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Abrupt ecological shifts of lakes during the Anthropocene

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ABSTRACT

Abrupt ecological shifts have become a pervasive feature of aquatic ecosystems with severe socio-ecological consequences. Yet, it remains uncertain whether these shifts happened synchronously or not among various lakes, and how multiple drivers interacted through time to drive these abrupt changes on a global scale. To address this knowledge gap, here we conducted a meta-analysis of 72 lakes worldwide based on integrated paleoecological records ranging from the 1850s–2010s. We found ecological shifts were mostly asynchronous across global lakes, but with an exceptionally increasing frequency since the 1950s. Driver-response results showed that abrupt shifts before the 1950s were dominated by climate change, whereas both anthropogenic drivers and climate change were responsible for most post-1950s shifts. Network analysis further indicated that interactions of multiple stressors are more prone to produce abrupt shifts, and global climate change is the most frequent co-occurrence driver, underscoring the need for global coherent collaboration to mitigate Anthropocene risk. Our findings provide new insights and empirical evidence for characterizing the Anthropocene from a global lake perspective.

1. Introduction

Global lake ecosystems are under formidable threats in the Anthropocene (Heino et al., 2021). Lakes contain nearly 90% of our planet's liquid surface freshwater, host remarkable biodiversity with more than 100,000 species (Shiklomanov and Rodda, 2003), and provide key ecosystem services supporting many millions of people worldwide (Reynaud and Lanzanova, 2017; Vadeboncoeur et al., 2011). However, multiple accelerating anthropogenic stressors have caused the unprecedented transformations in planetary landscapes over the past two centuries (Steffen et al., 2007; Taranu et al., 2015). Numerous lake ecosystems have been experiencing continuous degradation for centuries under multiple disturbances, owing to their high sensitivity to local and global environmental changes (Smol, 2019). Widespread increase of intense algae blooms and deoxygenation (Ho et al., 2019; Jane et al., 2021; Jenny et al., 2016), significant aquatic biodiversity loss (Keck et al., 2020), and lake thermal regions shift (Maberly et al., 2020) have been observed globally, especially since the Great Acceleration around the 1950s (Steffen et al., 2015). Moreover, increasing socio-ecological surprises are expected to emerge under the predicted future scenarios of increasing climate change and human activities, combined with the legacy of past perturbations (Mammides, 2020).

Pervasive abrupt shifts across global lake ecosystems have been occurring, and are likely to accelerate under future global changes (Cooper et al., 2020). Here, we define abrupt ecological changes as stepwise shifts in ecological structure and/or biomass, which may (or may not) be driven by reinforcing feedback loops beyond the tipping points (Scheffer and Carpenter, 2003; Turner et al., 2020). Following this definition, we consider that abrupt change happens either as an ecosystem shift to another stable state, or as an ecological structure change significantly but not necessarily in an irreversible manner. These ubiquitous abrupt changes are hard to predict, and are often difficult, costly, or even impossible to reverse (Spears et al., 2017). Consequently, obtaining a comprehensive understanding of abrupt ecological change has been identified as a priority for biodiversity conservation and ecosystem service management (Turner et al., 2020). However, the patterns of abrupt changes in lakes worldwide and the underlying mechanisms are still largely unknown.

The dynamics of abrupt changes in lake ecosystems have been examined by empirical, theoretical, and predictive approaches (Carpenter et al., 2011; Spears et al., 2017). Abrupt change can happen across different trophic levels of lake ecosystems (González Sagrario

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et al., 2020), driven by interactions between slow and/or fast pressures (Hilt et al., 2017), along with early warning signals (Wang et al., 2012), the various transition time of different lakes and possible cascading effects (Rocha et al., 2018). These findings have greatly improved our understanding of the underlying mechanism of abrupt change. However, most of previous studies have been performed at local or regional scales, and comprehensive information about the spatio-temporal patterns of abrupt lake changes on a global scale remains poorly understood. Moreover, as different lake ecosystems might respond heterogeneously even under the same stressor due to their specific-characters (Leavitt et al., 2009; Perga et al., 2015), it is also unclear how these shifted lakes responded on a global scale, and the shift timing and their underlying mechanisms in various lakes are not well understood. Such questions as when these abrupt lake ecosystem changes happened during the Anthropocene, and what the temporal patterns were among these shifted lakes with different physical and social settings from a global perspective, and how these shifts were affected by global changes (e.g., climate variability) interacting with local drivers (e.g., changes in land use and hydrology) through time, remain poorly explored, leaving the open question of how prevalent and large these shifts may be.

