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Research article

Talking the same language: Co-production of a palaeoecological investigation to inform heathland management

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A B S T R A C T

There is a recognised role for the integration of palaeoecological data into conservation management, but its application remains hampered by a disconnect between academics and practitioners. We co-produced a palaeoecological investigation with conservation practitioners at an internationally important lowland heathland in the UK, to highlight the value of synergistic working between researchers and managers. We used a multi-proxy approach to reconstruct the site's ecological history over the past c.200 years, focusing on changes in vegetation, hydrology, and fire regimes, and translated the results into accessible visual and spatial formats to support management decisions. Our results reveal significant ecological changes, particularly a post-1950 shift from diverse wetland habitats to a drier, Birch-dominated landscape, linked to increased wildfire frequency and site acidification, as well as the decline of several conservation priority species. The spatial analysis highlights the need to consider site-specific heterogeneity in conservation planning. The management recommendations arising from the improved understanding of historical ecological conditions are focused on rare species conservation, increasing natural variability and the value of a rewetting programme to enhance resilience to climate change. The study highlights the value of a palaeoecological perspective for informing contemporary conservation management; in particular regarding in-site spatial considerations when making recommendations, as well as illustrating the importance of effective communication between researchers and land managers.

1. Introduction

Biodiversity is in greater peril than at any other point in human history, with an estimated average 69% decline in global wildlife populations since 1970 (Habibullah et al., 2022; Meyer et al., 2022; WWF, 2020). In response to this urgent situation, conservation science has become a crisis discipline, where rapid action is necessitated often without holistic knowledge of the situation (Kareiva and Marvier, 2012; Soulé, 1985). Nevertheless, many conservation practitioners recognise that it is key for site management plans, recovery targets and policy frameworks to have a solid grounding in scientific evidence, which is being increasingly drawn from a wide range of disciplines (Parry et al., 2022). Palaeoecology, which can be defined as "the ecology of the past" (Birks and Birks, 2000; p.1), offers insights into past environmental change through use of natural archives such as sediment cores and has emerged within the last 20 years as an applied field in nature conservation with the ability to address conservation challenges (Dillon et al., 2022; Seddon et al., 2014; Siggery et al., 2024). Palaeoecology has provided key evidence to support decision makers and practitioners, for example by informing ecological restoration targets (Sayer et al., 2012), species reintroductions (Bishop et al., 2019), ecosystem service provision (Dearing et al., 2012) and habitat management (Ayres et al., 2008).

A relevant and timely example of a habitat management challenge that might be supported by palaeoecology is that presented by lowland heathlands in the United Kingdom (UK); a semi-natural habitat which has undergone dramatic international decline, but remains of high conservation importance (Duddigan et al., 2024). The UK plays a key role in conserving lowland heathland as it supports around 20% of the remaining global resource, but even here it is estimated that up to 85% of the former extent has been lost (Cordingley et al., 2015; Price, 2002). The loss of heathland in the UK can largely be attributed to historic land use change (intensification of agriculture, urban development and

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afforestation), in particular during the post-World War II economic acceleration after joining the European Union (EU) (Ridding, 2021). Despite legal protections afforded by the EU Birds and Habitats Directives (Council Directive 92/43/EEC; Directive 2009/147/EC) and resultant obligatory impact mitigation schemes (Thames Basin Heaths Partnership, 2009), most remaining areas of lowland heathland continue to decline in quality (Ridding et al., 2020). As historic, cultural landscapes with rich histories of human intervention and socio-economic activity, lowland heathlands across Europe have been the subject of many archaeological and geohistorical investigations (Doorenbosch and van Mourik, 2016). Many of these studies employ palaeoecological methods, such as undertaking pollen analysis on peat cores, but are focused on better understanding the human history and cultural heritage of the site, or vegetation changes across multi-millennial time scales (Brown et al., 2014; Grant et al., 2011; Simmonds et al., 2021). There is, however, a disconnect whereby archaeological, palaeoecological and neo-ecological heathland research efforts remain siloed, and a multi-disciplinary applied approach to support the conservation of these important landscapes is lacking (Ombashi and Løvschal, 2023). Whilst there are studies that reflect on the conservation value of their findings (e.g. Groves et al., 2012), these can lack the substance necessary for practitioners to make use of them (Ehrenfeld, 2000; Groff et al., 2023). There is increasing recognition of the value of fostering an inter-disciplinary approach through complementary specialisms to mobilise the study of past socioecological systems in the UK's lowland heathlands, to more explicitly inform land management and conservation decisions (Margetts et al., 2023).

A key conservation challenge in which palaeoecology can play a clear role is the increasing drought and related burn frequency which many lowland heathlands are experiencing as a result of climate change (Arnell et al., 2021; Gliesch et al., 2024). These issues are synergistic, as increasing drought exacerbates the fire risk on heathlands through drying of soils and vegetation, and fire in turn further dries out the site. This is particularly damaging to wet heath communities, where some species require permanently moist conditions (Natural England, 2020). Fire history is commonly studied via the presence of charcoal in sediments and can be used to analyse the use of fire management regimes by past societies. It is well documented that historic fire practices supported rare species, enhanced biodiversity and created a more resilient landscape rich in ecosystem goods and services, and their study can provide a valuable source of information for contemporary land managers (Ekblom et al., 2019; Russell-Smith et al., 2013). Despite this, in the contemporary context it is clear that drought and fires on the UK's lowland heathlands are becoming increasingly detrimental to continuity of ecosystem function and that a fresh management approach is needed. There is a role for palaeoecologists to better understand the history of these areas to inform new management approaches, as palaeoecology has been an important tool in understanding the fire history of other burn-prone landscapes (Gillson, 2022).

Whilst there is a precedent for the utility of palaeoecology to inform management of heathland landscapes, a key element of consideration is the ability of land managers to use and implement the findings of this type of research (Siggery et al., 2025). Conservation managers are subject to a variety of pressures that can dictate their ability to engage with and implement recommendations from academic research (Fabian et al., 2019). Additionally, the research being conducted can be fallaciously assumed to be relevant, useful and applicable to the challenges faced on an operational level by land managers (Dietl et al., 2023). In order to optimise the integration of palaeoecological research into conservation practice, co-production of research is understood to be best practice (Gillson et al., 2021; Saulnier-Talbot, 2015). By co-designing a study with the intended end-users, in this case, conservation practitioners, research can be situated within the context and nuances of on-the-ground conservation work, and remain focused on specific aims (Buxton et al., 2021). This collaborative effort can also help to reduce accessibility barriers, such as use of overly academic jargon, in particular, technical palaeoecological terminology and complex diagrams (Gillson, 2015; Roche et al., 2022). For lowland heathlands, co-production of research will be key to overcoming the siloing of disciplines and enhancing the ways in which palaeoecological information can support conservation management (Rick and Lockwood, 2013).

This study employs a palaeoecological approach to investigate the environmental history of a nationally important lowland heathland site in the UK, to understand the changes over time and what the key drivers behind the changes were. In addition, the paper will explore how best to inform conservation management of the site within the context of its environmental history alongside the contemporary challenges it faces; especially declining biodiversity, increasing wildfires and dehydration of the site. Conservation managers may be able to gain valuable insights from an enhanced understanding of the history of the site alongside their own experiential knowledge, but may not be familiar with interpreting palaeoecological findings. With this in mind, the research was collaboratively designed and authored with land managers of the site with the aims to; i) increase conservation value of the findings, and ii) gain insight into novel ways of communicating palaeoecological results for the discipline to develop as a more strongly applied science that can better aid habitat management.

