



## Perspective

# The Białowieża Forest as an example of the resilience of long-term studies in a changing world



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## ABSTRACT

Effective conservation of biodiversity requires a good understanding of ecosystem dynamics in response to natural and anthropogenic influences. Long-term studies (LTS) conducted over multiple decades provide essential insights into ecological processes and interactions over time, which can inform conservation strategies, but they are anchored within their wider society and geopolitics. The context of any LTS is therefore vulnerable to temporal instability, including disruptions and challenges but also scientific opportunities. The resilience and adaptability of LTS in the face of political, social or environmental change is key to their continuity and relevance for science and society.

Poland's iconic Białowieża Forest hosts unique remnants of European old-growth forest, and also diverse LTS lasting up to nine decades, revealing a dynamic ecosystem. The Białowieża Forest is a hub of international science, providing an essential reference for ecosystem functioning and evolutionary processes, and a key benchmark for wider perceptions of 'natural forest', which is increasingly relevant to ecological restoration elsewhere. Nevertheless, the Białowieża LTS have persisted against a backdrop of profound sociopolitical and geopolitical change, which has challenged their scope and viability. The Białowieża experience has a wider resonance for LTS in other regions, because change can affect science anywhere, even in situations that currently appear stable.

We describe how Białowieża's LTS have maintained continuity and relevance for our understanding of forest ecosystems by embedding core expertise among diverse institutions, building collaborative teams around visionary leaders and dispersing risks of financial, political and security vulnerabilities. However, issues remain around centralised data archiving and availability. These perspectives provide general lessons for supporting LTS in a changeable world.

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## 1. Introduction

In an era of rapid biodiversity loss and ecological change, long-term studies (LTS), especially those lasting for 20 years or more, are particularly valuable for the deep perspectives they provide (Lindenmayer et al., 2012; Hughes et al., 2017; Cocciardi et al., 2024). LTS are key to understanding ecological and evolutionary processes by capturing the temporal heterogeneity of natural phenomena, and creating opportunities for testing new hypotheses within well-understood frameworks. Essentially, LTS offer open-ended platforms for addressing scientific questions, providing benchmarks for other study systems, informing conservation strategies, and acting as hubs of multidisciplinary collaboration and knowledge exchange (Willis et al., 2007; Lindenmayer et al., 2012; Culina et al., 2021). However, LTS are anchored within their wider social and political landscape, which can be unpredictable. As such, LTS may experience challenges over time but can also exploit new opportunities (Kuebbing et al., 2018; Sheldon et al., 2022). The resilience of LTS is defined by their durability and adaptability in the face of changing circumstances, which underpins their relevance for science and society.

A case study of research resilience is found in the iconic Białowieża Forest, which has hosted diverse LTS for almost 90 years within a region of shifting geopolitics and societal change. The Białowieża Forest covers approximately 1500 km<sup>2</sup> straddling the border of Poland (containing 42 % of the forest) and Belarus (58 %). The forest is also bisected by the NATO and European Union (EU) boundaries on the same border. On the Polish side, the Białowieża National Park (BNP; currently 105 km<sup>2</sup>) was established in 1932 and contains remnants of old-growth temperate forest that retain many primeval features, such as very large trees, substantial amounts of deadwood and a mostly intact biodiversity, including large mammals like the European *Bison bonasus* and the Eurasian Elk *Alces alces*, Wolf *Canis lupus* and Lynx *Lynx lynx*. This near-primeval habitat provides a benchmark and a ‘window into the past’ for researchers (Tomiałojć and Wesołowski, 2005), allowing rare opportunities to observe natural processes in a forest ecosystem that has escaped significant degradation or species loss from human activities. These natural processes include community and population dynamics, interspecific relationships and habitat-species interactions within near-intact ecological networks, which can inform ecological restoration elsewhere (e.g. Bobiec, 2002; Vlasakker, 2014; Kowalczyk et al., 2021; Broughton et al., 2022).

