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Research article

Socioeconomic prerequisites determine national long-term biomonitoring efforts

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A R T I C L E I N F O

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A B S T R A C T

In the current anthropogenic era characterised by human-induced environmental changes, long-term biomonitoring has become a crucial component for understanding ecological patterns and detecting shifts in biodiversity. However, spatiotemporal inconsistencies in biomonitoring efforts hinder transboundary progress in understanding and mitigating global environmental change effectively. The International Long-Term Ecosystem Research (ILTER) network is one of the largest standardised biomonitoring initiatives worldwide, encompassing 44 countries globally, including 26 European countries that are part of the European Long-Term Ecosystem Research network (eLTER). To better understand the establishment and development of such long-term biomonitoring efforts, we analysed spatial and temporal trends within the eLTER network. Additionally, we evaluated the environmental, social, and economic factors influencing engagement in biomonitoring activities within this European network. Our findings reveal a spatial imbalance, with biomonitoring efforts concentrated in Central and Western European countries, where monitoring initiatives have typically been established for a longer duration. Furthermore, our analyses underscore the complex interplay of economic, geographic, and cultural factors in the development of long-term ecological research infrastructures. Countries with greater geographic connectivity, slower economic growth, and higher research activity are more likely to be involved in the eLTER network. The intensity of biomonitoring significantly increased with greater research investments, economic growth, and elevated levels of tourism. In contrast, it decreased in countries that are more inward-facing and exhibit a belief in their ability to control environmental outcomes independently. Addressing spatial gaps in monitoring necessitates enhanced support and funding to ensure comprehensive ecological monitoring over extended time periods. This is essential for achieving transboundary sustainability and effective biodiversity conservation in the face of global change drivers.

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1. Introduction

Following centuries of human alterations to nature, biodiversity and ecosystem services have been eroded and remain threatened by a multitude of persistent anthropogenic stressors (Bradshaw, 2004; Schulz et al., 2015; Vigiak et al., 2021; Aytan et al., 2023; Kurtul et al., 2024). Long-term research plays a critical role in advancing our understanding of the resulting ecological and environmental changes (Körschens, 2006; Lindenmayer et al., 2012; Kasraian et al., 2016; Bayçelebi et al., 2024; Haubrock et al., 2024a). Long-term biomonitoring allows for systematic tracking of subtle and radical ecological shifts over extended time periods in a standardised manner, detecting changes that may not be apparent or are potentially misleading in the short-term. In doing so, scientists can not only distinguish between stochastic variability and significant trends that could influence policy-making and conservation strategies (Santamaría and Mendez, 2012; O'Connor et al., 2020), but also identify and quantify stressors that alter biodiversity (Helmuth et al., 2014; Pergl et al., 2020; Tekwa et al., 2023). It is, therefore, imperative to acknowledge that any ecological study focusing on environmental change inherently relies on or should incorporate available long-term environmental data, as these datasets provide crucial context and historical trends essential for understanding past and current impacts of environmental variability and change on ecosystems (Emiroğlu et al., 2023). Additionally, long-term studies offer the opportunity to assess the resilience of ecosystems to various stressors and disturbances, helping inform management and restoration efforts (Lindenmayer et al., 2012). Tracking these shifts and patterns also presents the basis for ecosystem projections into the future (Haubrock et al., 2024b), which is necessary to predict changes that may impair ecosystem services and human well-being (Haines-Young and Potschin, 2010) and subsequently to develop approaches to mitigate them (Millennium Ecosystem Assessment, 2005; Duraiappah et al., 2005).

Landmark studies, such as Hallmann et al. (2017) or van Klink et al. (2020), have garnered substantial public attention by providing invaluable insights into long-term changes in e.g. insect biomass and biodiversity. Other long-term studies have tracked large-scale trends in non-native species occurrences (Haubrock et al., 2023a, 2023b; Haubrock and Soto, 2023) and their impacts (Fukuda et al., 2016), invasions of non-native species across continents (Haubrock et al., 2024b) and the effects of climate and land use change (Le Hen et al., 2023; Kasraian et al., 2016). Despite recent advances in compiling long-term data (Dornelas et al., 2018; Haase et al., 2023), progress is often hindered by the limited and heterogeneous spatial availability of long-term monitoring sites, variable sampling periods, or, among others, changes in the sampling methodology over space and time (Lindenmayer and Likens, 2018; Siqueira et al., 2024). This lack of consistency, as well as outright regional data gaps, can lead to biases and limitations in local, regional, and global understanding of biodiversity trends and spatial patterns. Such challenges in utilising long-term monitoring data have been noted in various ecological studies (e.g., Magurran et al., 2010; Vellend et al., 2013; Pocock et al., 2015), highlighting the need for standardised protocols and sustained efforts in long-term data collection and management (Pocock et al., 2015; Dornelas et al., 2018; Haase et al., 2023). Without spatially and temporally congruent sampling of coherent long-term monitoring sites, temporal changes in biodiversity may be misinterpreted, or even remain undetected, which can possibly result in misleading assumptions that may, in turn, lead to flawed decision making (AbouZahr et al., 2007; Webber et al., 2019). Given the significant financial, infrastructural, and cultural investments required to establish and maintain long-term monitoring sites, socioeconomic factors play a pivotal role in determining a country's ability to contribute to, and benefit from, national and regional biomonitoring efforts.

A prominent effort to address this challenge are the International Long-Term Ecosystem Research (ILTER; Muelbert et al., 2019) and the European Long-Term Ecosystem Research (eLTER) network (Mirtl, 2018), founded in 1996 and 2007, respectively. The eLTER network is a transdisciplinary network spanning 26 European countries that connects long-term monitoring sites across diverse ecosystems, including freshwater, marine, and terrestrial sites, to study ecosystem processes, biodiversity, and their interactions with human activities, including related socio-economic consequences (Orenstein et al., 2019; Wohner et al., 2021). This network's goal is to enhance our comprehension of the intricate relationships between humans and the natural world over extended periods. By doing so, it aims to promote impactful research and generate new understandings of the combined effects of climate change, biodiversity loss, soil degradation, pollution, and unsustainable resource use on land, freshwater, and transitional water ecosystems (https://elter-ri.eu/). For this, eLTER uses standardised methodologies and facilitates collaboration between researchers to foster a deeper understanding of ecological and socio-environmental changes. Similar to other comparable initiatives, such as the National Ecological Observatory Network (Keller et al., 2008) and the Global Lake Ecological Observatory Network (Weathers et al., 2013), eLTER sites are unevenly distributed among European countries, possibly reflecting differences in the available research infrastructures and public investment, among other reasons. In turn, this discrepancy might indicate a potential foundational national bias that has arisen during the creation and establishment of eLTER as well as national LTER networks joining being accredited by eLTER. Indeed, several European countries such as Estonia, Croatia, and Ireland, but also non-European Union countries like Türkiye, participate in various European research programs but have no accredited eLTER sites (https://deims.org/search/sites/lter). Establishing and maintaining such sites requires substantial long-term financial investments to align with the eLTER infrastructure standards and focal points, and thus requires substantial time, effort, and resources. Alongside historic geopolitical differences among states, this can explain, at least to some extent, why eLTER might not have accredited sites in every European country. To the best of our knowledge, however, a spatio-temporally explicit analysis of the factors that can facilitate or hamper their establishment and accreditation over time is lacking.