2. Methods

2.1. Study area and justification

The study was conducted at Chobham Common National Nature Reserve, Surrey, UK, which is a nationally prominent example of lowland heathland (Fig. 1). The site has been managed by the Surrey Wildlife Trust since 2002 and is owned by Surrey County Council, whilst also under the supervision of Natural England due to its legal status. The National Nature Reserve (NNR) site boundary covers a total of approximately 513 ha within the 574 ha overall site, composed primarily of a mosaic of European dry heath and North Atlantic wet heath, interspersed with valley mires, bare ground and scrub (Supplementary material 1). There are approximately 60 ponds on Chobham Common, and whilst most are recent in origin, there are some known to date to the medieval period (Surrey Wildlife Trust, 2023). The heathland at Chobham has developed over the tertiary deposits of the London Basin and lies on acidic soils formed from the Bagshot, Bracklesham and Barton Beds, including peaty soils in the lower-lying areas of the site. The site is bisected by the M3 motorway, which cuts across the Common from south-west to north-east; approximately one third of the site lies to the north of the motorway. The Common holds multiple legal designations (NNR, Site of Special Scientific Interest (SSSI), Special Protected Area, Special Area of Conservation) which underpin many of the management targets and the recognised indicators of habitat condition. The majority of management activity focuses on scrub management to maintain open heath areas, achieved by manual removal as well as use of conservation grazing by Belted Galloway cattle. Chobham Common has experienced recurrent severe wildfire events in recent years (Surrey Wildlife Trust, 2022), that have raised questions around future directions for the site and whether new approaches such as rewetting or natural afforestation would be appropriate management strategies (Wragg and Boddy, 2008).

A palaeoecological approach was taken to collect sediment core material from a shallow waterbody (Bee Garden Pond) on Chobham that provided a detailed representation of decadal to centennial timescales, as these were deemed most relevant to inform site management. Shallow lakes and ponds have been shown to be excellent locations for palaeoecological study to gain an understanding of local ecological change and wider landscape change (Sayer et al., 2012). Appropriate water bodies for coring on the Common were identified via a desk study of historical maps, to locate persistent, extant water bodies from the oldest accessible maps circa 1840 (Fig. 1). The maps were accessed from the National Library of Scotland online repository (National Library of Scotland, 2023). Following a pilot visit in February 2023 to locate and

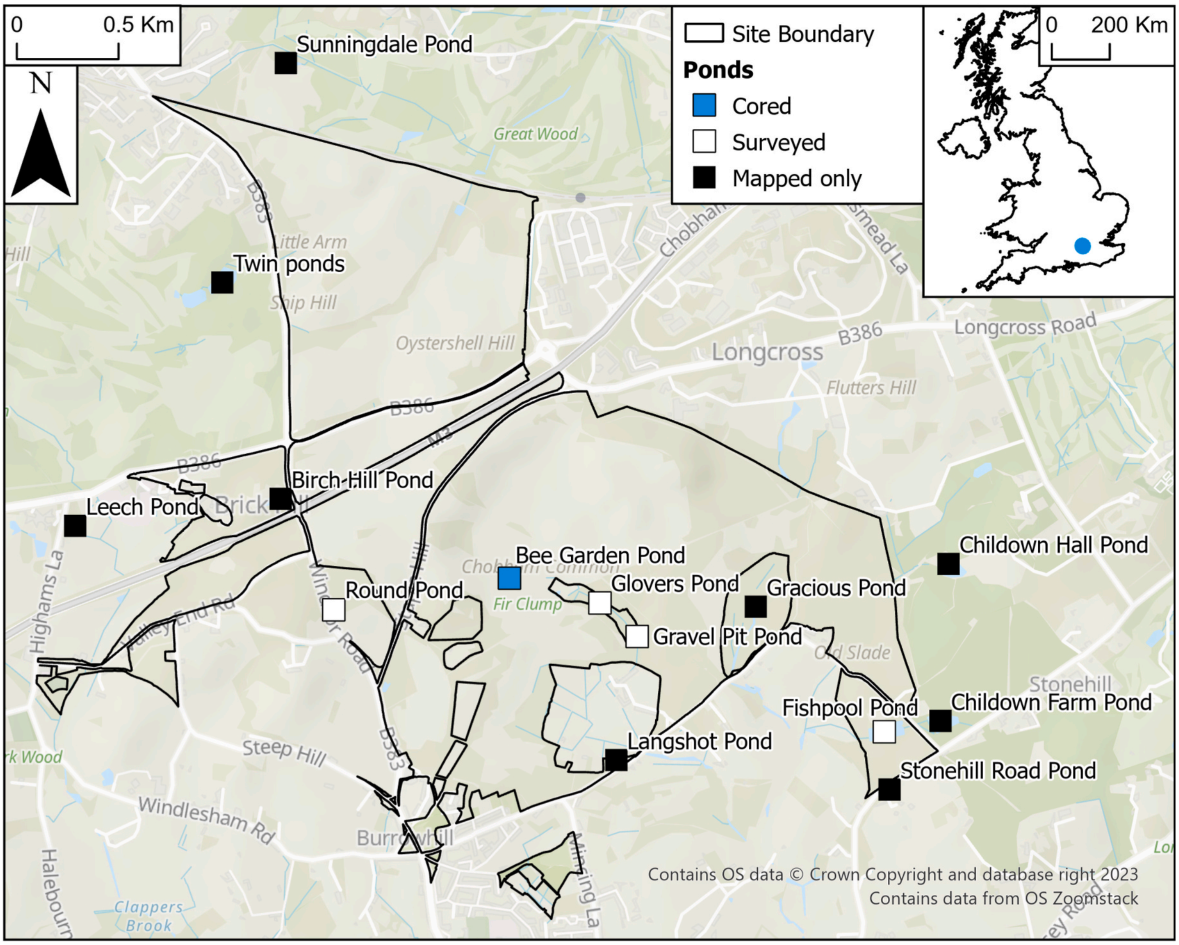

Fig. 1. Site map of Chobham Common with ponds identified from historic maps. Symbols indicates those which were visited in the pilot study in Feb. 2023 (white squares) and the location of coring in May 2023 (blue square). Insert shows location of Chobham Common in the UK (blue dot).

assess the depth of potential coring sites, a 45 cm deep core (BGP1) was collected from Bee Garden Pond (BGP) (SU 97542 64213) on May 9, 2023 using a wide diameter piston corer (Livingstone, 1955). The core was extruded in-situ at 1 cm intervals and subsequently stored in sub-4 °C temperatures prior to analyses.

2.2. Core analysis

A multi-proxy approach was taken to analyse the sediment core, with proxies selected to assess the changes in sediment composition (lithostratigraphy), ecological condition (diatoms, plant and animal macrofossils), vegetation fluctuations (plant macrofossils) and fire history (macro-charcoal) of the site. All analyses were conducted on alternating intervals down the core, 20 intervals in total, where quality of preservation and quantity source material were sufficient for analysis. Plots for all proxies were generated in C2 (Juggins, 2003). Full data is available in Supplementary Material 2.

Spheroidal Carbonaceous Particle (SCP) analysis was used to derive sediment accumulation rates and approximate a chronology for the core (Rose et al., 1995). SCPs were extracted, prepared and counted under microscopy following the methods recommended in Rose (1994, 2008). Results of SCP counts are expressed as concentration of SCPs in sediment, in units of gDM^{-1}. Approximate dates were estimated following guidance in Rose and Appleby (2005). The chronology between identifiable SCP dates was estimated using linear interpolation.

Lithostratigraphic analysis was conducted using standard methods, with the sediment heated to 105 °C, 550 °C and 950 °C to ascertain dry weight, organic content, and carbonate ($CaCO_3$) content respectively (Heiri et al., 2001). The sediment retained at each increment was weighed, and the loss expressed as % dry weight, % organic content and % of $CaCO_3$.

Macro-charcoal sample preparation and counting followed the methods described by Stevenson and Haberle (2005), utilising a 6% concentration of hydrogen peroxide (H_2O_2). Results are expressed as counts of macro-charcoal pieces.