The remainder of the Białowieża Forest complex, outside of the BNP, is under varying regimes of multi-purpose management, primarily for forestry. The approaches to forestry and timber production have caused tension between different stakeholders over competing visions of exploitation versus conservation (Blicharska et al., 2020), besides having substantial and long-lasting impacts on tree stand composition and dynamics (Jędrzejewska et al., 1994; Mikusiński et al., 2018). Nevertheless, the juxtaposition of managed forest alongside the unmanaged, old-growth stands of the BNP offer useful comparisons for research into the effects of management. Such comparisons have been incorporated into numerous studies, e.g. of bird communities and distributions (Wesołowski, 1995; Czeszczewik et al., 2015), the availability of tree-cavity resources (Walankiewicz et al., 2014), the effects of insect outbreaks (Kamińska et al., 2021) and the diet of ungulates (Churski et al., 2021).

Despite varying challenges over time, ranging from economic and social changes to militarisation and border security, multiple LTS have been maintained within the Białowieża Forest complex. These studies have been instrumental in highlighting the ecological value of the Białowieża Forest's old-growth stands, in particular, by providing evidence that supports their protection as a major scientific and cultural resource (Jaroszewicz et al., 2019; Blicharska et al., 2020).

Here, we summarise the types of LTS in the Białowieża Forest and provide insights into the key characteristics that have enabled them to persist in the face of social, economic and geopolitical change, which is

intimately entwined with the conservation of the forest ecosystem itself. The example of the Białowieża Forest offers important lessons for the wider research community in how to maintain LTS through the inevitable challenges and opportunities that result from social, political and scientific change that occurs over time.

## 2. Long-term studies in the Białowieża Forest

The first LTS to be established in the Białowieża Forest comprised permanent study plots of tree stands that were first surveyed in 1936, and have been re-surveyed almost every decade since (Brzeziecki et al., 2020). This study and subsequent LTS have revealed significant ecological change, and a dynamism of natural patterns and processes, which take place over the (often) long timescales of forest ecosystems. Some examples of LTS involving different taxa or environmental variables are introduced below, with further examples and details in the supplementary material (Table S1).

### 2.1. Vegetational studies

The LTS of permanent study plots has revealed the mortality rates of various tree species under natural conditions (Brzeziecki and Zajączkowski, 2023), with varying recruitment between species (Brzeziecki et al., 2016). Other key findings from the vegetational studies show dynamic shifts in the forest's composition and phenology driven by herbivore activity (Kuijper et al., 2010a, 2010b) and climate change (Sparks et al., 2009), nitrogen pollution and outbreaks of diseases (e.g. Dutch Elm Disease *Ophiostoma novo-ulmi*, Ash Dieback *Hymenoscyphus fraxineus*) and insects (e.g. European Spruce Bark Beetle *Ips typographus*), including the human response to these outbreaks (Mikusiński et al., 2018). The presence of ongoing LTS are particularly valuable in situations of disease or insect outbreaks, or other extreme events, as they allow a ‘before and after’ assessment of singular or episodic phenomena affecting ecosystems (e.g. Wesołowski and Rowiński, 2006), which is an increasingly frequent driver of forest change worldwide (McDowell et al., 2020). The LTS also show that the tree diversity buffers stable assemblages of epiphytic organisms even when certain host trees decline to near-extinction (Wierzchowska et al., 2024; Łubek et al., 2020).

Generally, in the unmanaged areas of the Białowieża Forest, which have been largely free from direct human intervention for varying lengths of time, the deciduous trees are progressively replacing conifers, and increasingly shade-tolerant, nutrient-demanding vegetation is homogenising plant communities (Bernadzki et al., 1998; Cholewińska et al., 2020). These fluctuations in tree stand composition demonstrate the temporal shifts in dominance through natural processes (Kuijper et al., 2010a; Bobiec, 2012), with the entire forest acting as a dynamic supersystem of developmental phases (Bobiec et al., 2000).

Such findings contextualise observations from managed stands in the Białowieża Forest complex, and elsewhere, and can inform the planning of sustainable forestry and conservation perspectives, by indicating how forests behave with and without human intervention (Kirby et al., 1991; Blicharska et al., 2020), including their potential carbon storage (Matuszkiewicz et al., 2021). Results from the Białowieża LTS also have conservation implications by indicating how management can influence the availability of microhabitats within the forest structure (Wesołowski, 2012; Walankiewicz et al., 2014; Przepióra and Ciach, 2023). Overall, the dynamic shifts in the forest structure and composition revealed by the LTS parallel the changes in other components of the biotic community.

