan balsam. There is a many triumphant yell as one is spotted amongst the undergrowth and paraded for all to see before destruction.

Mention should be made of those at the Wildlife Trust who put an enormous effort in seeking funds from various sources to enable rewilding projects to take place. Theirs is a thankless task but one which has met with spectacular success in recent years.

And so, our team continues to thrive under the big sky. Covid was an unwelcome interruption but back we came with a vengeance. As I write, a wagon load of sundews and white-beaked sedge has just arrived – only 10,000 plants this time. The delivery will keep our heads down in the autumn months and renew our mental and physical fitness and well-being like no other activity.

Malcolm Colin Davies, 27th August 2021.

[1]Figure 9A. [2]Figure 3B. [3]Figure 8C. [4]Figure 8A.

in-kind' given by volunteers is used as match-funding in many funding bids. The Wildlife Trust's national strategy is to have 30% of UK land and sea restored for nature by 2030, and Tom Burditt, current LWT CEO has stated that volunteers are 'centre-stage in delivering this strategy'.

A recent review suggested "defining social capital as a multidimensional concept comprised of trust, reciprocity and exchanges … embedded in networks of relationships" (Barnes-Mauthe *et al*., 2015). These values are echoed in the essay above (Box 3), with the overall aim of improving biodiversity as well as sequestrating carbon.

9 Conclusions

Ten years is a short time in which to expect any significant repair from the extensive level of damage to LWM. Progress made so far, in increasing the natural capital of LWM, is a testament to the vision and expertise of those involved in the original and subsequent management of the site, and the huge amount of time and resources – financial, and also human capital – committed to it. There was recent high-profile recognition of the work of Lancashire Peatlands Initiative, when the project won the 2021 CIEEM (Chartered Institute of Ecology & Environmental Management) Best Practice award for Practical Nature Conservation (Large-Scale) for delivery of its 'pioneering and nationally significant habitat restoration'.

This energy and creativity, ranging from engineering to horticulture, and much of it voluntary, has ensured that progress has been maintained. The rapid increase in plant cover and indications of a higher, more stable water table are the result of bunding in several stages, as described in Section 3.