To identify and examine the factors possibly influencing the establishment and accreditation of eLTER sites, we compiled a comprehensive database encompassing potential economic, social, and cultural predictors at the national European level. We expected to find (*i*) significant variations in the occurrence and number of eLTER sites among European countries over time, possibly showing spatial and temporal patterns, and hypothesised that (*ii*) economic prerequisites such as gross domestic product (GDP) and research expenditure are the primary determinant for the establishment of long-term research sites, whereas (*iii*) social and cultural norms may function as obstacles, halting their implementation over space and time. Understanding these dynamics could inform the development of strategies to overcome barriers and expand this network with the inclusion of so far underrepresented regions, thereby strengthening our capacity to address present and future ecological challenges, not only at the European level, but also for other international long-term monitoring endeavours elsewhere.

2. Methods

2.1. Data compilation

To investigate drivers determining the number of sites part of the European network of Long-Term Ecosystem Research (eLTER), we extracted information from the *Dynamic Ecological Information Management System – Site and Dataset Registry* (DEIMS-SDR) database (https://deims.org/search/sites/lter; Wohner et al., 2019). This database contains comprehensive information on all 625 research sites within the eLTER network (Fig. 1). To determine national differences that could contribute to the number of eLTER sites, we identified the number of eLTER sites in continental Europe, thus excluding sites maintained on other continents (https://deims.org/networks/4742ffca-65ac-4aae-815f-83738500a1fc; n = 578) and selected a series of broadscale national predictors extracted from various sources that could explain national differences in the presence and number of accredited eLTER sites (Table 1). In this study, we used eLTER sites as proxy because a long-term monitoring site is one that is specifically established with the intention of continuously tracking these ecological variables, allowing for the detection of trends and changes over time, even if the exact monitoring period is not predetermined. Accordingly, we here define long-term biomonitoring as the systematic and repeated observation of biodiversity or other ecological factors over extended periods, with the duration not strictly defined and potentially extending far into the future.

Although data from Water Framework Directive (WFD)-compliant freshwater ecosystem monitoring have previously been used to investigate the dynamics of freshwater organisms in Europe (Goertzen et al., 2022), the majority of sites analysed in a recent study (Haubrock et al., 2023a) revealed significant spatio-temporal biases. Specifically, many sites of good ecological quality were sampled only once every three or more years, whereas sites of poor ecological quality that required annual sampling were not monitored consistently. Furthermore, the duration and number of samples per site, even among those that were sampled multiple times, varied sporadically and lacked uniformity. As a result, these data would only allow for a space-for-time analytical approach, which is incompatible with the annually sampled biodiversity data required for long-term monitoring efforts like those conducted at eLTER sites. Similarly, while Natura 2000 sites, assessed under the Habitat Directive, provide valuable information on the conservation status of habitats across Europe, the monitoring efforts within these sites are often imbalanced among EU countries and do not always align with the consistent and long-term data collection needed for ecosystem monitoring on a broader scale. The variable implementation of monitoring protocols at Natura 2000 sites, especially concerning the structure and function of habitats, further complicates their integration into standardised long-term ecological monitoring frameworks like eLTER.

Originated from extensive cross-cultural research conducted in the early 1990s, Trompenaars' first and seventh dimensions of culture—universalism versus particularism and sequential versus synchronic time (Trompenaars, 1996)—were included as cultural predictors to assess their influence on the establishment of eLTER sites. These dimensions were selected due to their relevance in understanding how different cultural orientations towards rules and time management might impact collaborative scientific initiatives across diverse regions. Each economic predictor—GDP reflecting the overall economic output, gross national income per capita highlighting the average income of citizens, and country growth, indicating the dynamic changes in economic performance over time—was included to capture different dimensions of a country's economic situation. By considering these distinct aspects, we aimed to provide a comprehensive understanding of how economic conditions influence long-term biomonitoring efforts. Furthermore, we grouped the countries into four regions based on their geographic locations (Southern, Western, Eastern and Northern Europe; Table 1) to account for regional and possibly cultural differences (Beugelsdijk et al., 2006). These predictors were chosen because they reflect both the economic capacity and cultural context that are critical in sustaining long-term ecological monitoring. This allows us to assess not only the presence of infrastructure but also the underlying national commitment to biomonitoring and ecological research.

2.2. Statistical analysis

2.2.1. Model selection and analyses

Aiming to identify and elucidate those factors that influence the likelihood of European countries having accredited eLTER sites, we conducted two distinct approaches using generalised linear models: (1) we selected a quasibinomial regression model for the occurrence of sites (i.e. the presence of accredited eLTER sites in a European country while accounting for overdispersion; Blasco-Moreno et al., 2019) implemented in the *glm* function of the stats R package (Wiley and Wiley, 2019) and

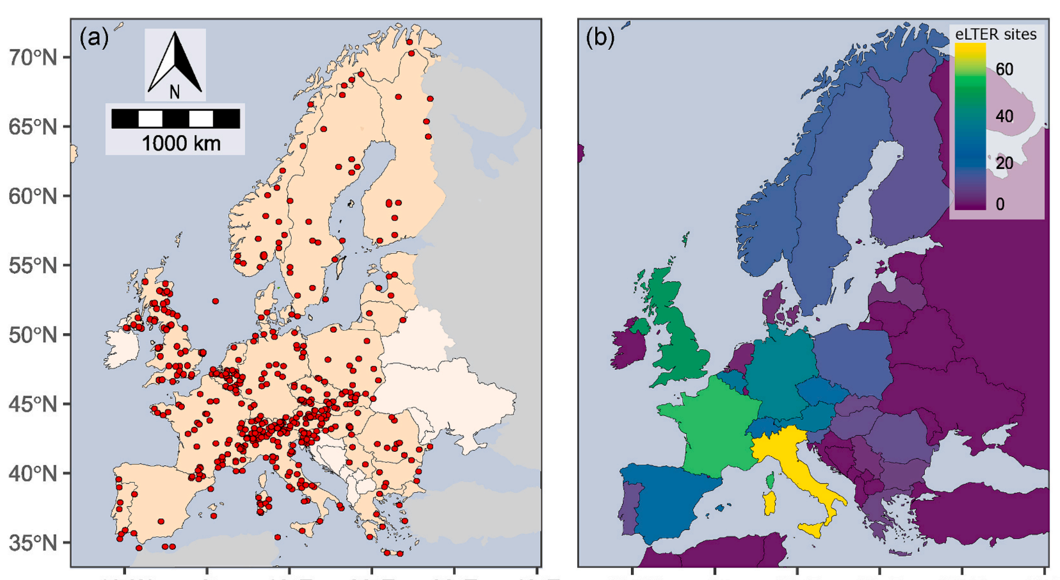

Fig. 1. Distribution of eLTER sites (red dots) in Europe, with countries in light orange having no sites (**a**) and the number of eLTER sites per country (**b**). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
List of considered predictors, their units of measurement, explanation, and source. Please see Supplement 1 for a detailed account of these predictors.