### 2.2. Mammalian studies

Among the mammals, the unique LTS of European Bison has been instrumental in the species' recovery from near extinction, restoring their ecosystem functions to Białowieża and facilitating their wider reintroduction in Europe (Kraśnińska and Kraśniński, 2007; Jaroszewicz

et al., 2009; Vlasakker, 2014). Other LTS have been instrumental in our understanding of how herbivores interact with large predators in temperate forest ecosystems. For example, results from the Białowieża LTS show how Eurasian Lynxes and Wolves limit herbivore populations but do not regulate them, with abiotic factors being more important by driving food availability (Jędrzejewska et al., 1997; Jędrzejewska and Jędrzejewski, 2005). LTS of the large carnivores' use of space (Schmidt et al., 2009) have also revealed behaviourally mediated impacts on their prey, with gradients of predation risk at the landscape-scale (Bubnicki et al., 2019) and finer-scale (Kuijper et al., 2015) redistributing the patterns of herbivore activity. A significant finding is how these multi-scale risks determine the intensity of herbivore browsing, which is crucial for driving the patterns of tree recruitment and vegetation structure in temperate forests (Bubnicki et al., 2019; Kuijper et al., 2013, 2015; van Ginkel et al., 2019). Such information can help to inform wildlife management in the wider context of forest restoration and trophic rewilding, supporting the reinstatement of natural processes and ecosystem dynamics in other regions (Manning et al., 2009).

### 2.3. Avian studies

The LTS of Białowieża's bird assemblage have involved 50 years of annual censuses, using standardised methods of intensive territory mapping, which have continued since 1975 (Tomiałojć et al., 1984). The data for bird communities in the BNP's old-growth forest, with its primeval characteristics, provide a unique benchmark for other forests (Wesołowski, 2007a; Wesołowski et al., 2022), and show a high diversity but comparatively low densities for many species, probably driven by high nest predation rather than limited food availability or nest sites (Wesołowski, 2007a). Many bird populations exhibit short-term fluctuations but longer-term stability over multi-decadal timescales (Wesołowski et al., 2022), with a gradual shift in community composition, especially where the forest composition is under dynamic change (Wesołowski et al., 2015, 2022). Climate change has advanced avian breeding phenology (Wesołowski and Cholewa, 2009; Wesołowski et al., 2021), with mixed indirect effects on fecundity (Czeszczewik et al., 2020; Wesołowski, 2023).

The LTS of Białowieża's bird communities have facilitated parallel studies at the species level, layered within the LTS, which have been instrumental in understanding the ecology of some birds that are of conservation concern elsewhere in Europe. For example, studies of Wood Warblers *Phylloscopus sibilatrix* and Marsh Tits *Poecile palustris* in the Białowieża Forest, operating alongside the bird census LTS, have provided essential information on reproduction (Wesołowski and Maziarz, 2009; Wesołowski, 2023), inter-specific relationships (Maziarz et al., 2020) and dispersal or settling patterns (Wesołowski et al., 2009; Wesołowski, 2015; Broughton et al., 2020). Such studies have contextualized research from other parts of Europe, where these species are in rapid decline, which can inform conservation actions for habitat management (Maag et al., 2022, 2024; Broughton, 2025). Furthermore, the intensive species-level studies in Białowieża were largely possible only due to the existing framework of the ornithological LTS, which provide established study sites, necessary expertise and training, and collaborative opportunities for research. These examples show how LTS can remain adaptable and responsive to emerging questions and opportunities, supporting a range of shorter to medium-term research projects that are nested within the wider framework.

Another key finding from the LTS in BNP is the superabundant tree-holes used by cavity-nesting birds, compared to managed forests (Wesołowski, 2007b; Walankiewicz et al., 2014). In North American forests, for example, woodpeckers (Picidae) play a keystone role of creating tree cavities utilized by other species. However, the Białowieża LTS show that cavities used by European birds largely originate from tree damage and decay, with woodpeckers performing only a minor role (Wesołowski, 2007b; Broughton et al., 2022). Unique long-term monitoring also demonstrated the multi-decadal longevity of tree cavities in

Białowieża, and the importance of retaining the large living trees that develop them (Wesołowski, 2012). Such insights are important for understanding ecological networks to underpin sustainable forest management and restoration that supports biodiversity, such as the promotion or retention of cavity-bearing trees (Przepióra and Ciach, 2023; Spinu et al., 2023).