Characterizing large spatio-temporal patterns is hampered mostly by the lack of long-term and temporally continuous empirical data, which is critical for detecting and understanding abrupt changes in ecosystems (Turner et al., 2020). Paleolimnology provides a powerful avenue for retrospective assessments, by providing high-quality datasets that can be used to address these issues (Smol, 2019). A variety of paleobiological indicators in lake sediments, including biological residues (e.g., diatom, chironomid, cladoceran, and aquatic macrofossils) and biomarkers (e.g., pigment and DNA), can be used to directly reflect the paleoecological changes in biomass, community composition, and structure. Although paleo-data is increasingly becoming available to study the long-term abrupt changes of various lakes (Rühland et al., 2008), a suitable integration of such studies at a broader spatio-temporal scale is still lacking. A global assessment of abrupt shifts in lake ecosystems would help to anticipate the nature and timing of potential impacts, and identify leverage points that could reduce the risk of multiple abrupt shifts simultaneously to avoid unexpected consequences (Heino et al., 2021).

The primary goal of this study is to analyze the patterns and drivers of abrupt shifts in lake ecosystems over the past two centuries on a global scale. We conducted a meta-analysis to examine abrupt ecological changes by using published long-time series of paleoecological data spanning the past 200 years across the globe, with a broad range of physical characteristics and anthropogenic pressures. The key objectives are: (1) to reveal the spatial-temporal patterns of lake ecological shifts worldwide over the past two hundred years; (2) to examine the dominant drivers and underlying mechanisms that caused various lake shifts. Establishing these links is critical for robust prediction of future shifts under accelerating environmental changes. This is the first study to address these questions at a global level.

2. Material and methods

2.1. Criteria for lake selection

We conducted a systematic review of published literature that recorded abrupt lake ecological changes spanning the past two centuries, by searching on the ISI Web of Science database, Google Scholar, and China National Knowledge Infrastructure (CNKI, http://www.cnki.net) up to December 2020. Potential case studies were recognized by different combinations of the following key-terms: lake sediment, paleolimnology, paleoecology, and biological, with regime shift, abrupt change, alternative stable states, critical transitions, abrupt shift, threshold change, tipping point, and stark shift. For instance, the appropriate papers were searched on ISI Web of Science using Boolean search query “TS= (abrupt change* OR regime shift* OR critical transition* OR alternative stable states OR abrupt shift* OR threshold change* OR tipping point* OR stark shift*) AND (pal*eolimnology OR pal*eoecology OR sediment*) AND (lake*)”. In addition, those literature with a particular description of lake eutrophication and ecological shifts from a macrophyte-dominated clear state to a phytoplankton-dominated turbid state based on the paleolimnological records were also included (Scheffer, 2001). A total of 1248 pieces of literature were selected by our search.

The following criteria were used to further select appropriate case studies: (1) the time span of the examined paleolimnological studies should be within the past two hundred years, with a minimum timescale of 50 years (covering the period of the Great Acceleration around the 1950s); (2) a demonstrated/observed abrupt change of lake ecosystem over the studied period based on the established chronologies (e.g., ^{210}Pb and ^{137}Cs dates), and the timing of transitions was identified/discussed by the original authors; (3) either the abrupt change is identified as a critical transition, or the shift is reversible without alternative stable states over the temporal horizon of the original study; (4) drivers that caused the abrupt shift are also needed to be explicated by original authors, which was discussed by qualitative/quantitative analyses of potential climatic and/or anthropogenic stressors in the original studies. For some lakes that showed two or more change points, the most statistically significant value will be selected if the author has analyzed based on the detection methods of abrupt changes in the original paper, otherwise, we choose the timing of shift based on the paper’s explanation and key conclusion combined with the other environment records such as historical archives and monitoring records. Based on the above four screening criteria, ultimately, we selected 66 pieces of literature which included 72 appropriate case studies of lake ecological shifts worldwide during the past two centuries. The other studies were excluded either due to the inappropriate time-scale of investigations, or the improper studies which mainly focused on the methodology of regime shift, when we screened their abstracts, methods and main conclusions. Consequently, a shift-driver dataset of 72 lakes worldwide was built, covering lakes from shallow to deep, small to large, oligotrophic to hypertrophic, and tropical to arctic. More details of the site information (e.g., geographic coordinates, mean water depth, lake area, the intensity of human pressure in the watershed, and time-scale of lake sedimentary records), and transition information including the timing and the corresponding driver(s) of each abrupt shift in lake, as well as paleo-proxy used to identify abrupt change and corresponding shift detection approaches used in the original literature are available in Supplementary File 1.