Selected samples were prepared and analysed for diatoms using standard techniques (Battarbee et al., 2001). A total of 16 of the 20 slides were viable for species identification, poor preservation preventing the analysis of the samples below 35 cm. At least 300 valves were identified and counted from each sample using phase contrast microscopy and a 100x oil immersion objective (magnification 1000×). Principal floras used in identification were Krammer and Lange-Bertalot (1986), Barber and Haworth (1994), and Krammer and Lange-Bertalot (2000, 2007) although other taxonomic floras were employed as necessary. All diatom data are expressed as percentage relative abundance. Additionally, the diatom assemblage data were subject to standard analyses including cluster analysis in CONISS (Grimm, 1987), implemented in TGView version 3.0.3 (Grimm, 2023) to define zones throughout the core. Principal components analysis (PCA) was employed to analyse the variance downcore within the diatom assemblages using C2 (Juggins, 2003). A diatom-pH transfer function was applied to reconstruct pH utilising the Surface Water Acidification Programme (SWAP) calibration set (Stevenson et al., 1991).

Plant and animal macrofossils were prepared as described in Birks (2001) and sieved through meshes at increments of 355 μm and 125 μm, as per Clarke et al. (2014). The entirety of the 355 μm samples and approx. 10% of the 125 μm samples were systematically searched for identifiable remains with a binocular dissecting microscope at 20x magnification. Samples below 40 cm were poorly preserved and remains were not able to be utilised for analysis. Identification of remains was guided by the UCL Reference Collection, and pictorial refence material (Birks, 2013; Groningen Institute of Archaeology, 2023; Stachowicz-Rybka et al., 2009). A representative samples of Trichopteran case remains were identified to species level by Dr Ian Wallace, lead of the National Trichoptera Recording Scheme. Interpretation was guided by various texts including (Dieffenbacher-Krall, 2007; Gaillard and Birks, 2007). Macrofossils are presented as numbers per 100 cm^3. As with diatoms, cluster analysis was performed in CONISS (Grimm, 1987), also implemented in TGView version 3.0.3 (Grimm, 2023).

2.3. Core interpretation

A mixed-methods interdisciplinary approach was necessary to situate findings of the palaeoecological investigation within the socio-ecological context of the site and its management. Through a collaborative and iterative process of discussion with conservation practitioners who manage Chobham Common, we developed end-user friendly ways of presenting data and communicating findings. Options for alternative graphical representations of palaeoecological data were explored and refined with land managers.

Land managers of Chobham Common use GIS software to plan and monitor conservation delivery on site, organised via disaggregation of the site into 25 management compartments (Surrey Wildlife Trust, 2023). Spatial data and representation are key elements of management planning and play an important role in conservation workflows, and thus were employed to present the results of this study, such that findings could be viewed in the context of the whole site and other important geospatial data (Nowak et al., 2020; Sonti, 2015). Mapping of the site and spatial analyses were conducted using ArcGIS Pro 3.2.2 (ESRI Inc, 2023) using a variety of in-built geoprocessing tools. Diatom area of representation was calculated as the local hydrological catchment watershed of BGP. To calculate the watershed of BGP, various hydrological tools within the spatial analyst toolbox of ArcGIS Pro 3.2.2 were employed, including Flow Direction, Flow Accumulation, Fill, Snap Pour Point and Watershed. Macrofossil and macro-charcoal areas of representation were calculated as radii surrounding BGP, generated using the buffer tool and area calculations also in ArcGIS Pro 3.2.2. Data to inform dispersal and representative distances for palaeoecological proxies were derived from the literature, with local and long distance macro-charcoal transport distances based on (Tinner et al., 2006; Vachula et al., 2018) and Birch macrofossil dispersal distance taken from (Tiebel et al., 2020). Spatial data for Chobham Common management compartments was provided by the Surrey Wildlife Trust. Additional data such as the LiDAR Digital Terrain Model and SSSI boundaries were provided by the Environment Agency and Natural England respectively, available under the Open Government Licence v3.0.

2.4. Limitations

As with any palaeoecological study, there are key limitations to be aware of in terms of proxy use and definitive statements that can be made from them, which must also be communicated to end-users of the findings. Firstly, the use of SCPs to approximate chronology comes with inherent inaccuracies for estimated dates. This is mitigated as much as possible through comparison to established regional SCP chronologies (Rose and Appleby, 2005). Additionally, diatom and macrofossil taphonomy is a key consideration; preservation bias, inter-species variant production and limited dispersal of material can lead to false negatives. The estimated chronology implied that sedimentation rates (and hence degree of time-averaging) varied throughout the core, which can also influence the assumed abundance of species based on macrofossil remains. Aspects of the vegetation history could have been further elucidated by a palynological analysis to complement the macrofossil analysis, though Birch pollen is typically representative of much larger areas. Concerns around conclusions being falsely drawn about spatial representation of results were addressed through the mapping described in 2.3. With regards to macro-charcoal, the results must be considered in the light of findings that concentrations of H_2O_2 above 1% have been found to bleach and remove some particles from the solution (Schlachter and Horn, 2010). As this study presents findings from a single core, prepared homogenously without comparators, this has limited relevance but may mean counts were slightly lowered due to bleaching.

3. Results

The SCP data from BGP1 largely follows a standard SCP profile (Fig. 2), with complete absence in the lowermost samples, followed by low-level presence, then a rapid increase mid-core which reaches a peak before declining sharply in the upper core. An approximate chronology can be derived based on the standard profile features (Rose et al., 1995). The absence of SCPs below 30 cm suggests that this sediment represents the period prior to c.1850s when there would have been minimal fossil fuel combustion. Concentrations fluctuate between 0 and $30gDM^{-1}$ in section 30-20 cm, suggesting that this represents the period c.1850s-c.1950s, whilst the point of rapid increase at 17 cm can be dated approximately to c. 1950s. The peak at 7-6 cm, represents c.1970s, the time after which legislation reduced industrial pollution. The macro-charcoal data from BGP1 shows presence in the lower core (23 at 40 cm) before declining to negligible counts from 35 to 20 cm (Fig. 2). The subsequent period between 20 and 12 cm shows a rapid increase in macro-charcoal to a peak of 78. This drops to 35 at 11-10 cm before rapidly climbing to a second peak at 3-2 cm of 122 pieces.

The lithostratigraphy of BGP1 shows a very low, but gradually increasing organic matter content between 40 and 24 cm, which accelerates at approximately 23-22 cm (Fig. 2). There is an interesting spike at 20-19 cm where there is a rapid increase in organic matter for a single sub-sample which then subsequently returns to prior levels. From 18 cm to the top of the core there is a continuous, rapid increase in organic matter up to a peak of 67% at 7-6 cm, with a minor decrease afterwards to 56% at 2-1 cm. The $CaCO_3$ content of BGP1 fluctuates throughout the core, whilst remaining at relatively low levels throughout, ranging between approximately 1-3%. The bottom of the core has 1% $CaCO_3$ content, which shows a relatively stable, gradual increase until 23-22 cm. Between this interval and the top of the core, the $CaCO_3$ content changes rapidly across an approximately 2% range, with a peak of 3.2% at 13-12 cm. The top interval (2-1 cm) has 2.1% $CaCO_3$, which indicates an overall increase from the bottom of the core.

There are marked changes in the diatom assemblages in BGP1 with three zones identified by cluster analysis (Fig. 3). Zone 1 (40–21.5 cm) is characterised by *Pinnularia* spp. as well as lesser quantities of *Eunotia* spp. and several other genera (*Tabellaria* spp.*, Cymbella gracilis, Stauroneis anceps, Stauroneis phoenicentron*). The assemblage is indicative of an acidic environment, aligning with the range of reconstructed pH values of 5.0–5.3. In Zone 2 (21.5–11.5 cm) there is a shift in the community composition away from *Pinnularia* spp. dominance, with an increase in *Eunotia* spp., *Frustulia rhomboides* var. *saxonica* and *Tabellaria* spp., with a notable increase in *Tabellaria quadriseptata*, and the decline of taxa favouring circumneutral pH values (e.g. *Achnanthes minutissima* var. *gracillima*). These shifts correspond to a decrease in pH values to <5, reaching a minimum of 4.8 at 11-10 cm. Finally, in Zone 3 (11.5-0 cm) many of the taxa that decline in Zone 2 increase in relative abundance once again, notably *Pinnularia* spp., whilst taxa associated with strongly acidic waters such as *Frustulia rhomboides* var. *saxonica* and *Tabellaria quadriseptata* declined. Consequently diatom-inferred pH increases to >5. These compositional shifts are reflected in the PCA scores, with axis 1 being largely driven by the changes in the dominant *Pinnularia* spp. and axis 2 capturing the shifts in other species, and with marked changes coinciding with the zone boundaries.