### 2.4. Abiotic variables

Importantly, the LTS across the Białowieża Forest cover not just biotic factors but also major abiotic influences on the ecosystem. Meteorological data have been recorded continuously since the 1950s, with soil temperatures and groundwater levels monitored since the early 2000s. These datasets underpin the ecological investigations associated with phenology and climate change, a declining water table and warmer soils (e.g. Sparks et al., 2009; Czeszczewik et al., 2020, and also see Table S1 for data availability).

## 3. Integration of novel methods

The growth of remote sensing has facilitated the evolution of monitoring Białowieża's forest dynamics (Laurin et al., 2020; Dobrowolska et al., 2022), creating novel multidisciplinary approaches for studying vegetation structure and the habitat use of various animals (Broughton et al., 2020; Klich et al., 2023). Remote sensing has provided new LTS opportunities via repeated data collection over time, and has also been utilized for conservation by monitoring and documenting recent controversial logging activity in the forest complex (Mikusiniński et al., 2018; Pałaś and Zawadzki, 2020), and also insect outbreaks (Stereńczak et al., 2019) and historical human activity (Stereńczak et al., 2020).

Similar advances in automated recording (e.g. camera trapping and acoustic monitoring) are proliferating as a widely adopted tool in Białowieża studies for the measurement of animal abundance, diversity, distribution and interactions (Kuijper et al., 2015; Bubnicki et al., 2019; Maziarz et al., 2019; Diserens et al., 2022; Budka et al., 2023). These remote sensing and autonomous recording approaches are increasingly being embraced within the adaptive LTS frameworks, where they provide baseline data for future LTS while complementing existing methods (Dobrowolska et al., 2022), and advancing expertise in data collection, transfer, processing and analysis (e.g. Bubnicki et al., 2016, 2024).

## 4. Multidisciplinary value of long-term studies

The accumulated multi-disciplinary and multi-taxa data series from the Białowieża Forest LTS (Table S1) enhances their combined value and has allowed increasingly diverse collaborations to facilitate holistic data exploration. One study has utilized multiple LTS datasets from ornithological, vegetation and mammal research teams to unravel cascading, multi-trophic impacts of climate-induced changes on the frequency of tree masting events, which influenced the abundance of forest rodents and their depredation of migratory songbirds (Czeszczewik et al., 2020). Another multidisciplinary example used long-term vegetation data from enclosure experiments within a LTS (Kuijper et al., 2010b) to show how disease outbreaks increased Wild Boar *Sus scrofa* mortality, leading to reduced acorn consumption that, in turn, precipitated increased recruitment of oaks *Quercus* spp. in the forest (Bogdziewicz et al., 2022).

As ecological and evolutionary questions become more complex, the presence of multiple LTS and their established infrastructure and experienced researchers provides the necessary capability to tackle them. Data from Białowieża LTS have also contributed to international collaborations, such as demonstrating the buffering effect of forests on local temperatures (Zellweger et al., 2019), and changes in biomass productivity, along with rodent population dynamics, which are related to climate warming (Cornulier et al., 2013). As such, the Białowieża Forest

LTS are increasingly international in their value.

Fundamentally, the knowledge gained from the multiple Białowieża Forest LTS have an important role in society for demonstrating to scientists, policymakers and the public what ‘natural’ old-growth forests looks like, how they function over time (including evolutionary processes) and their role in mitigating climate change and biodiversity loss. Showing how the diverse species of a forest community interact within a functioning, dynamic ecosystem has a broad value as a focus for science, tourism and culture. On this basis, the Białowieża Forest was listed as a UNESCO World Heritage Site in 1979. With its complement of native large herbivores and predators, and surviving areas of old-growth forest, the Białowieża Forest offers a popular vision for future large-scale ecological restoration, rewilding and conservation elsewhere in Europe (Monbiot, 2014; Macdonald, 2020), providing insights into species interactions from this system that can be applied elsewhere (Churski et al., 2024). This wider public appreciation of the value of the Białowieża Forest is primarily based on what has been learnt from the LTS and the associated research embedded within them.