Predictor	Unit/ measurement	Explanation	Origin/reference
gross domestic product of 2021 (GDP_{2021})	US$ million	the total value of goods and services produced in a country in 2021	statista.com
population density	people per km^2	the number of people per unit area in a region	macrotrends.net
sustainable development index		a composite measure of a country's economic, social, and environmental progress	Sachs et al. (2022)
number of tourists (2021)	millions of people	total international visitor arrivals in the year 2021	worlddata.info
number of airports		total count of facilities for aircraft takeoff and landing	cia.gov/the-world-factbook/field/airports/country-comparison/
number of international airports		count of airports with customs and immigration for international travel	https://www.transtats.bts.gov/Data_Elements.aspx
port traffic	twenty-foot equivalent unit (TEU)	the number of ships cargo arriving and departing from a country's ports	https://data.worldbank.org in Twenty-foot equivalent unit (TEU)
import volume	cost, insurance, and freight; in millions	the total value or volume of foreign goods and services purchased	wits.worldbank.org
gross national income per capita	US$ millions; Atlas method (current US$)	total national income divided by the human population	wits.worldbank.org
country growth	US$ million	annual percentage growth rate of the country's trade value (export or import), by sector, at market prices in current U.S. dollars	wits.worldbank.org
number of border countries/ shared borders		the count of countries adjacent to a nation's borders	cia.gov
surface area	km^2	the total land and water area of a country	ec.europa.eu/eurostat/statistics-explained/index.php?title=Land_cover_statistics#Land_cover_in_the_EU_Member_States
percent of surface being agricultural land	%	proportion of land used for farming	data.worldbank.org/indicator/AG.LND.AGRI.ZS?locations=BE
ecological footprint	ha per capita	human demand on natural resources relative to ecosystem capacity	worldpopulationreview.com/country-rankings/ecological-footprint-by-country
percentage of population living in urban areas	%	proportion of people living in cities	data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS?locations=EE-FI-FR
Trompenaar's 1st cultural dimension	universalism vs. particularism	describes the ethical dilemma between applying general rules universally or adapting decisions based on specific circumstances and relationships	www.thtconsulting.com/culture-factory/culture-explore/compare-countries/
Trompenaar's 7th cultural dimension	internal direction vs. outer direction	contrasts the belief that individuals can control their environment and destiny with the belief that external forces or fate control the environment and destiny	www.thtconsulting.com/culture-factory/culture-explore/compare-countries/
research expenditure as percentage of annual GDP	%	the percentage of GDP spent on research and development	data.worldbank.org
number of researchers		the count of professionals conducting research per million people	data.worldbank.org
known native biodiversity	species richness	the diversity of native species in an ecosystem	worldrainforests.com

(2) a linear regression model with a negative binomial distribution for the count data (i.e. the number of eLTER sites, excluding countries without accredited sites) to account for overdispersion, implemented in the MASS R package (Venables and Ripley, 2002a). This methodical approach ensured that the model was optimised to accurately reflect the underlying patterns and influences in the data.

To assess correlations among predictors (Dormann et al., 2013), we employed the variance inflation factor (VIF) analysis using the *vif* function from the R package car (Fox et al., 2012, 2013). To address potential biases or double standards arising from separately considering GDP, gross national income per capita, and country growth, we carefully examined multicollinearity among these predictors using VIF analysis. This ensured that the final model appropriately accounted for the combined effects of these economic indicators, providing a balanced and comprehensive assessment of their influence on long-term biomonitoring efforts. For both the quasibinomial and the negative binomial regression model, the import volume (CIF value; in million) and the number of airports were excluded due to their VIF values surpassing the threshold of seven, indicating high multicollinearity with other predictors. Subsequently, we applied a stepwise model selection using the glmulti package in R (Calcagno and de Mazancourt, 2010). The model selection process identified relevant predictors based on all of the candidate's models, retaining the country growth, the number of border countries, the ecological footprint, the number of researchers, and the native biodiversity for the binary analysis of European countries with and without eLTER sites; and the number of tourists per capita and border countries, country growth, Trompenaars 7th dimension, research expenditure (as %GDP), and the number of researchers per million citizen as predictors for the number of eLTER sites per European country. Following both GLMs, we used robust standard errors estimated with the *vcovHC* function of the sandwich R package (Zeileis et al., 2019) to adjust the variability of the model coefficients, ensuring more accurate significance tests and providing robust inferences even in the presence of heteroscedasticity. This analysis serves to correct any potential bias in the standard errors, leading to more reliable p-values and confidence intervals for our predictors.

2.2.2. *Identifying national outliers*

To statistically identify outliers (i.e. countries that are over- or under-represented) among predictors related to the number of eLTER sites per European country, we built a series of null models for each predictor

(Briski et al., 2024; Cuthbert et al., 2024). These models were based on the assumption that the number of accredited eLTER sites in the respective countries mirrors the distribution of each predictor. Our approach entailed generating a defined region around the null model to represent the probability of a predictor being significantly over- or under-represented, as evidenced by a country's placement inside or outside this region. The region's boundaries were determined using a quasi-Poisson distribution's upper and lower quantiles, adjusted for multiple comparisons via a Bonferroni correction. Specifically, we aimed for (1-α/m) × 100 % of the distribution to fall within these boundaries, where α represents the significance level set at 0.05, and m is the number of eLTER sites in a given country. This adjustment ensures that the statistical threshold for identifying outliers becomes more stringent as the number of species increases, thus controlling for false discovery rates.

2.2.3. Network analysis

To assess whether geographical variation exists in the factors predicting the number of accredited eLTER sites in European countries, we visualised the interconnections among European countries based on the number of predictors identified as relevant by the model selection using network analyses. We utilised the vegan R package (Oksanen, 2012) to generate a Euclidean-based similarity matrix and constructed a bipartite network using the igraph R package (Csardi, 2013), where nodes represented countries while the links between countries represent the similarity of the factors predicting the number of eLTER sites per country.

2.2.4. Temporal analysis

Because the year long-term monitoring sites were accredited by eLTER was not publicly available, we used the year each currently accredited eLTER site was established as a proxy to investigate temporal trends in the creation of long-term monitoring efforts. For this, we analysed the cumulative number of long-term sites that at some point were accredited by eLTER over time per country and overall across Europe. This underlying information on the year these sites were established was again compiled by systematically scraping the DEIMS-SDR database, using the rvest package in R (Wickham, 2024) and contacting authorised personnel from eLTER to ensure the reliability of our obtained data. To further infer drivers that may affect the rate at which these sites were established over time, we first used a modified Mann–Kendall trend test (Pilotto et al., 2020) to identify country-specific monotonic trends (Kendall, 1949; Mann, 1945). When we detected temporal autocorrelation within a time series, we used auto- and cross-covariance using correlation functions (Pilotto et al., 2020; Venables and Ripley, 2002a, 2002b), applying the modified Mann–Kendall