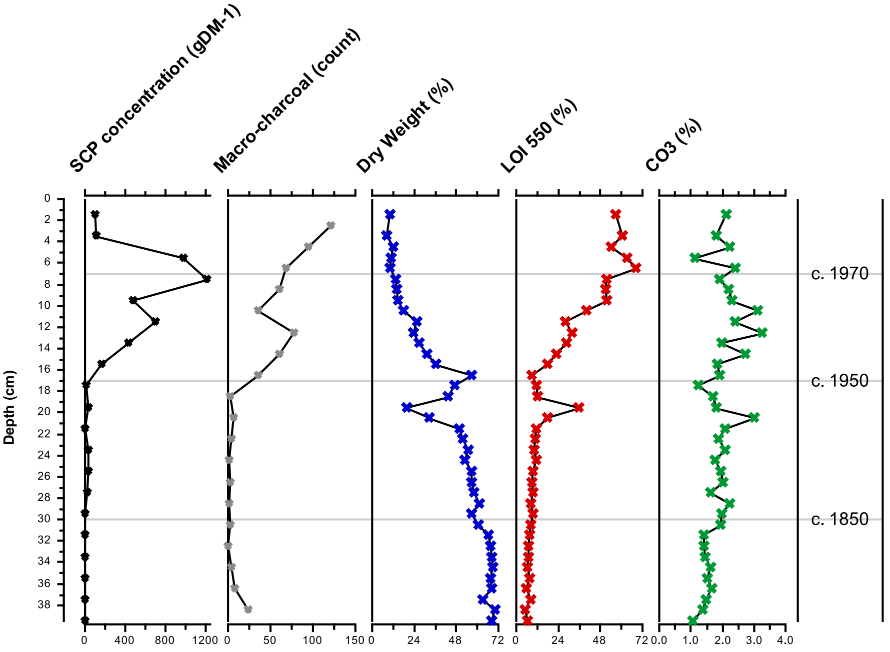

Fig. 2. SCP profile for BGP1 (black) and macro-charcoal profile (grey) plotted against core depth. Lithostratigraphic results for BGP1, showing dry weight (blue), loss on ignition (red) and carbonate (CO_3) (green). Horizontal lines correspond to approximate dates from SCPs.

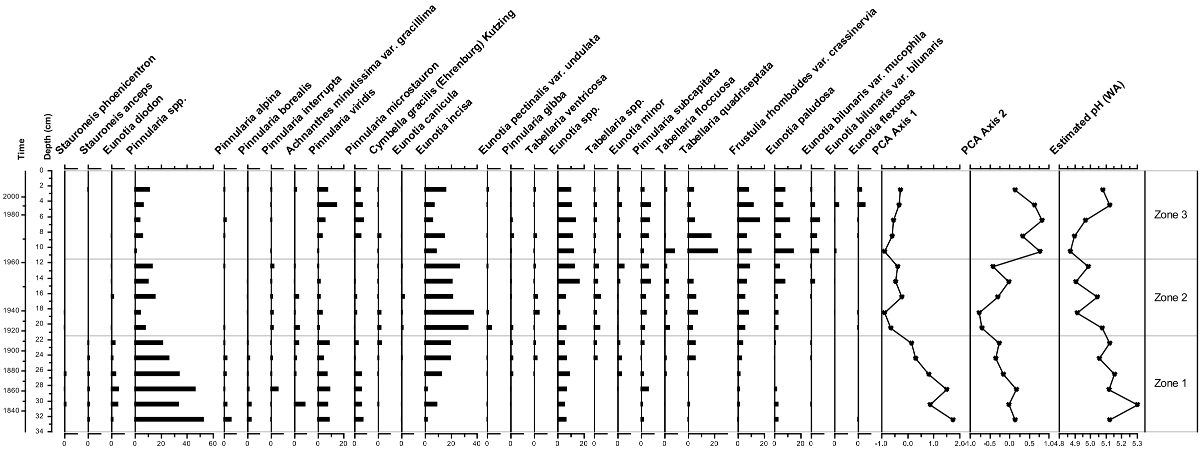

Fig. 3. Diatom plot for BGP1 with diatom species profiles expressed as percentage relative abundance. Also presented are PCA axis 1 & 2 values, transfer function reconstructed pH and characteristic zones derived from CONISS analysis.

There are also evident changes in the macrofossil data with three zones identified by cluster analysis (Fig. 4). In Zone 1 (40-32 cm) very few remains of any taxa were found. There are low numbers of invertebrate remains accompanied by some fungal spores and charcoal pieces. Zone 2 (32-14 cm) exhibits an expansion of diversity and abundance of remains. In this zone, there is a higher species richness and presence of aquatic macrophyte species (*Potamogeton polygonifolius*) and wetland grass and sedge species (inc. *Molinia caerulea* and *Carex canescens)*. There are also abundant Trichopteran remains, suggesting that the site was of high enough quality to support a rich invertebrate fauna. *M. caerulea* remains are abundant between 23 and 13 cm after a period of low-level abundance between 30 and 23 cm. These seeds have been identified as *M. caerulea* with the caveat that they are morphologically similar to *Glyceria fluitans* and could have been misidentified in some instances, although the seeds present in the sample appear to be homogenous. Zone 3 (14-0 cm) is characterised by an increase in *Betula* spp. which becomes dominant, and conversely the reduction of many species in the earlier zones which predominantly favour wetter environments, including a sudden drop off in Trichopteran remains. The other plant abundant during this period is *Eriophorum angustilfoium,* whilst *C. canescens, M. caerulea* and *P. polygonifolius* decline as the *Betula* spp. increase.

4. Discussion

The discussion will focus on two main elements that emerged through the co-production of this study: First, on making the findings visually and spatially interpretable for conservation practitioners and secondly, the application of those findings within the context of the site and its current management.