2.2. Definition of different lake types

To assess the difference and similarity of abrupt changes among different examined lakes, we defined the lakes in our database as three types according to their physical and geographic characteristics. Based on water depth, the lakes were divided into shallow lakes (mean depth $\leq$ 6 m), intermediate depth lake (6 m $<$ mean depth $<$ 20 m), and deep lake (mean depth $\geq$ 20 m). Based on latitude and altitude, the lakes were classified into temperate-tropical lakes, arctic lakes, and alpine lakes. In terms of human footprint (HF) intensity within the associated catchment, the lakes were separated into low-HF lakes (HF = 0–4), moderate-HF lakes (HF = 5–12), and high-HF lakes (HF $>$ 12). The HF data and classification criterion were conducted according to Venter et al. (2016a, 2016b) (more details in Supplementary File 2).

Apart from classifying lake types based on their physical and geographic characteristics settings, we also divided the lakes based on different paleobiological proxies into three groups: diatoms, cladoceran and chironomid, and others (e.g., pigment, DNA, aquatic pollen, and plant macrofossils), given that the different biological communities might respond heterogeneously. Then we examined the timing of lake shifts inferred from the same paleoproxy groups, and compared the results with that from all various biological proxies together. A summary

Table 1
Overview and summary of the abrupt ecological shifts of lakes worldwide.

Category	Subgroups	Number of lakes	Mean depth (m)	Lake area (km^2)	Human-footprint (HF)	Timing of transition	Time span
Lake depth	Shallow	36	2.17	133.6	17	1960 ± 39 (1945)	157 ± 56 (161)
	Intermediate depth	18	10.87	2945.91	15	1960 ± 23 (1963)	200 ± 48 (184)
	Deep	18	65.34	1927.44	15	1967 ± 24 (1960)	195 ± 67 (170)
Human footprint	Low-HF	15	19.8	1878.53	1	1950 ± 49 (1935)	200 ± 59 (187)
	Moderate-HF	16	33.97	1899.2	8	1955 ± 32 (1950)	187 ± 47 (175)
	High-HF	41	14.86	845.77	25	1963 ± 22 (1962)	160 ± 59 (159)
Climate /latitude region	Temperate-tropical	49	15.37	1411.81	18	1965 ± 23 (1963)	158 ± 55 (163)
	Arctic	11	22.06	2209.41	0	1950 ± 56 (1929)	200 ± 64 (194)
	Alpine	12	37.81	27.17	22	1937 ± 27 (1939)	182 ± 55 (169)
Sedimentary proxy	Diatoms	37	19.99	1018.85	16	1960 ± 38 (1953)	200 ± 57 (175)
	Cladoceran &Chironomid	17	20.95	33.67	18	1963 ± 25 (1958)	160 ± 59 (169)
	Others	18	19.67	3183.91	16	1960 ± 28 (1951)	158 ± 57 (155)
Geographical area	America	18	16.88	3170.47	9	1950 ± 47 (1936)	200 ± 57 (197)
	Asia-Oceania	33	10.27	259.13	18	1970 ± 25 (1965)	160 ± 48 (158)
	Europe-Africa	21	38.42	1426.04	20	1950 ± 22 (1950)	160 ± 64 (161)
Detection approach of abrupt shift	CONISS	39	21.68	747.57	16	1960 ± 27 (1956)	190 ± 53 (174)
	STARS	12	2.86	149.38	17	1970 ± 23 (1965)	126 ± 32 (129)
	F-statistic	7	3.34	473.54	23	1970 ± 21 (1967)	110 ± 37 (124)
	Others	33	19.96	2723.84	15	1960 ± 40 (1949)	172 ± 58 (173)

Mean values of lake mean depth, lake area and the intensity of human footprint within watersheds are listed by groups. Median values with standard deviation (SD) and mean values (in parentheses) of the timing of transitions, as well as time span of sedimentary records are summarized by each lake type/group. The abbreviations involved in table are the constrained cluster analysis (CONISS), and Sequential T-test Analysis of Regime Shifts algorithm (STARS).

Table 1 was listed to exhibit the key information of lake shifts with different lake types, various paleoproxies and specific groups.

2.3. Statistical analyses and network simulations

To account for the imbalanced data from the potential statistical artifact, we conducted a bootstrapping procedure and K-nearest neighbors method SMOTE (Synthetic Minority Oversampling Technique) using *Imblearn* package of Python 3.8, to examine the frequency of abrupt shifts of these examined lakes during the studied period compared with the observed values per given time bin.