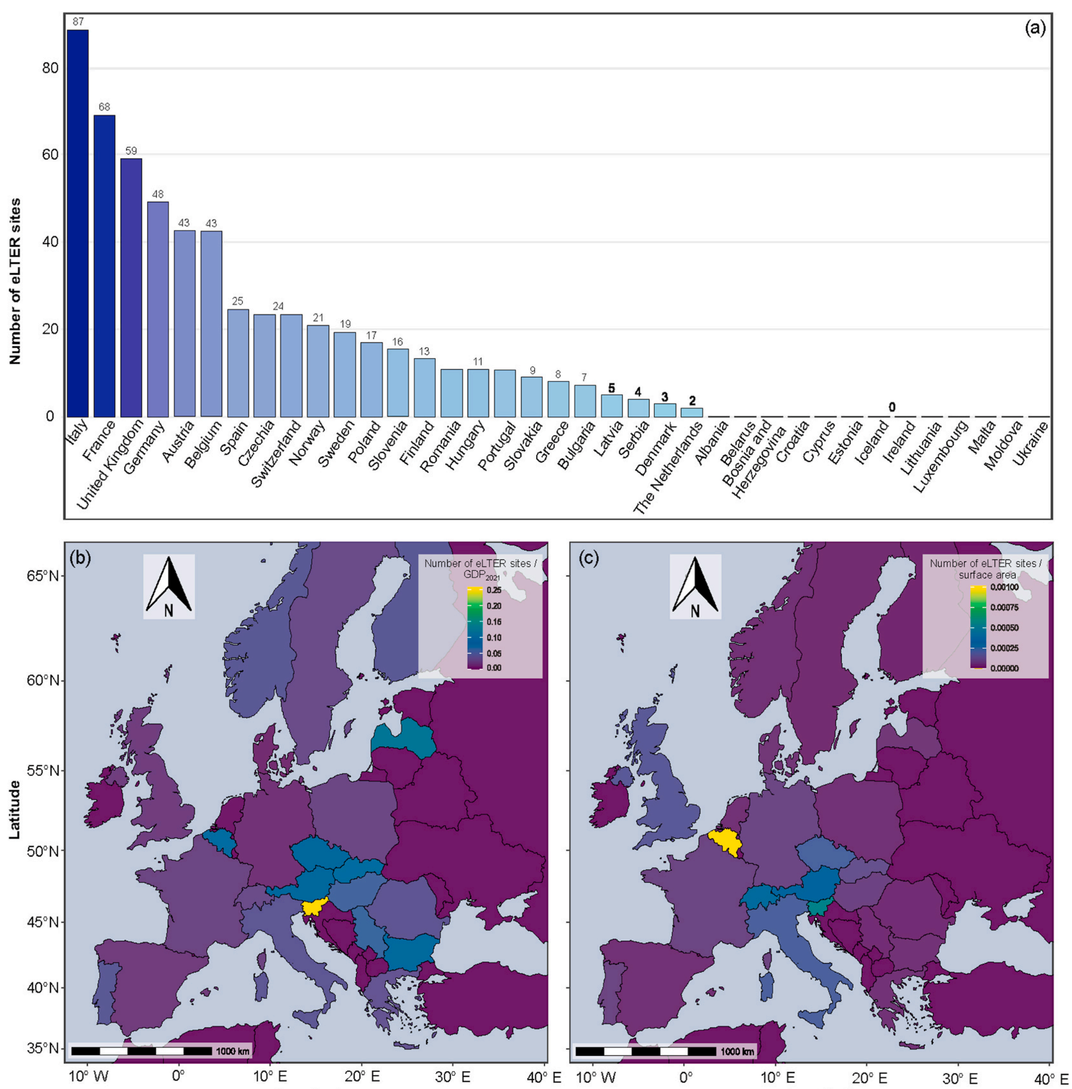

Fig. 2. Total number of eLTER sites among European countries (**a**), standardised and mapped by GDP_{2021} (**b**) and the country's respective surface area (in km^2; **c**).

variance correction (Hamed and Rao, 1998). We then employed a model selection using the glmulti R package (Calcagno and de Mazancourt, 2010) to identify relevant predictors followed by a meta regression model implemented in the metafor R package, which uses the Mann–Kendall test statistic (S) and its variance to quantify the effect size of each trend (Kendall, 1949), while accounting for the variance of each individual country's slope and treating each one as a single isolated entity (Viechtbauer and Viechtbauer, 2015).

3. Results

The number of accredited eLTER sites varied widely across European countries. Italy has the highest number with 87 sites, followed by France with 68, and the United Kingdom with 59 (Fig. 2a). Germany has 48 sites, Austria and Belgium have both 43. Spain has 25 sites, followed by Czechia and Switzerland with 24 sites each, and Norway with 21. These were followed by Sweden (19), Poland (17), Slovenia (16), Finland (13), as well as Hungary, Portugal, and Romania (each 11), Slovakia (9), Greece (8), Bulgaria (7), Latvia (5), Serbia (4), Denmark (3), and the Netherlands (2). Several countries have no accredited eLTER sites, namely: Albania, Belarus, Bosnia and Herzegovina, Croatia, Cyprus, Estonia, Iceland, Ireland, Lithuania, Luxembourg, Malta, Moldova, and Ukraine (Supplementary Table 1). When standardised by GDP, Slovenia had the most eLTER sites, followed by Latvia (Fig. 2b). Standardised by surface area, Belgium had the largest number of eLTER sites, followed by Slovenia, Switzerland and Austria (Fig. 2c).

3.1. Model results

The odds for the presence of accredited eLTER sites in a country increased most strongly with the number of border countries ($p < 0.01$), followed by the number of researchers ($p < 0.05$), and were found to decrease strongly with a positive country growth ($p < 0.05$; Fig. 3a and b; Supplementary Table 2a). The analysis of robust standard errors confirmed these findings, but indicated aside from generally higher levels of significance that also a high ecological footprint negatively predicted the presence of accredited eLTER sites (Supplementary Table 2b).

Research expenditure (as a percentage of GDP) was the most influential predictor, showing a strong positive relationship with the number of eLTER sites ($p < 0.001$). The positive correlation between research expenditure and the number of eLTER sites underscores the importance of sustained financial investment in national biomonitoring efforts, suggesting that countries with higher research funding can support more robust and long-term ecological monitoring programs, which is essential for effective national and regional biomonitoring. The second strongest positive predictor was country growth, followed by the number of tourists which was also a significant positive predictor of the number of eLTER sites (both $p < 0.001$). Trompenaar's 7th dimension (towards inner direction), the number of border countries and the number of researchers per capita showed negative relationships with the number of eLTER sites in the analysis (all $p < 0.001$; Fig. 4). The analysis of robust standard errors confirmed these results, highlighting the high significance of both negative and positive predictors ($p < 0.001$; Supplementary Table 3b).

3.2. Identifying national outliers

In general, there were few outlier countries, and therefore the numbers of eLTER sites tended to correspond to the assessed factors. The analysis revealed that Germany was an outlier concerning GDP_{2021}, population density, and imports (CIF value). The Netherlands was highlighted for its distinctive population density, while Norway exhibited unique patterns in country growth. Additionally, Spain was identified as an outlier in the number of international airports (Supplementary Fig. 1).