4.1. *Presentation of palaeo-data*

When presenting data to practitioners, visualisation is of key

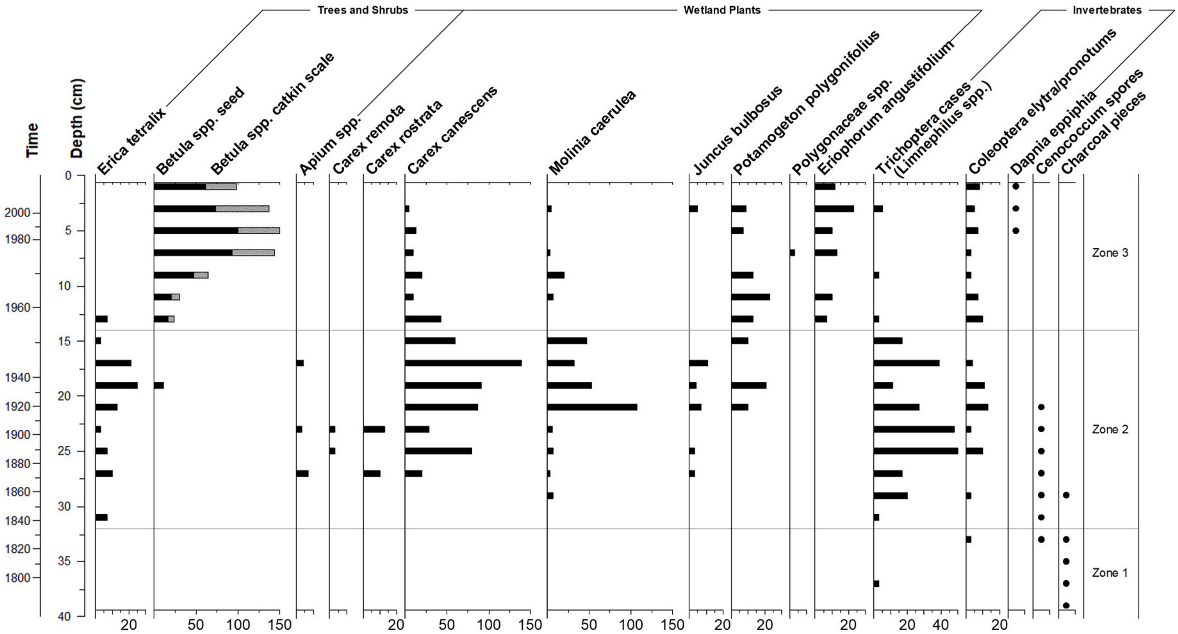

Fig. 4. Macrofossil plot for BGP1, expressed as number per 100 cm^3 of material. Zones designated by CONISS analysis shown on far right.

importance. Traditional palaeoecological plots (as expressed in the results section) can be difficult to interpret for non-experts and, as such, it is important to consider alternatives when relaying findings to practitioner collaborators. A 'synthesis plot' of the key proxies analysed in this study better conveys the key messages for land managers in terms of timescales and potential drivers of change (Fig. 5). The proxies presented on the graph are chosen to summarise key aspects of the data, via a metric that is likely to be more familiar to conservation practitioners. A clear example of this is the use of a transfer function to calculate diatom-inferred pH. Whilst transfer functions have attracted criticism for oversimplifying ecological systems through confounding interacting variables (Juggins, 2013), they have established utility in translation of palaeoecological data into quantitative and well-understood metrics for habitat management (Battarbee et al., 2014; Bennion et al., 2005). Within this study these concerns are mitigated due to pH being one of the strongest controls on diatoms and the transfer function used having a high predictive power based on the extensive and well-calibrated SWAP dataset to minimise error and misinformed interpretation. Additionally, the plant macrofossil remains have been simplified to illustrate two key trends drawn out in the cluster analysis – the dominance of wetland plants in Zone 2 and the subsequent expansion of *Betula* spp. in Zone 3. The signals from both were summed and normalised to a range of 0–1 to allow accurate comparison when plotted. This provides a clearer representation of community shift and ecological change, removing much of the 'noise' from the original plots. Depth was also substituted for an approximated time axis based on the SCP profile data, with key historical events annotated, to facilitate interpretation within the socio-economic context of the site.

By providing a combined plot with the principal information, instead of multiple single proxy plots, practitioners can also gain an improved understanding of the coincident timing of events and changes throughout the core. Simple but effective changes such as placement of time on the X-axis, rather than its traditional placement in palaeoecological work on the Y-axis, and scaling the plot by time rather than depth, are obvious but not often implemented adjustments. There is clear value in this method of data presentation for enabling practitioners to more 'ergonomically' understand coincident shifts in components of the ecosystem and historic land use changes, and by taking time to create simplified, combined plots, palaeoecologists can improve the interpretation of their findings. It is important to note, however, that whilst the timing of major land use changes is important and useful in context, it would be misleading to claim that these are the sole and definitive causes of ecological change. This does highlight a risk of oversimplification of results in the pursuit of making them more accessible to collaborators. Indeed, similar co-produced palaeo-studies have also discussed the "clarity-complexity trade off" of sharing their findings with the collaborating party (Dietl et al., 2023). Transparent communication with practitioners is key to maintain credibility of the findings, but support usability; this is an important area for future exploration through further collaborative research.

A second key point raised during the process of co-design was the importance of providing the land manager with an understanding of spatial extent represented by proxies. Whilst on some smaller sites this may not be relevant, large sites such as Chobham Common require an understanding of whether the reconstruction is relevant to the entire site or only to certain sections. A misunderstanding of the scale of application could dramatically misinform restoration targets and management plans. Whilst multi-proxy studies in the past have highlighted the importance of macrofossils for local signals when compared to pollen (Birks and Birks, 2000), there have been limited attempts to contextualise what 'local' means within the bounds of the study area. For land managers, it is important to understand, with a degree of certainty, whether 'local' refers to the broad assemblages across the entire reserve or is limited to the location of the sediment core and its immediate surroundings. To help address this, several non-traditional methods of representing palaeoecological data were explored and presented spatially (Fig. 6). Firstly, mapping the area represented by diatom analysis was undertaken by using hydrological flow modelling tools to delineate the watershed for BGP. It is common practice for diatoms to be assumed to represent the watershed of a natural lake or reservoir, so the same logic should be applicable for a pond (Battarbee and Bennion, 2011; Schroeder et al., 2016). Through mapping the watershed, it was illustrated that the diatom-based reconstructions were representative of a large area of the southern half of Chobham Common. Secondly, for macrofossils and macro-charcoal the radii of the likely areas of representation of the core were mapped, based on dispersal distances for plant macrofossils and distance of travel from source of macro-charcoal. There were difficulties in obtaining the values to use with confidence for mapping, as the literature provided a varied account of travel distances for macro-charcoal and there was a limited account of dispersal