To better understand the relative importance of drivers underpinning each abrupt lake shift in our dataset and their co-occurrence patterns, we built the shift-driver database. Then, a simulated co-occurrence network was constructed using R's *bipartite* packages (Dormann et al., 2008) and Gephi v 0.9.2 for graphic visualization, where a driver is connected to an abrupt lake shift if there is a causality discussion for each examined lake. The network was analyzed by considering one-mode projection, a network of drivers connected by the lakes they drive.

For assessing paleolimnological temporal trends and comprehensive analyses of shifting time, the time-series of lake paleoecological indicators were digitized from the original literature, and *Z*-score normalized, to compare and assess the integrated trajectories of ecological changes. To unify the rising trends of paleoecological records over time for synthesis, the downtrend curves were multiplied by −1. Generalized additives models (GAMs) were performed to estimate the general trend in paleobiological time-series over the past two centuries using *mgcv* package in R v 3.6.3 (Simpson, 2018; Wood, 2018). These original time-series were grouped into three categories and plotted in Fig. S1 in Supplementary File 2.

3. Results

3.1. Timing of abrupt change across lakes

Based on the data synthesis collected from the paleoecological records in 72 lakes worldwide (Fig. 1), we analyzed the timing of abrupt lake ecological shifts during the Anthropocene. From a global perspective, a great majority of lakes have undergone abrupt ecological changes around the 1950s–1960s (Fig. 2a), though all the timings ranged from the 1850s to the 2010s. The frequency of abrupt changes has increased significantly since the 1950s (Fig. 2b). Specifically, over two-thirds of lakes (52 out of the 72 lakes) have experienced abrupt changes after the 1950s, only 3 and 17 lakes shifted prior to 1900 and during the 1900s–1950 periods, respectively (Fig. 2b). In terms of the defined lake groups, lakes with different water-depth showed similar abrupt shifting time (i.e., the 1960s) (Fig. 2c, Table 1). In contrast, the timing of shifts varied largely with the gradient of latitude and HF intensity. For instance, lakes in temperate and tropical regions mainly shifted around the 1960s, whereas the majority of alpine and arctic lakes were close to the 1930s–1940s (Fig. 2d, Table 1). Lakes in high-HF, moderate-HF and low-HF regions exhibited the major shifting time of the 1960s, the

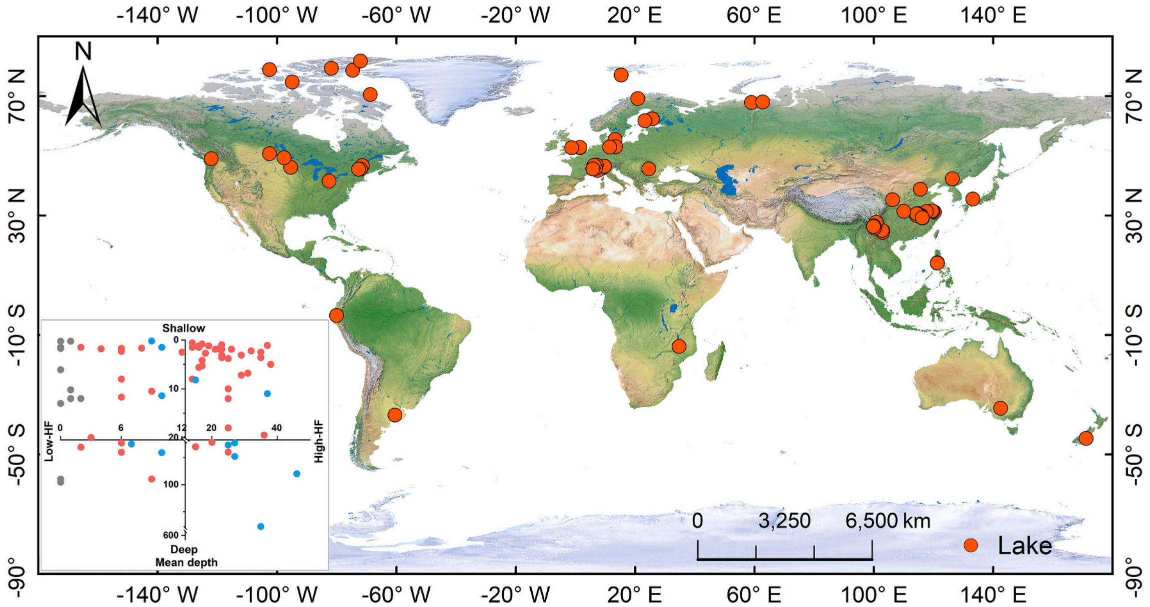

Fig. 1. Locations of 72 lakes worldwide examined in our meta-analysis. The inset figure shows the lakes classified into different types based on mean water depth (m) and human pressure (HF), and further divided into alpine lakes (blue dots), arctic lakes (grey dots), and temperature-tropical lakes (pink dots) (more details in Supplementary File 1). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

1950s, and 1950, respectively, along the gradient of human-footprint intensity (Fig. 2e).