3.3. Network analysis

The network analysis revealed no clearly distinguishable geographical pattern in factors predicting the number of established eLTER sites. Western European countries, however, largely grouped together, with the exception of Belgium and Austria. Countries from other regions also showed no clear pattern. Yet, Italy, the country in Europe overall with the highest number of eLTER sites (n = 87), occupied a central position within the network and compared well to several countries from other

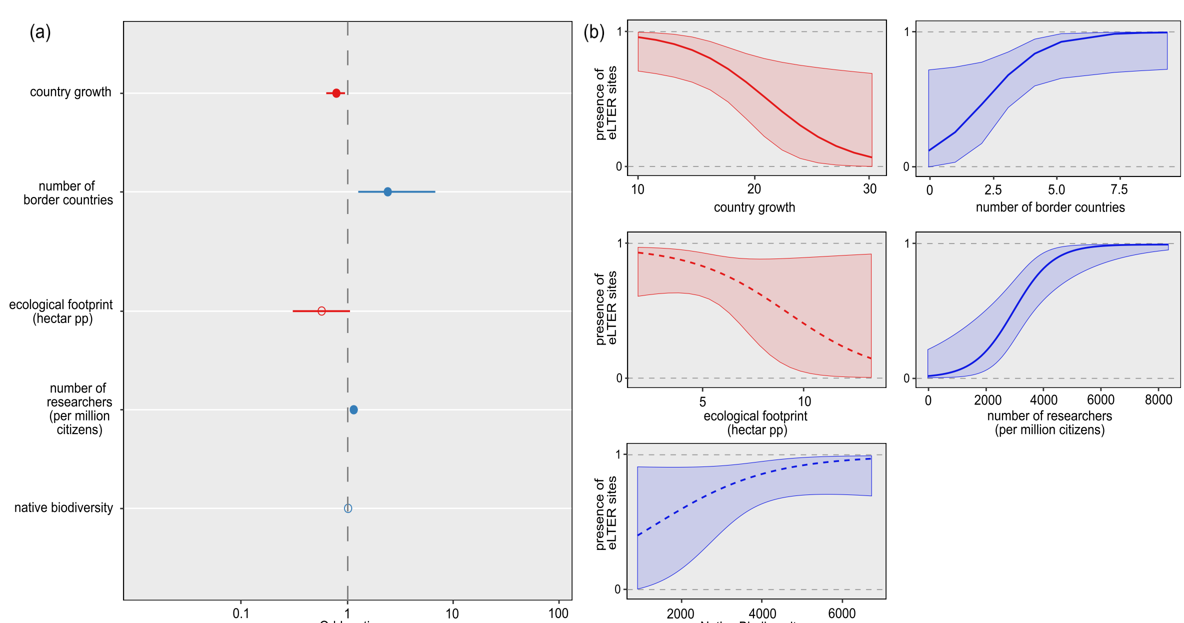

Fig. 3. Odds ratio (blue = positive; red = negative) of the predictors identified as relevant by the model selection to the presence of eLTER sites, indicating each predictor's relative effect size (hollow circles indicate non-significance and solid circles significance) (**a**) and their relationship with the presence of eLTER sites where dashed lined indicate non-significant and solid lines significant trends (**b**). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

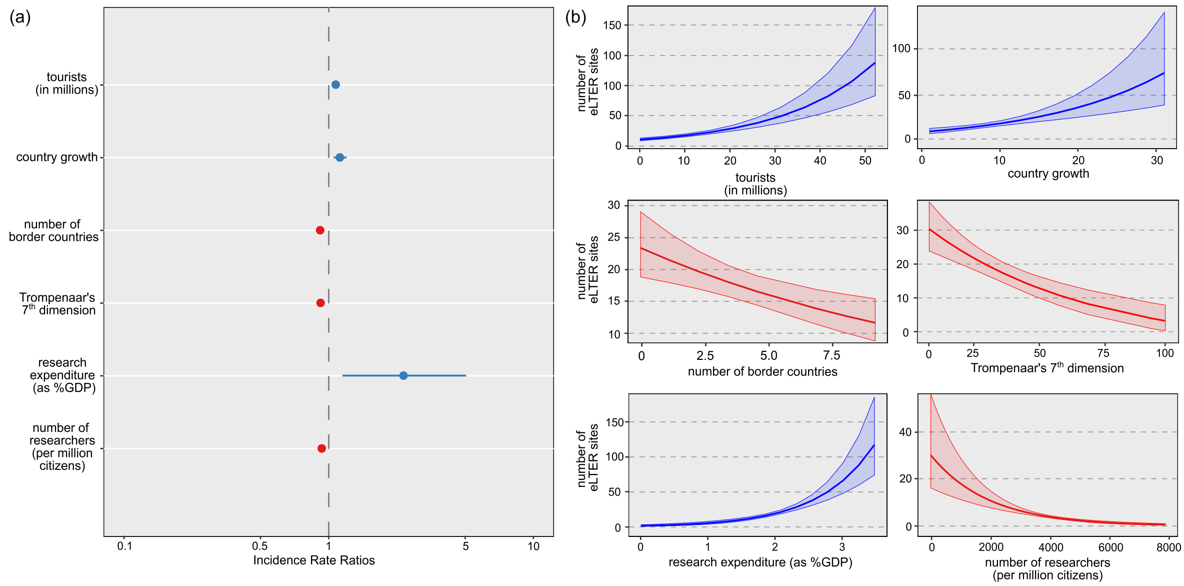

Fig. 4. Effect sizes (blue = positive; red = negative) of the predictors identified by the model selection as relevant in determining the number of eLTER sites (significant predictors are displayed using a solid circles and insignificant predictors with a hollow circle) (**a**) and their relationship with the number of eLTER sites (significant trends are displayed using a solid line and insignificant trends with a dashed line; **b**). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

European regions. France (n = 59 sites) and the United Kingdom (n = 68) which maintained the most eLTER sites in Western Europe, and Germany (48), occupied outlying positions (Fig. 5).

3.4. Temporal analysis

The temporal analysis showed increasing trends in the number of established eLTER sites over time (Fig. 6a), but signs of plateauing at the European level in recent years (Fig. 6b). The meta regression model, which could only be applied to 17 of 26 countries due to data dependencies (e.g., lack of variability or data points), showed that these trends were significantly positive in all countries and for Europe overall (Fig. 6c). Although the model selection suggested that Trompenaar's 1st dimension, surface area, the number of tourists and gross national income (GNI) per capita were relevant predictors to the rate at which long-term sites were established, the model identified that only the number of tourists was a significant predictor of a positive growth rate (Fig. 6d; Supplementary Table 4).

4. Discussion

Long-term ecological research infrastructure, such as the monitoring conducted by the European Long-Term Ecosystem Research Network (eLTER), is crucial for a sustainable future as it provides continuous and standardised data that help us understand ecosystem dynamics over time. These findings highlight the complex interplay between socio-economic factors and national commitments to biomonitoring. The uneven distribution of eLTER sites reflects not only geographic and ecological factors but also significant socioeconomic barriers that limit the participation of some countries in long-term monitoring efforts. Addressing these barriers is crucial for ensuring a more equitable and comprehensive monitoring network across Europe. This invaluable information can help identify and quantify the impact of direct human-induced stressors and climatic shifts on ecosystems, guiding policy-makers and researchers in developing adaptive management strategies to conserve biodiversity and support resilient, sustainable environments. However, knowledge of the environmental, social, and economic drivers of the uptake of biomonitoring and involvement in the network remain unclear. We therefore examined the spatio-temporal dynamics in the presence and number of eLTER sites on the European continent and the various factors that influence their establishment and extent at the national level, which could potentially lead to spatially biased monitoring of biodiversity trends. To this end, we found that eLTER sites are heterogeneously distributed across Europe, underpinned by spatial, economic, and socio-cultural discrepancies among European countries. Particularly, research investments, bordering countries, economic growth, and number of tourists were among the significant predictors of the presence and number of biomonitoring sites, as well as cultural degrees of insularity and control. These insights aid in overcoming barriers presently hampering the development of such networks or even expanding them to include underrepresented regions, thereby strengthening the capacity to address present and future ecological challenges at an international scale.