### 5. Maintaining the continuity of long-term studies

The ability to undertake and sustain the LTS in the Białowieża Forest has varied substantially over time, alongside fluctuating social, economic, political and scientific contexts. Importantly, periods of stability and social openness have allowed for greater integration of LTS via collaborative links between studies, research teams and institutions. However, during the 20th Century alone the Białowieża Forest region experienced several periods of war and prolonged occupation by authoritarian regimes, including Soviet and Nazi invasion followed by 46 years of Communism in a one-party system, with long-term partition of the forest. During this time, scarce resources and restrictions on travel, along with government oppression and martial law, meant that conducting research was typically challenging, and sometimes dangerous, both physically and politically (Anon., 2022).

Poland's post-1989 independence, restoration of democracy and later accession to the EU in 2004 allowed greater scientific collaboration and innovation via economic development and reduced barriers to travel and collaboration. This fostered a broader internationalisation of researchers involved in LTS, benefiting from increased freedom of movement, and also a surge in ecotourism that boosted the local economy and reputation of the Białowieża Forest (Czeszczewik et al., 2019). Research activity, investment in the Białowieża Forest's LTS and the resulting scientific outputs increased substantially during this era (Table S1).

More recently, however, domestic and international politics increased the instability for LTS once again. A period of national-conservative government from 2015 to 2023 brought increased authoritarianism (Applebaum, 2020) that reduced support for environmental science and expanded logging within the Białowieża Forest (Stokstad, 2018). Since 2021 there have also been growing tensions and an emerging hybrid conflict with neighbouring Belarus along the EU/NATO border through the forest, leading to a humanitarian ‘migrant crisis’ and heightened security concerns. The escalating militarisation and construction of a border wall disrupted the research community by enforcement of periodic restrictions on movement and entry to the forest. There has also been direct damage to the forest ecosystem via increased disturbance, heavy traffic, construction of infrastructure and associated habitat loss, as well as the physical barriers to animal movement that they pose (Nowak et al., 2023; Błaszczuk et al., 2024).

Of particular concern is the potential long-term effect of border infrastructure on the conservation and LTS of the Białowieża Forest's large mammals (Jaroszewicz et al., 2021; Nowak et al., 2023), including the potential effect on habitat connectivity (Bluhm et al., 2023), spatial behaviour and population genetics. This new reality on Poland's border through the Białowieża Forest has crystallized since 2022 after Russia's full-scale military attack on neighbouring Ukraine, which borders

eastern Poland and was partly launched via a complicit Belarus. Although research activity in the Białowieża Forest remained buoyant, it has been within a more hostile environment (Nowak et al., 2023). This restrictive, unsettled period is just the latest challenge to face Białowieża's LTS and shows how progress can be partially reversed, with no guarantee of ongoing stability.

Despite the challenges, most LTS at the Białowieża Forest have been remarkably resilient over time, allowing continued data collection, and this provides valuable lessons for studies elsewhere. Table 1 lists significant challenges, opportunities, impacts and mitigations that have hindered or enabled Białowieża's LTS to be maintained throughout periods of instability and change, as identified by the authors as practitioners who are familiar with them.

Principally, an overriding factor for maintaining the LTS is that the Białowieża Forest, and particularly the BNP, was not yet devastated or completely destroyed by human impacts, such as warfare, intensive logging or deforestation, which has enabled the fundamental research viability. This preservation underpinned recognition of the exceptionally high value of the forest, with the designation of part of it as a National Park in 1932, a larger area of the forest complex being listed as a UNESCO World Heritage Site in 1979, and EU Natura 2000 designation in 2007. These designations provided a higher degree of domestic and supranational protection for long-term study plots and research infrastructure.

### 6. All long-term studies should consider resilience

Anywhere in the world, a LTS may eventually face some challenges similar to those experienced in the Białowieża Forest. Changes in the socio-economic or geopolitical landscape can disrupt research activities by affecting the access to sites and facilities, the availability of funding and the retention of expertise. For example, in Eastern Europe the LTS in Ukraine's Chernobyl exclusion zone were abruptly interrupted during Russia's temporary occupation in 2022 (Ponsford, 2023). In Central Africa, meanwhile, long-term studies of primates in the Democratic Republic of Congo have been repeatedly disrupted and damaged by wars and political instability (Furuichi et al., 2012).