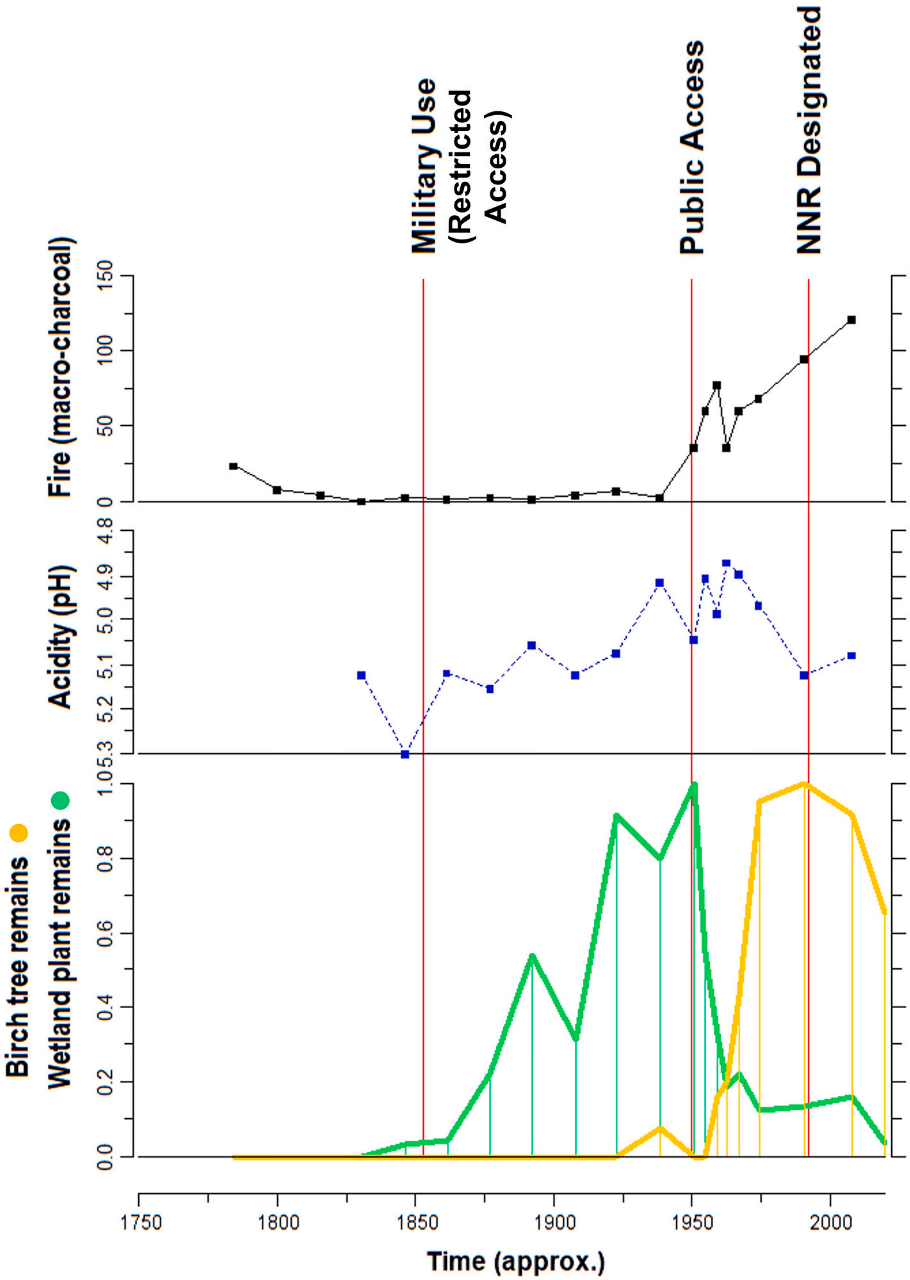

Fig. 5. 'Practitioner friendly' combined synthesis figure of key proxies with estimated dates from SCPs. Time plotted via estimated sedimentation rates, assuming a linear relationship between identifiable SCP dates. Macrofossil remains are presented as normalised counts.

distances for macrofossil remains. There would be value in additional experimental studies to ascertain the likely area of representation for macrofossil remains. In addition, the dispersal distances of all of these are likely to be influenced by many additional factors that were not accounted for, such as topography, prevailing wind direction and average wind speed. In further developments of these methods of data visualisation, it would be valuable to show the influence of these variables in the likely area of dispersal for macrofossils, comparable to similar models that have been developed for macro-charcoal (Vachula and Richter, 2018).

The final spatial element was to map the watershed and representative radii alongside the management compartments delineated in the Chobham Common management plan (Surrey Wildlife Trust, 2023). When overlain with contextual information relevant to the management of the site, it became clear that different proxies offered recommendations with varying areas of influence. Chobham Common is naturally split into northern and southern sectors by the topography of the site; a ridge now occupied by the M3 motorway segregates these two sectors. The area represented by the core is largely constrained to the southern sector of the site because of this and other factors (Fig. 6). The *Betula* spp. macrofossil signal was localised to management Compartment 9, the location of BGP. The modelled watershed spanned several other management compartments (including 6, 7, and 8). The concentrated charcoal signal covered a substantial area of the southern sector of the site, whilst the widest potential charcoal signal (not shown) covered the entire site, and to a substantial extent that of the surrounding area (Table 1). The presentation of palaeoecological results in this way is a novel approach to integrating these into conservation management practice, but with clear benefits in its translational capacity for practitioners to integrate findings into the implementation of their management plans. The concept of spatial presentation of palaeo-data alongside management information provides an important basis for further

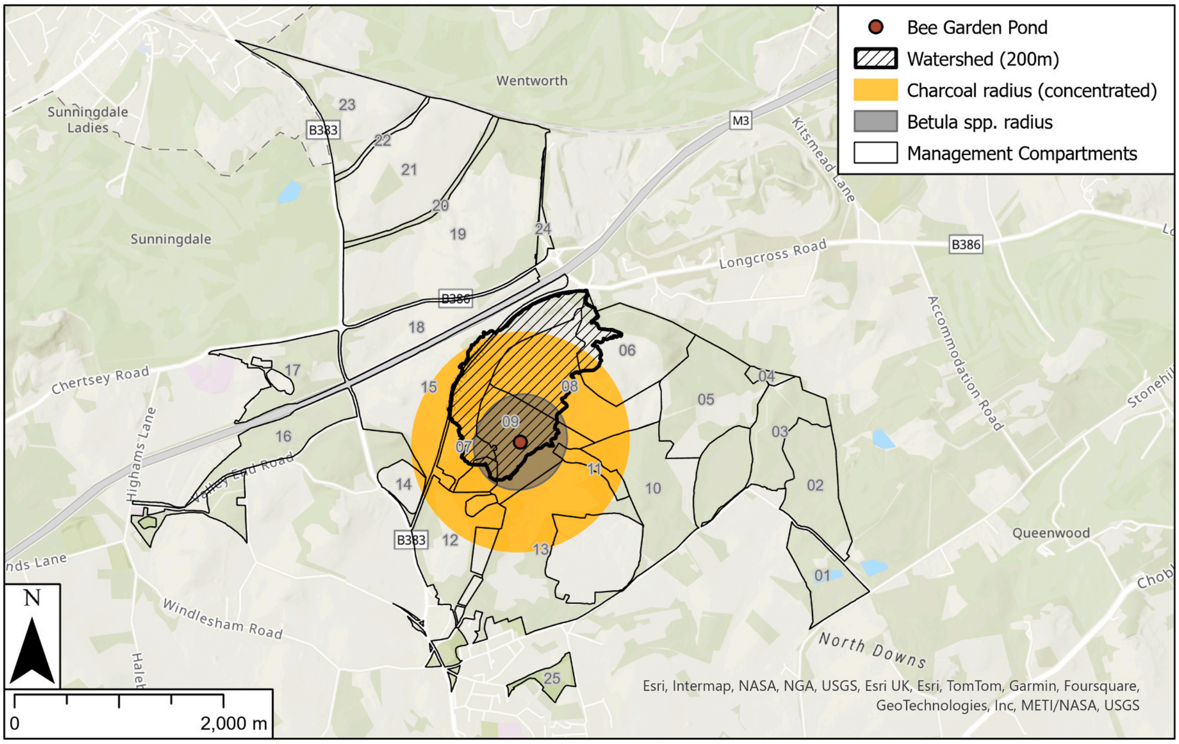

Fig. 6. Map of Chobham Common management compartments with signals from various proxies overlain to illustrate approximate areas of representation.

Table 1
Areas and percentages of land management parcels covered by areas of selected proxies from Fig. 6. N/A indicates no intersect between proxy area and management compartment. Compartments with no intersect with any mapped proxy are excluded from table.

Management Compartment	Compartment Area (ha)	Watershed coverage (%)	Charcoal (concentrated) coverage (%)	*Betula* spp. radius coverage (%)
6	29.51	16.5%	14.7%	N/A
7	24.59	80.9%	69.2%	5.4%
8	34.09	58.4%	80.6%	5.3%
9	23.31	66.5%	100.0%	82.7%
10	29.6	N/A	14.4%	N/A
11	3.8	N/A	85.3%	10.5%
12	23.1	N/A	37.2%	0.0%
13	47.1	N/A	47.4%	1.6%
14	5.5	N/A	9.5%	N/A
15	35.8	2.6%	32.6%	N/A

developments in this area.

4.2. Interpretation of palaeoecological data for site management

The multi-proxy analysis of BGP1 tells a story of a changing hydrological and vegetative landscape on Chobham Common over the past c.200 years, which has the potential to inform current and future management of the site. Of key importance to the practical use of palaeoecological data for land managers is the interpretability of recommendations in the context of the existing management plan for the reserve. Management plans have, and continue to be, a key mechanism of the conservation process and it is vital that these are informed by appropriate evidence in order to deliver optimal outcomes for habitats and species (Pullin and Knight, 2003). In addition to modern management practices, it is important to consider the socioeconomic history of the region, for example, Chobham's rich military history as well as the localised timings of events such as the modern revival of public access to the Common and the subsequent introduction of legal protections. By presenting and interpreting palaeoecological data alongside local contextual knowledge we demonstrate the importance of a broad, holistic perspective when integrating palaeoecology into conservation practice. The remainder of the discussion will be structured around three key conservation issues on site, and how the palaeoecological data can inform their management.