4.1. Drivers and deterrents of long-term monitoring networks

Aside from hurdles and obstacles in joining and expanding the eLTER network, numerous factors may function as prerequisites for the establishment of eLTER sites, while others may deter their establishment. Identifying these determinants is crucial for understanding the dynamics behind the development of long-term ecological research sites and national long-term infrastructures, and for guiding future policy and investment strategies to foster environmental research and conservation while avoiding biases (Chapin III et al., 2012; Musche et al., 2019).

In order for long-term sites to join national LTER networks or national networks to be accredited by eLTER, they need to align with the eLTER standard by meeting certain scientific, technical, and organisational criteria in line with eLTER's mission and objectives (Mirtl et al., 2018), but the feasibility may depend on several factors. We found that the number of border countries was a positive predictor of the presence of accredited eLTER sites, i.e. countries joining the eLTER network. This suggests that countries with a richer history of reciprocal trade and exchange of commodities may benefit from, e.g., enhanced trade and the exchange of ideas (Davis et al., 2013) and, thus, tend to show a higher environmental awareness (Jayadevappa and Chhatre, 2000; Zhang, 2023). The number of border countries could also be an indicator of higher environmental impact since environmental challenges such as biological invasions are tied to trade and the number of national borders

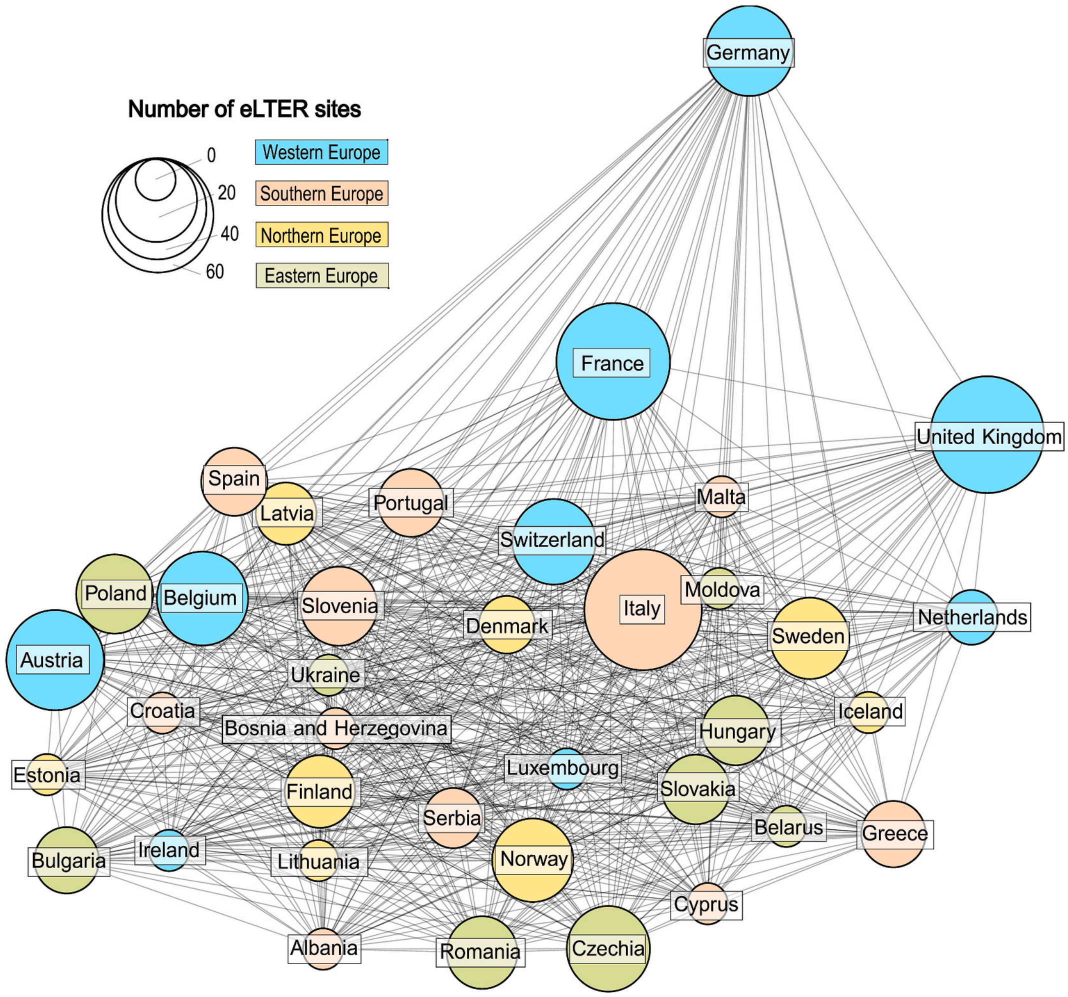

Fig. 5. Network analysis based on the predictors identified as relevant in defining the number of eLTER sites per country. Node sizes represent the number of eLTER sites per country, the length of the links indicates the degree of similarity in the considered predictors (GDP_{2021}, number of international airports, number of tourists, Trompenaar's 7th dimension, research expenditure as %GDP, and the number of researchers per million citizens), and the colours correspond to the cultural European region. Colouring by the number of eLTER sites per country can be found in Supplementary Fig. 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(Hudgins et al., 2023; Zhang et al., 2024). This could thus reflect the connectance between nations, where countries with more borders might experience greater pressures, but could also be indicative of distinct histories of industrialization, shaping their approach to and valuation of nature (Helliwell, 2000). The presence of eLTER sites also ties in with the number of researchers per capita in a given country, indicating a higher national research expenditure and thus, a possibly higher investment in sustainability. In contrast, we found country growth rate to hinder national eLTER networks from joining eLTER or establishing long-term sites that could join eLTER, suggesting that establishing long-term sites and getting accredited by eLTER is less likely in countries with growing economic activities. These countries could show a greater reliance on trade and, thus, a growth-orientated economic structure and, consequently, a divergent valuation of natural resources and ecosystems (Muradian and Martinez-Alier, 2001; Jorgenson and Rice, 2005; Hesse, 2009; Tekin, 2012). This could furthermore influence environmental management practices and laws, indicating a lower awareness of the value of nature and effort to monitor and study the direct and indirect effects of human activities on natural ecosystems, thus hindering the development of sustainable land use strategies and conservation policies within these countries (Baudron and Giller, 2014; Bernués et al., 2016). This coincides with the negative effect of high ecological footprints, which, although lacking statistical clarity, indicates that these countries experience competing land uses, greater environmental degradation, and prioritisation of economic activities over ecological research and conservation efforts (Chen et al., 2022). Interestingly, we also found that native biodiversity did not play a significant role in predicting the presence of eLTER sites, suggesting that neither a high nor a degrading biodiversity incentivizes long-term research investments.