Even in historically stable regions, such as the UK or USA, political decisions can destabilise LTS. The 2016 Brexit decision was a policy shock that ended the UK's EU membership and cross-border freedom of movement for researchers and equipment, with significant impacts on scientific funding, international collaboration and recruitment (Highman et al., 2023). Along the USA-Mexico border, the erection of new physical barriers under the 2017–2021 Trump regime led to local researchers experiencing harassment and damage to study sites (Peters et al., 2018; Nowak et al., 2023). The second Trump regime from 2025 is likely to involve escalation of border infrastructure, substantial funding cuts and increased hostility to environmental science, and broader repressive policies for the USA's scientific community that will inevitably affect many LTS (Jones et al., 2025).

More widely, the height of the COVID-19 pandemic in 2020–2021 involved severe restrictions on local and national movements that seriously disrupted or temporarily suspended research activity and tourism worldwide, including in the Białowieża Forest (Primack et al., 2021). Future pandemics seem inevitable (e.g. Dye and Barclay, 2024), and these examples of significant and sudden shifts in the long-term status quo show that the stability of any LTS cannot be taken for granted. As such, researchers involved in LTS should be alert to potential challenges and consider their resilience.

### 7. Reputation, location and personnel

At the Białowieża Forest, national and international interest has been maintained in the LTS through reputation-building in prolific scientific publications, outreach and advocacy, and this has helped to attract collaboration, funding and goodwill to support research resilience.

**Table 1**

Summary of the significant challenges experienced by LTS at the Białowieża Forest in Poland since the early 20th Century, with the associated impacts and examples of mitigating factors or opportunities that may facilitate LTS continuity.

| Challenge/opportunity   | Impact   | Mitigation or opportunity   |
|---|--|---|
| Warfare   | Loss of access, infrastructure, staff/expertise; reduced/lost funding; personal risk   | Dispersed expertise and datasets to reduce risk; build/maintain international links to provide support or refuge  |
| Occupation or domestic authoritarianism and political/social oppression | Restricted access and freedoms; restricted collaborations; linguistic barriers; personal risk; limited/lost funding  | Focus on uncontentious, low cost & low (personal) risk scientific questions; seek/foster collaborations where possible; support staff wellbeing; safeguard data   |
| Political union/alliance (e.g. EU) or liberalisation                    | Internationalisation, freedom of movement; new research funding streams (but high competition); increased supranational site protections; wider recruitment; regulatory changes                              | Training to exploit new opportunities & align with new regulations/standards; diversify funding streams; embrace diversity in recruitment; exploit international collaborations and movement  |
| Limited funding   | Scarce resources; low salaries; limited recruitment, 'brain drain'; limited infrastructure; publication barriers   | Develop low-cost robust methods of data collection; recruit citizen scientists, students and postdocs, with suitable training/promotion of talent; build/retain expert field skills; seek multiple funding streams including better-resourced international collaborations  |
| Staff turnover and retention  | Loss of expertise and knowledge/metadata; instability and unpredictability from high turnover; limited innovation or progression of junior personnel from low turnover; reliance on dedicated core personnel | Maintain wide pool of researchers and multiple stakeholders for continuity (permanent and temporary staff); optimise data archiving, metadata and sharing; foster new talent, innovation and scientific freedom; increase the competencies of permanent staff via training; retain key skills via staff career progression and incentivisation; cultivate local citizen scientists/volunteers |
| Political barriers or militarisation at borders                         | Loss of access, restricted freedoms, intimidation, personal risk; site damage; reduced recruitment and collaboration   | Exploit novel research questions (e.g. impacts of barriers) and tools (e.g. automated data collection); maximise appeal for domestic recruits; improve staff retention, safety and support via training/counselling   |
| Scientific culture  | Competition between institutes, personal rivalry; limited collaboration/data sharing/reduced   | Foster positive culture through leadership, mentoring & training; encourage collaboration   |