4.2.1. Rare species conservation

As a highly protected site, Chobham Common holds important populations of many nationally rare flora and faunal species; in particular for 467 recorded notable invertebrate species (Surrey Wildlife Trust, 2023). Palaeoecological investigations can provide important evidence to support conservation efforts and inform management plans for rare species (Ayres et al., 2008; Robson et al., 2023). With regards to Chobham, there are two species of note that appear to have been very common earlier in the macrofossil record that have subsequently undergone severe declines, raising questions around their inclusion and consideration in any conservation management plans. Firstly, White Sedge *Carex canescens* was prevalent during the pre-1950s section of the core but has since become very localised on the site. In the wider region, this is now a rare species in the south of the UK and only remains in isolated pockets in lowland heathlands. Secondly, the caddisflies *Limnephilus* spp. were very abundant in the macrofossil record prior to the 1950s and underwent a sudden decline during Zone 3 of the core. This assemblage included the caddisfly *Limnephilus bipunctatus* whose distribution status is currently Nationally Scarce and it is now very rare in Surrey, with only a handful of post-2000 records in the county, and none in the vicinity of Chobham Common (Wallace, 2016). Sediment core findings flag both these as important species to monitor and to consider for taking action by improving connectivity between remaining sub-populations. Whilst neither of these species are listed explicitly in the management plan, awareness of their status is important for the land managers. As these represent relatively recent declines, and the species remain threatened across the wider south-east region, they present realistic, but time-critical, recovery goals for Chobham. We recommend that both species are included for routine site monitoring. To facilitate their persistence on-site, existing water bodies should remain open and wet, through non-intensive pond management. Limiting grazing pressure in compartments with extant populations is also recommended, as currently undertaken for compartments containing Marsh Gentian *Gentiana pneumonanthe*. Whilst increasing monitoring efforts has resource implications, it could be conducted via citizen science initiatives and in collaboration with local recording groups.

In addition, the management plan discusses the potential for on-site reintroductions, including for Natterjack Toads *Epidalea calamita*. This is a protected species which became locally extinct on Surrey heathlands and has greatly declined nationally (McGrath and Lorenzen, 2010). Palaeoecology can play an important role in understanding the viability of species reintroduction programmes through examining historic conditions (Bennion et al., 2024; Bishop et al., 2019). There are no formal records for Natterjack Toad on Chobham Common since 1902, but elsewhere in Surrey the species has been reintroduced on two sites, although persisting on only one (SBIC, 2024). Previous palaeoecological work has examined the role of freshwater acidification in the decline of Natterjack Toads and found that ponds with acidity that had increased below pH 5 had a much lower survival rate (25%) than those >5 pH (83%) (Beebee et al., 1990). The pH reconstruction in this study suggests that BGP has now recovered from the acidification it experienced during the late 20th century, which may have been responsible for the loss of Natterjacks on the site and then prevented any nearby populations from re-colonising. As the pH has recovered above 5, to previous levels at c.1900 when the species was last recorded on site, it is now within a suitable range to again support a viable population of Natterjack Toad, and thus supports the consideration of Chobham as a reintroduction site. We recommend that a reintroduction project for Natterjack Toad on Chobham Common is considered in the area covered by the watershed mapped on Fig. 6, but also suggest it is supplemented by palaeoecological surveys of other ponds on site to better understand the Common's recovery from acidification. Whilst potentially being at significant cost, such programmes remain attractive to external funding and could be financed through opportunities similar to the government's Species Recovery Programme 2023; Shelley-Jones and Phillips, 2023).

4.2.2. *Natural variability and disturbance*

Land managers of the Common were interested in using the palaeoecological study to investigate the natural range of variability on Chobham. On the Common, as for many designated sites in England, conservation practitioners are beholden to prescriptions set by Natural England (the presiding government conservation body), which outlines management targets and ultimately ascertains whether the site can be viewed as appropriately managed for nature conservation. The managers of Chobham Common can find these prescriptions to be restrictive and furthermore suspect that they sometimes do not allow sufficiently for natural flux in the biodiversity of the site, and that the parameters of what is considered as 'favourable' or 'healthy' are narrower than they would have been historically. With the increasing incidence of wildfires and desiccation caused directly from climate change, it is important to better understand the tolerance of the site to disturbance and its response to past pressures.

The findings from the palaeoecological investigation documented fluctuations in vegetation communities during periods of elevated biodiversity and minimal wildfire activity, between 1850 and 1950 when the site was regularly used by the national army, and thus under War Office control. In interpreting this, it is critical to understand how the military history of Chobham Common is reflected in the results, and to not make false assumptions about the stability of the site during this period. The heaviest military activity on Chobham Common, including a fixed encampment, was largely on the northern sector of the site, with less frequent training activities on the southern section (Webster, 2015). In the latter stages of this period (post-1942), the Common became a key testing site for armoured fighting vehicles (AFVs) manufactured locally. The key information provided by Fig. 6 highlights that the reconstructions from BGP1 are representative only in the south of Chobham, aligned with the lighter military activity. It can then be assumed that the extent of disturbance caused by these training activities was not detrimental to the dynamic stability and related biodiversity of Chobham Common, and indeed that this may have been enhanced. Further research would be needed to understand the impact of the more intense activity on the northern section of the Common, ideally by taking a sediment core optimally situated via use of the spatial representation estimated in Fig. 6.

BGP1 documents the transition away from a comparatively diverse wetland community towards a drier *Betula*-dominated landscape during the post-WWII period and after the War Office quit the site, when it was returned to public access. It is known that areas within the southern sector of the Common were ploughed and seeded with "an annual grass" at some stage after WWII to encourage natural recovery from perceived, localised damage by AFVs, which could be responsible for some of the vegetation changes during this period (Surrey Wildlife Trust, 2010). It was also reported that, during this time, visitors frequently brought vehicles onto the Common from which erosion was a serious concern, which correlates with the estimated higher sedimentation rate during this period (Fig. 5). In 1992 the site was designated as a NNR and from this date the management plan took a more conservation-orientated approach. There is evidence in the top layers of the core that *Betula* has declined since the 1990s, showing that the scrub management efforts have had some success although this remains well above the historic levels found in Zone 2 of the core.

To summarise, the comparative lack of disturbance post-1950, possibly in combination with other anthropogenic factors such as elevated nitrogenous pollution and climate change have caused a deterioration to Chobham Common. Between 1850 and 1950, there would have been less widespread, indirect disturbance from public access but more regular, creative successional dynamism of greater scale and significance than on site today, as a protected nature reserve. The natural fluctuations but overall resilience of biodiversity between 1850 and 1950 supports the hypothesis of the land managers that there is greater room for flexibility in the land management prescriptions. We recommend that current land managers open avenues for discussion of available options with Natural England of available options on adjusting management prescriptions in at least some regions of the Common This would allow for differential management regimes to be implemented based on evidence in this study, indicating that the site was significantly more dynamic but relatedly, also more resilient in the past.

4.2.3. *Wildfire management*

Chobham Common is increasingly suffering from fire events, exacerbated by the site having an increased 'fuel-load' (i.e. the quantity of flammable material) of scrub, and more frequent drought conditions. Fires on the site are managed via a wildfire management plan, in partnership with Surrey Fire & Rescue Service. A large part of this has involved scrub management on the Common, since its NNR designation to reduce the 'fuel-load'. There is also consideration for implementing a more co-ordinated and higher-impact rewetting strategy for the Common (to date this has been achieved only on an *ad hoc* basis) as part of wildfire prevention and climate resilience strategy. The 'future proofing' of the site is currently a key priority for land managers.