With regard to the number of eLTER sites in a given country, we identified that research expenditure was the primary positive predictor, followed by high economic growth. Although the latter negatively predicted the likelihood of a country's national LTER network being accredited by eLTER, the positive effects of both these predictors on the number of eLTER sites likely reflect the relevance of a strong economy in funding existing research (Stephan, 1996; Coccia, 2008) and underscore the critical role of financial investments in maintaining research infrastructure (Florio and Sirtori, 2016). Although acknowledging the relevance of funding from, e.g., the European Union and especially the Horizon program, wealthier nations are evidently more capable of sustaining research initiatives, which is an expected outcome (May, 1998). While GDP, gross national income per capita, and country growth each provide unique insights into a nation's economic capacity, we acknowledge that considering them separately could introduce biases. Therefore, we examined how these economic predictors collectively contribute to addressing ecological challenges on an international scale,

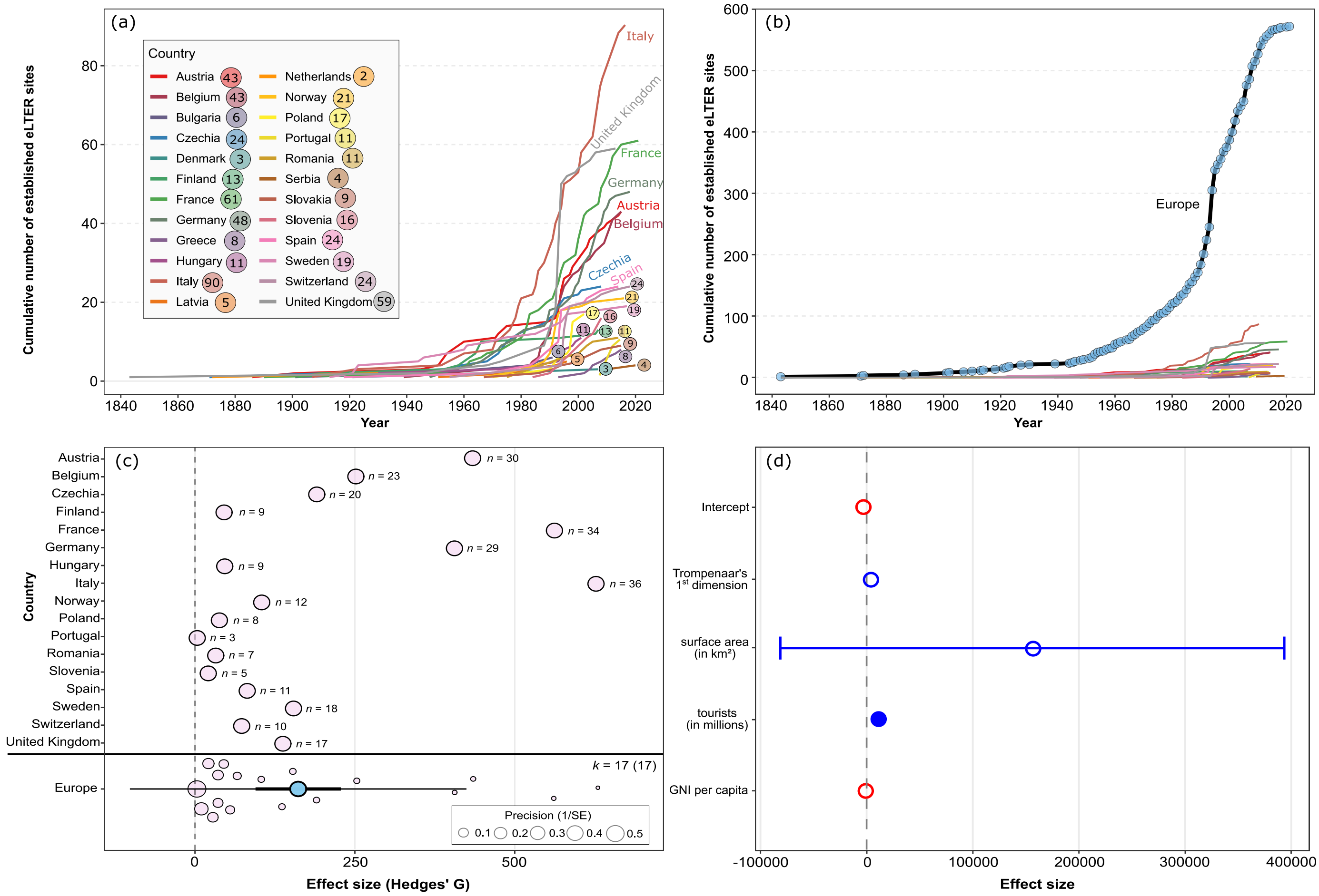

Fig. 6. Cumulative number of the establishment sites that were at some point accredited by eLTER, broken down by country (**a**) and for Europe overall (**b**), as well as the effect sizes for national and European trends in the establishment of eLTER sites (**c**) considering the effect of relevant predictors (blue = positive; red = negative; filled dots indicate significance; **d**). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

ensuring that our analysis avoids redundancy and offers a holistic view of economic influences on long-term monitoring. In line with the meta regression, we also identified that a high degree of tourism was a significant positive predictor for the number of eLTER sites that also facilitated the rate that which long-term sites were established over time. Although previous studies suggested that tourism and environmental actions may compete with each other as one often impedes the other (Graci, 2009; Zhu et al., 2021), our findings add to a large body of literature suggesting that tourism can raise environmental awareness and boost environmental actions (Sunlu, 2003; GhulamRabbany et al., 2013). The interplay of socio-cultural factors, population density, and tourist presence is particularly relevant in the context of sustainable biomonitoring. High population density and significant tourist activity can intensify environmental pressures, necessitating more comprehensive and sustained biomonitoring efforts to track and mitigate ecological impacts. Moreover, socio-cultural factors, such as a nation's values and attitudes towards nature, play a crucial role in determining public and governmental support for long-term ecological monitoring. Countries with stronger environmental awareness and cultural emphasis on sustainability are more likely to implement and maintain effective biomonitoring programs, ensuring that these efforts contribute meaningfully to conservation and ecological management at both national and regional levels. For instance, ecotourism, which emphasises responsible travel to natural areas and aims to conserve the environment while improving the well-being of local people, further supports the notion that tourism can have positive environmental impacts (Ramaswamy & Sathis Kumar, 2010). It is thus possible that the positive effect of tourism reflects a greater pressure on the environment overall or on a limited number of remaining natural habitats, resulting in greater attempts to monitor and protect environmentally important sites.