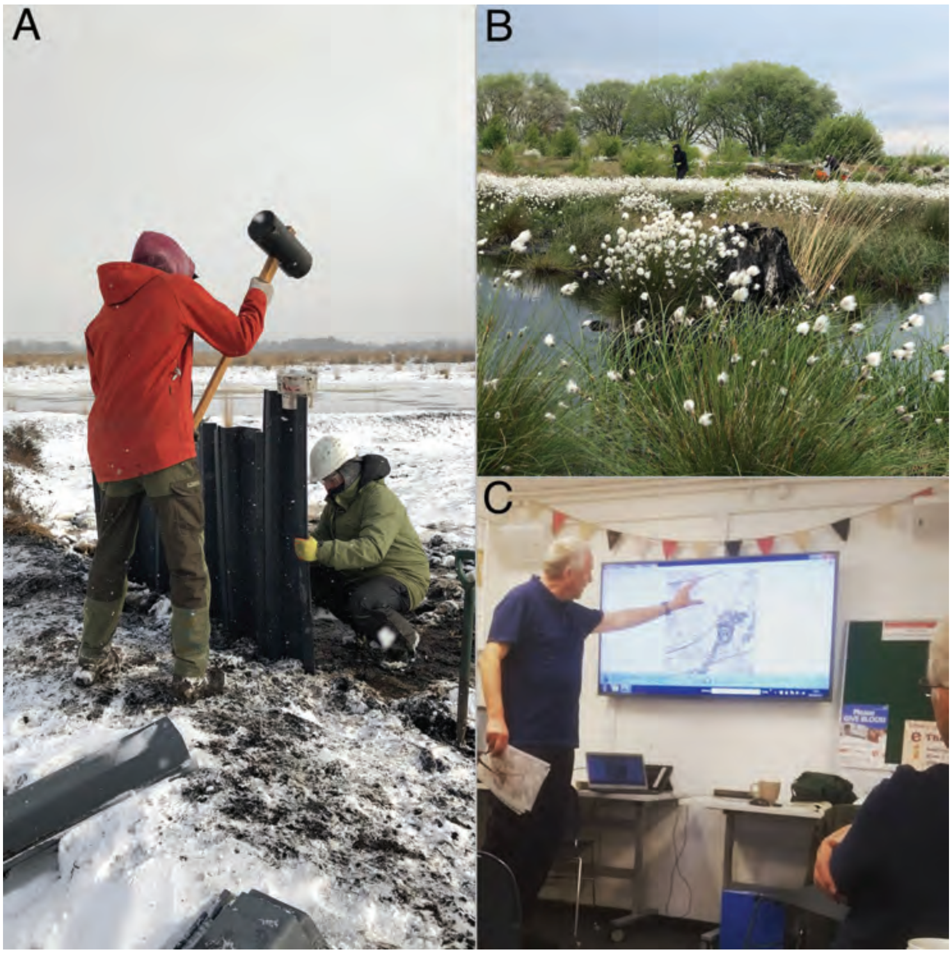

Figure 9: (A) Volunteer work party installing plastic piling in 'Siberian' conditions, February 2018 – air temperature -7°C, brisk easterly bringing significant wind chill; (B) Planting plugs of Sphagnum *moss amongst mature cottongrass; (C) Ornithology presentation to Friends of Chat Moss group (https://friendsofchatmoss.org/). (Images: A. Osborne).*

There is reason for continued optimism; the project is now unlikely to fail, and 100% plant cover in the next 3-5 years a realistic possibility. Establishing a widespread *Sphagnum* carpet will be a major occupation over the coming decades. This site is also a great educational resource for learning about peatland ecology, biodiversity and restoration management, carbon sequestration and storage, and Chat Moss history. It has been used as an academic study site, for work and student placements, by corporate team-building groups, by school and community groups, and the general public, for a variety of purposes and benefits. These include building knowledge and skills for improved employment prospects and personal development, and the well-being and satisfaction derived from contributing to conservation of a vulnerable habitat and spending time in a green space. The restoration of vast areas of severely degraded peatlands across the northern hemisphere is a necessity in the face of dangerous climate change and ongoing biodiversity loss. We hope that the quantitative evidence and qualitative testimony in this review will be of value to teams faced with similarly daunting tasks in the future (Box 4).

Box 4: Key points: Main lessons learned.

Funding:
Establish good relationships with funders and seek a diverse range of grants to broaden restoration attention across the site.
Bunding:
Install long bunds along contours for maximum water retention.
Control sub-surface flow.
Identify and remove old drainage pipes.
Create 20 cm-deep scrapes during bunding – ideal for *Sphagnum* establishment.
Plant propagation:
Transplanted *Eriophorum* spp. turfs establish well in harsh conditions.
Plug plants are very useful in soft/moist peat, but away from water edges (geese predation).
Sphagnum cuspidatum can be introduced early in the project into semi-permanent water.
Terrestrial *Sphagnum* requires permanently moist peat and good vascular plant cover in order to establish (i.e., later-stage restoration work).
Staffing:
Professional staff are essential to steer restoration efforts, and long-term management will be required.
Community engagement and volunteers increase enormously what can be achieved by a small number of paid staff.
Site knowledge:
Detailed site knowledge/understanding is invaluable for planning and monitoring, to maintain restoration progress.
Use GIS based applications to map the site (e.g., QGIS, Google Maps), and log work efficiently (e.g., Epicollect5 – http://five.epicollect.net).
Review progress regularly, planting across the entire site and re-planting areas that are slow to establish.
Monitor water levels, repair damaged/leaking bunds and add extra overflow pipes to areas prone to flood damage to support hydrological integrity throughout the site.

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Conflicts of Interest
Non declared.

Author's Contributions
AO and AK – concept, lead writing and review; AO, AK, AR, DS – data collection; AO – data processing, statistical analysis. All authors contributed critically to the drafts and gave final approval for publication.

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