**Table 1 (continued)**

| Challenge/opportunity            | Impact  | Mitigation or opportunity   |
|----------------------------------|---|---|
| Ecological or management changes | opportunities for syntheses from LTS; staff retention; Progression/support for junior staff<br>Change in study-site character; decline/loss of study species; degradation of habitats             | through workshops, conferences, meetings; collaborate on shared funding opportunities<br>Exploit novel research questions (e.g. climate change, disease outbreaks); foster multi-species, multi-trophic studies; foster national prestige and international support by building 'brand' of LTS and study site |
| Disease pandemic                 | Loss of staff; restricted travel/access to field sites; disrupted data collection   | Disperse teams to limit individual impacts; researchers based near/on site allowing easy access without travel; opportunity to explore existing data for continued scientific output; hybrid working; welfare support   |
| Economic and social change       | Turnover and recruitment via free movement and international competition/hiring; salary inflation; higher research costs; linguistic barriers; publication costs                                  | Foster diversity; optimise retention via salary, training or benefits packages; utilise LTS/site 'brand' in recruitment and funding applications; diversify funding sources; develop strategic reserves   |
| Technological change             | Redundancy or compatibility with continuity of established data collection methods; cost of equipment, maintenance and training; opportunities for enhanced data collection, analysis and sharing | Maintain expertise in existing methods to ensure compatible integration with new methods; embrace new opportunities; collaborate to gain access to improved technology/equipment; ensure adequate training  |

Public and scientific attention fosters national prestige that further promotes the protection of the forest, as the protests and publicity that surround threats or mismanagement carry reputational damage for the authorities concerned (Blicharska and Van Herzele, 2015).

The location of several research institutes within the Białowieża Forest has facilitated continuous research activity and a daily presence. These bases include the Białowieża Geobotanical Station of the University of Warsaw, the Mammal Research Institute of the Polish Academy of Sciences, and the Forest Research Institute, which maintain LTS datasets and have facilities to host resident and visiting scientists, students, fieldwork teams and international conferences. A critical factor in LTS continuity has been the organic dispersal of activities among these different research institutes, and teams elsewhere (including internationally), which builds cooperation, innovation and resilience to staff turnover or over-reliance on individual funding streams.

Another overriding influence on the continuity of Białowieża LTS has been the personal dedication and perseverance of key individuals. During challenging periods the actions of core personnel in providing visionary leadership and training has been crucial to the continuation of LTS throughout the changes, ensuring a continuity of data collection and scientific output (Anon., 2022). Such individuals tend to be vital as the focus around which the research teams are built and the focus of the LTS are maintained (Lindenmayer and Likens, 2010). Open-ended institutional support for such individuals, who are typically professors or heads

of science groups, is essential for ensuring a minimum reliable funding stream, academic freedom for collaboration, travel and advocacy, and sufficient research facilities. Valued qualities of the leaders themselves include a long-term commitment to the LTS (often at the expense of professional mobility), an ability to attract, retain and develop other researchers to build multi-disciplinary teams, and a certain degree of stubbornness to keep going through the inevitable challenges, while also being able to embrace new opportunities as they arise.

Despite relatively low salaries in public sector science, the long-term job tenure of researchers at institutions associated with the Białowieża Forest has been beneficial for promoting a stable framework to train students and attract early career researchers within the LTS. Job security and long-term funding enables younger researchers to plan for the future, have stable personal lives and build their career (Kuebbing et al., 2018).

## 8. Future challenges and opportunities

For the Białowieża Forest, the LTS demonstrate a somewhat circular relationship of established research informing scientific, public and political support for the conservation of the ecosystems in which they operate, with these protections then promoting research continuity. The broad range and longevity of the Białowieża Forest LTS has helped to create an iconic 'brand' that can garner support when new threats emerge, whether through forest mismanagement, exploitation or political change (Blicharska et al., 2020; Nowak et al., 2023). To consolidate the conservation effort and scientific base, expanding the National Park status to the whole forest complex within Poland would further protect and enhance research viability by averting some of these potential threats in the future (Wesołowski, 2005, 2007a).