The number of border countries emerged as a significant negative predictor for the number of accredited eLTER sites. It is also important to acknowledge spatial discrepancies in biomonitoring intensities, with some southern European countries exhibiting larger numbers of sites and a steeper increase over time in particular. This coincides with a larger effect size for countries such as Italy which receives relatively large sampling efforts, and highlights a sampling imbalance to address at a coarse spatial scale. Additionally, our findings suggest that cultural dimensions, specifically Trompenaars' 7th dimension (internal vs. outer direction), may indeed serve as an obstacle for effective long-term monitoring. Countries that emphasize internal direction, believing they can control their environment, may prioritise short-term solutions over the sustained effort required for long-term ecological research, thereby hindering the development and expansion of monitoring networks. While this contrasts this predictor's effect on the presence of eLTER sites, it could reflect a higher environmental impact due to trade and travel across national borders (Hudgins et al., 2023; Zhang et al., 2024) and thus, greater economic pressures (Helliwell, 2000). Moreover, we found that a high value in Trompenaars' 7th dimension (internal direction vs. outer direction) indicated an inverse relationship with the number of eLTER sites. Indeed, a high value in Trompenaars' 7th dimension may indicate that a country tends to be controlling and believes in its ability to control the environment to achieve goals (Smith et al., 1996; Trompenaars, 1996), therefore favouring immediate, decisive actions over prolonged, uncertain outcomes, while indicating a preference for short-term, perceived cost-effective measures rather than long-term monitoring. These particularist countries often prioritise specific circumstances over universal research standards, leading to less support for systematic ecological monitoring. Another cultural dimension, despite not tested here, could be Trompenaar's 6th dimension of time orientation (Sequential vs. Synchronous Time), which contrasts sequential and synchronous cultures. Sequential cultures, like those in the U.S. and Germany, view time linearly and prefer to do tasks one at a time. However, even within these structured cultures, a reactive tendency may emerge, where decisions are carefully considered before action is taken (Luţ, 2016). These insights highlight the complex interplay of economic, social, and cultural factors that influence the development of long-term ecological research initiatives. In addition to addressing the challenges associated with joining the eLTER network, it is crucial to recognise the fundamental significance of establishing eLTER or other biomonitoring sites monitored following EU Directives (e.g. WFD, Habitats Directive), particularly in countries where such infrastructure is lacking. This is especially relevant given certain scientific perceptions that may undervalue the importance and effectiveness of long-term ecological research. Moreover, in light of these findings, it is crucial that European and national institutions take targeted actions to address the gaps and biases in long-term biomonitoring efforts (Kurtul and Haubrock, 2024). The European Commission and the European Environment Agency should lead the charge in coordinating and standardizing monitoring efforts across member states, ensuring that data collected from these sites are effectively integrated into EU-wide environmental policies and directives. However, in addition to European-wide efforts, the various national environmental agencies and governmental bodies in charge must strengthen their commitment to maintaining and expanding long-term monitoring sites, particularly in underrepresented regions. This can be achieved through increased funding, improved infrastructure, and enhanced collaboration with international networks like eLTER. By focusing on these areas, these institutions can ensure that the drivers of ecological change identified in our study are addressed in a systematic and coordinated manner, contributing to more effective biodiversity conservation and environmental management across Europe.

Over time, the number of accredited sites was found to be generally increasing across countries, but seemingly plateauing at the European level, suggesting a stagnation that might warrant further investigation. Moreover, the reliance on funding likely played a crucial role, as eLTER sites rely on major national funding. Such funding can originate from European Union investments from frameworks like Horizon 2020 and Horizon Europe (which do not benefit all countries equally; Mahoney and Beckstrand, 2011), but also from member's own contributions in providing resources, personnel infrastructure and operational costs from their own budgets, as well as smaller-scale collaborative projects funded through various European and international funding bodies (Veugelers et al., 2015). This may ultimately create spatial gaps where ecological change is not captured and large-scale drivers are diluted.

4.2. eLTER as a spatio-temporal model

Our analysis focused exclusively on European long-term sites accredited by eLTER, excluding other unaffiliated efforts and potential other long-term networks such as NEON in the United States (Keller et al., 2008) or the International Long-Term Ecological Research network in other regions (Kim, 2006), such as LTER Lithuania (Švažas et al., 2005). Although this specificity allowed us to focus on the characteristics and predictors relevant to the eLTER network and to consider it as a proxy for other programmes given its adherence to ILTER, it may limit the generalisability of our findings to other ecological research initiatives given geopolitical and investment differences. Yet, the eLTER network in Europe stands out due to its robust infrastructure and spatial homogeneity in those countries that maintain these sites. This may, in turn, serve as a model for similar (national and supranational) networks globally, as it facilitates extensive and reliable ecological monitoring, positioning the eLTER network as a benchmark for developing long-term ecological research infrastructures worldwide. Considering that the ILTER network has gradually expanded (Mirtl et al., 2018), the eLTER network faces a critical opportunity to expand internationally in the future as well. It is, however, important to note that our study did not consider differences in which parameters (e.g. biodiversity, water chemistry, soil characteristics, climate, pollutants, land use, taxonomic groups, etc.) are being monitored at each eLTER site, the method used at each site, and the data that are being collected, which could lead to substantial variability in the interpretation and application of any finding, as different sites may prioritise diverse ecological parameters (i. e. context dependency) and research goals (Lindenmayer and Likens, 2010).

Adhering to the policies of the ILTER, eLTER has generated a simple description and guideline as to how national networks are typically initiated and set up. Yet, despite surface area not being a limiting factor, numerous European countries had no maintained eLTER sites. *Vice versa*, it is possible that the distance between sites and habitat, ecosystem, or biotope diversity (which were not considered here) may explain why countries such as Italy maintain relatively high numbers of eLTER sites, despite being a country investing very little in research compared to other European countries (statista.com). The reasons for this disparity may be manifold and possibly originate from 434 infrastructures and sites that already existed when eLTER was established in 2003, without clear indication about the year these and other sites were accredited by eLTER. This raises the question as to whether countries with a history of long-term monitoring efforts, potentially reflecting cultural and economic differences, are more likely to have national LTER networks or even to become part of eLTER. Although this could not be tested due to a lack of congruence in the available data with regard to the year sites were established, joined national and respectively eLTER networks, it should be acknowledged that eLTER is a key transition project bringing together a voluntary network of sites to form a comprehensive European Research Infrastructure (Mirtl et al., 2018a), which might in part explain the heterogeneous distribution of eLTER sites across European countries.

5. Conclusion

Our findings collectively highlight the complex interplay of economic, geographic, and cultural factors in the establishment and maintenance of long-term ecological research infrastructures. In light of unprecedented anthropogenically-driven changes and alterations to the natural environment, long-term monitoring efforts are more critical than ever to reliably determine rates of ecological change and impacts. The eLTER network in Europe, with its robust infrastructure, may possibly serve as a global model for ecological research networks. However, the observed spatial gaps in monitoring, particularly in countries with high economic growth rates or a preference for short-term actions, undermine it and underscore the need for increased support and funding. Indeed, understanding the determinants behind the establishment of eLTER sites can guide future policy and investment decisions. By prioritising financial investment in research infrastructure and recognising the influence of geopolitical and demographic factors, we can enhance global ecological monitoring efforts. This, in turn, could support the development of adaptive management strategies that preserve biodiversity, support resilient ecosystems, and contribute to sustainable development. To achieve this, key decision-makers, including relevant governmental branches, ministries, university councils, and institutional bodies in countries lacking eLTER infrastructure should step forward and take proactive measures.

CRediT authorship contribution statement

Phillip J. Haubrock: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ismael Soto:** Writing – review & editing, Visualization, Methodology. **Ali Serhan Tarkan:** Writing – review & editing. **Rafael L. Macêdo:** Writing – review & editing, Visualization, Methodology. **Antonín Kouba:** Writing – review & editing, Conceptualization. **Ross N. Cuthbert:** Writing – review & editing, Visualization, Methodology. **Elizabeta Briski:** Writing – review & editing. **Teun Everts:** Writing – review & editing. **Irmak Kurtul:** Writing – review & editing, Writing – original draft, 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.

Data availability

The data used in this work is available as supplementary material or freely available, indicated in the methods section.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.122431.

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