There is a clear decline of wetland plants in the period represented by the upper part of BGP1, indicating that the area has become drier over time. This interpretation is also supported by the expansion of woody vegetation such as birch in the same period (and therefore fuel-load). The results are also illuminative of the changes in fire prevalence on Chobham Common. The macro-charcoal signal suggests that there were more frequent and severe wildfires in the period represented by the upper part of the core, which may be related to the drying of the site and increased fuel-load from birch coverage. The recovery from acidity in the diatom-inferred pH could also be representative of increasing wildfires, due to the alkaline ash deposited by the fires (Korhola et al., 1996; Kwan et al., 2024). This is consistent with the most recent recorded fire history of the site, including a severe burn occurring in 2020 which destroyed over 40 ha of heathland. The macro-charcoal values between 10 and 5 cm may represent other large burn events in the 1980s and 1990s. There is a poor official record of fire occurrence and extent prior to the 1990s, but it is recognised that burns were relatively frequent and severe between the 1950s and 1970s, which may correspond with the second peak seen in the core at 14-13 cm. The lower levels of macro-charcoal between the 1850s–1950s correlate with the period of military use, when accidental fires would presumably have been carefully monitored given concern for the proximity of munitions. This was, however, also during a period in which Chobham Common was likely to have been much wetter and thus highlights the fundamental role of on-site water levels and retention in facilitating wildfire resilience.

An unexpected finding from BGP1 was in relation to Purple Moor-grass *Molinia caerulea*, which is commonly perceived as invasive and thus undesirable on lowland heathlands. *M. caerulea* is also typically considered significant as a contributor to fire spread and extent, and the management plan for Chobham Common recommends that there should be no more than 33% cover of *M. caerulea* in dry heath and 66% in wet heath, and that it should “not dominate to the exclusion of other species”. As a result, a large effort is put into controlling *M. caerulea,* such as through use of conservation grazing with cattle. Anecdotally, it is thought that *M. caerulea* was less abundant on the Common in the past and is believed to have increased in response to nitrogenous deposition in the 20th Century (Tomassen et al., 2003). However, this does not concur with findings from the macrofossil remains in BGP1, which suggest that *M. caerulea* was likely to have been more abundant during the early part of the 20th Century and has declined since - almost completely disappearing by the top 10 cm of the core. However, this finding must be considered within the context of Fig. 6 and that it is uncertain whether this phenomenon is confined to Compartment 9, or is relevant across the wider site. There could be justification for experimental management in Compartment 9 where *M. caerulea* removal is less intensive, due to constancy within a diverse wetland community in the past. As with the implementation of any of these recommendations, this would need to happen in a way that ensures that the site, as a whole, remains accountable on obligatory scrub management targets under the site’s Countryside Stewardship scheme conditions, which provides a key source of funding for its management.

As mentioned, palaeoecology has been an important tool in understanding fire-prone landscapes which can provide interesting parallels with, as one example of this, the Cape Floristic Region (CFR) in South Africa to UK lowland heathlands. Findings indicate that, similar to Chobham Common, grazing and burning pressures there have markedly increased in comparison to pre-1950 levels, and are higher now than at any point during the past 700 years, throughout its sustainable management by pre-European communities (Forbes et al., 2018). The palaeoecological records indicate that the system was stable yet dynamic, during the majority of its history and able to recover from burn events. A situation which is echoed remarkably by the comparative stability of Chobham between c.1850–1950. In the CFR, it is predicted that if the current intensity of grazing and burning persist, the system will pass a threshold through which ecosystem resilience would be lost and the region would develop into a more homogenous landscape, which moreover would be more vulnerable to wildfires (Gillson, 2022). Chobham is likely on a similar trajectory and, as such, management focusing on reducing scrub encroachment acts to maintain resilience and highlights the value of maintaining open habitat mosaics. The recommendations for the CFR suggest that an adaptive management approach be taken, whereby fire events and grazing pressure are monitored and adapted in response to progressive climate change. This kind of reactive and flexible approach would also be important for managers of Chobham, where fire risk is anticipated to continue to increase and the resilience of the site is likely to be nearing thresholds of concern.

Fire frequency on site remains high compared to historic levels and the quality of the wetland plant community has continued to decline, despite success in reducing scrub. Both the increasing frequency of fire and dehydration of the site are occurring within the context of worsening global climate change, which will inevitably be a key factor influencing the outcomes of site management. To address both issues in a holistic manner that would also benefit the biodiversity recovery of the site and its climate resilience, rewetting seems to be an unquestionably appropriate action for managing the site. This approach would be the obvious solution for Compartment 9 but, as with other recommendations, additional sediment cores would help to understand the value of this action elsewhere on site. Rewetting Chobham Common would necessitate a variety of considerations such as theoretical legal liabilities as well as potential conflict with public access. Managers would also need to consider the costs of installing and maintaining water storage infrastructure. This, however, can be achieved in a cost effective and biodiversity co-delivery approach through natural flood management techniques, for example deploying ‘leaky dams’, or via reintroduction of Eurasian Beaver *Castor fiber* on site. The latter would of course, be of an initially inflated scale-of-costs and have further related considerations. As part of strategic flood alleviation policy implementation, rewetting should also reduce costs of potential downstream floodwater management, which is noted in the emerging Surrey Heath Local Plan as a concern specifically sourcing from Chobham Common. Overall, the ecosystem service benefits of rewetting the Common would be numerous, both in terms of directly restoring biodiversity and improving climate resilience, and this approach is being increasingly taken on other sites facing similar pressures (National Trust, 2024).

5. Conclusions and recommendations

The palaeoecological analysis in this study has provided valuable recommendations for the management of the lowland heathland on Chobham Common, based on the environmental history of the site. Whilst managers would want to work towards recovering a past vision of the site as illustrated by palaeoecological reconstruction, there is also a clear need to consider future proofing of the site against climate change, as well as stakeholder and financial considerations. Co-production of the research with land managers has illustrated how this balance can be achieved and has also enabled recommendations to be presented within the parlance and context of protected site conservation management, thereby framed to be most useful and relevant to the site’s managers. We present two sets of recommendations: first directed at site conservation managers with regards to heathland management, and secondly at research palaeoecologists on improving the application and accessibility of their research.

Recommendations for Chobham Common management.

- Increase efforts for *Carex canescens* and *Limnephilus bipunctatus*, as key wetland quality indicator species, potentially via a citizen science initiative; as well as consideration of a reintroduction programme for *Epidalea calamita*, particularly for Compartment 9.
- Experimental management of *Molinea caerulea* in Compartment 9, with relevance to and in context of agreements with Natural England and Countryside Stewardship scheme obligations, to help better understand natural ecological variability of the site.
- Further palaeoecological investigations, located at sites unrepresented by this core, could be beneficial for understanding other aspects of the site. Analysis of other proxies, such as pollen, could also be beneficial and support interpretation of vegetation dynamics.
- A rewetting programme has the potential to have a significant positive impact as a multi-purpose nature-based solution for the future management of the site. Based on the findings of this study, it appears an optimum strategy for recovery to resilient and the peak-

biodiverse conditions of the past; wildfire suppression; delivery on carbon sequestration and climate mitigation; and facilitative of threatened species conservation via reintroduction.

Recommendations for palaeoecologists.

- Understanding of area of spatial representation for palaeoecological proxies is vital for their relevance to management recommendations and their integration into existing management plans. We recommend that additional studies are conducted to focus on establishing likely dispersal distances for example for common macrofossil tree species.
- Novel approaches to presenting data in a format that is easier to understand for non-palaeoecologists is of key importance to accessibility of research. We recommend use of combined, simplified plots as well as mapped figures to spatially represent palaeoecological data.
- Co-production of research with land managers of the study site provides a unique opportunity for elevating the quality of research, as well as ensuring that the findings are relevant and useable for managers. Vital information for situating research within a site-specific context, such as site management plans and funding mechanisms, can only be accessed through closer collaboration.

CRediT authorship contribution statement

Ben Siggery: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Helen Bennion:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **James Herd:** Writing – review & editing, Visualization, Conceptualization. **Shanjana Kodeeswaran:** Investigation, Formal analysis. **Richard Murphy:** Writing – review & editing, Supervision. **Stephen Morse:** Writing – review & editing, Supervision. **Mike Waite:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.124652.

Data availability

Data has been included in supplementary materials

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