Regional instability, border security and the prospect of future war are an increasing threat to the Białowieża Forest at present, including its LTS and researchers. However, while border infrastructure is inherently destructive (Nowak et al., 2023), some Białowieża researchers have identified potential opportunities from these threats, such as harnessing habitat conservation and restoration as a form of border protection (Żmihorski et al., 2024). The researchers suggest that promoting the natural accumulation of large fallen deadwood, removal of access roads and re-wetting of the forested borderlands would create physical obstacles to hinder or deter a hostile military incursion on that axis. Such measures would doubtless also have substantial conservation benefits for the Białowieża Forest ecosystem, underpinned by knowledge gained from the LTS, by essentially restoring to a wilder state substantial areas that are currently managed as commercial forestry, while also reducing the risk of potential invasion.

Despite the resilience of the Białowieża Forest's multiple LTS and its vibrant research community (Table 1, Table S1), a major long-standing gap has been the lack of a centralised repository or portal for the storage, cataloguing and dissemination of complementary datasets. To support future research and conservation of LTS sites, such as the Białowieża Forest, and to maximise the wider value of their outputs, relevant datasets must be discoverable, accessible and sufficiently documented to be understood (Lindenmayer et al., 2012; Vanderbilt et al., 2015). At Białowieża, as with many LTS elsewhere, different institutions and teams have generally evolved their own data management systems and may have had little incentive to integrate or share datasets (Mills et al., 2015). Many historical datasets may also remain undigitized. This carries a risk of data being lost during staff turnover and remaining unknown or inaccessible to other researchers. Even where data are adequately documented and available in publications or repositories, they may be widely dispersed and difficult to discover by other teams and projects.

To provide a firm basis for the future continuity and evolution of any LTS, there is a critical need and opportunity to create an integrated, multi-institutional, georeferenced and adequately resourced portal that curates, catalogues and archives the primary data and published outputs

(Culina et al., 2021). Some progress has been made towards this aim for the Białowieża studies, via the Open Forest Data repository (<https://openforestdata.pl/>), although resourcing of this facility has been limited. Sustaining such a resource with an adequate funding framework in perpetuity, perhaps at the national or supranational (EU) level, would be an invaluable opportunity to centralise the research base for Białowieża LTS. The establishment of such a repository, with sufficient back-up facilities and a rigorous commitment to data standards, would ensure that datasets are secure, reliable, discoverable and accessible for broader syntheses of their value to science and conservation (Sutherland et al., 2019).

## 9. Conclusions

Overall, the Białowieża Forest LTS show that change is inevitable, whether ecological, social or political, and this creates challenges and opportunities for any long-term research and conservation agenda. Maximising the viability of LTS is achievable via the dispersal of expertise and effort among institutions to offset systemic vulnerabilities in the funding and political landscape. Sustaining and transferring knowledge and skills is also critical, relying on the ongoing training of recruits in standard methods (such as field skills and data management) and protocols, as well as embracing innovation and technological advances to collect and analyse data in increasingly powerful ways. The LTS at the Białowieża Forest and elsewhere are often focused around the expertise and commitment of core personnel. These focal points are strengthened by building broad, multi-disciplinary teams around them that balances leadership with attracting and supporting the development of junior members. The sharing of skills and data through organic collaborations between researchers at various institutes also dilutes risk and maximises opportunities and outputs, further ensuring the continuity of LTS in an unpredictable world.

Nevertheless, the remarkable example of the multiple LTS in Białowieża Forest shows that a large body of collected evidence does not necessarily lead to the secure conservation of habitats and biodiversity. The debate over future management of the Białowieża Forest is ongoing, with periodic threats of intensified commercial logging after changes in the political regime, alternating with drives for greater protection (Blicharska and Van Herzele, 2015; Mikusiński et al., 2018). Political shifts elsewhere in the world are also increasingly impacting the funding and policy directions of environmental science and protections. The experience of the Białowieża LTS therefore provides lessons for how researchers and practitioners can mitigate or resist some of the harms and exploit some of the opportunities that come with significant change and instability.

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## CRediT authorship contribution statement

**Richard K. Broughton:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Marta Cholewa:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Dorota Czeszczewik:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Robert J. Fuller:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Bogdan Jaroszewicz:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Dries P. J. Kuijper:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Marta Maziarz:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Grzegorz Mikusiński:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Grzegorz Neubauer:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization.

## Declaration of competing interest

The authors have no interests to declare.

## Data availability

No data was used for the research described in the article.

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