By exploring the possible effect of different proxies on the timing of lake abrupt changes, we found that the timing of lake abrupt changes demonstrated similar trend around the 1950s–1960s based on three categorized paleoproxies, diatom, cladoceran and chironomid, and others, respectively (Fig. 2f and Fig. S2). For example, lakes with different water-depth presented similar variations based on the same paleoproxy (Fig. S2a) compared with that from all proxies together (Fig. S2). Similar patterns can also be found among the lakes at different latitudes based on similar paleoproxies (Fig. S2b) or human impact intensity (Fig. S2c), when compared with results from all paleoproxies together (Fig. 2d and Fig. 2e, respectively).

3.2. *Network of drivers*

A total of 30 drivers were identified that were attributed to the abrupt ecological changes from 72 lakes worldwide, among which climate change and nutrient loads were the most frequently reported drivers, and both were responsible for 29 lake shifts during the past ~200 years (Fig. S3). All the drivers were further grouped into five broad categories, including climate effect, habitat modification, nutrients and pollution, hydrological modification, and biological effect referring to Rocha et al. (2015) (Fig. 3a, more details in Sheet "driver category" of Supplementary File 1). Before the 1950s, abrupt changes were mainly caused by climate effects, whereas nutrients and pollution plus recent climate effects often collectively resulted in the shifts after the 1950s. For different lake types, shifts of temperate-tropical lakes with high-HF were linked to nutrients and pollution, while high-latitude arctic lakes under low-HF were associated with climate effects during the past centuries (Fig. 3b). Additionally, habitat modification from land-use change and urbanization, and damming showed significant influence on temperate-tropical shallow lakes especially after the 1950s.

Furthermore, our synthesis showed that the majority of abrupt shifts in lake ecosystems were outcomes of simultaneously interactive effects of multiple drivers. The mean number of drivers per abrupt lake shift was two, and only 23 abrupt changes were underpinned by only one dominant driver, whereas 49 lakes showed at least two acting drivers were responsible for their ecological shifts during the last two hundred years. One-mode projection of the drivers indicated that climate change and nutrient loads were the most frequent co-occurrence drivers, identified as the number of drivers they connected in the simulated network, with the high degree of 14 and 15, respectively (Fig. 3b and Fig. S3). Network synthesis further demonstrated that co-occurrence drivers were prone to induce lake abrupt changes, where the most frequent co-occurring driver groups included the combinations of climate change with their indirect effects (e.g., ice melt and thermal stratification), pollution input and nutrient loads, respectively, and nutrient loads in combination with fish introduction and water level fluctuation, respectively.

4. Discussion

4.1. *Asynchronous timing of abrupt change*

The synchronization of abrupt shifts of different ecosystems in time or space is a subject of debate. Previously, some studies suggested the Earth's biophysical system shifted synchronously around the 1980s (Reid et al., 2016), others pointed out that the marine ecosystem experienced an abrupt shift around the 1970s, 1980s, and also 1990s across different oceans worldwide (Beaugrand et al., 2015, 2019). However, our synthesis suggests that abrupt lake ecological changes happened asynchronously over the past ~200 years across the globe. The timing of these shifts varied among lakes, ranging from the 1850s to the most recent. Moreover, our findings revealed the varied timing of transition along the gradient of altitude and latitude, as well as human pressure intensity (Fig. 2d, e, and Table 1). The shift timings of alpine and arctic lakes in the low-HF region were earlier than temperate-tropical lakes in those higher HF areas. Due to the lakes' unique biophysical characteristics and geographical settings, they normally act as filters to modify the disturbances on a site-specific basis (Heino et al., 2021; Leavitt et al., 2009). For instance, the Arctic began to warm in the mid-19th century with the spatio-temporal heterogenicity due to continentality, ocean heat transport, glacier distribution and vegetation, and thus lakes responded diversely. As a result, temporal correlations typically induced by sharing drivers can be broken by spatial heterogeneity, indicating that context matters. Our results align with previous findings that heterogeneity response of lake ecosystems when facing disturbances on the

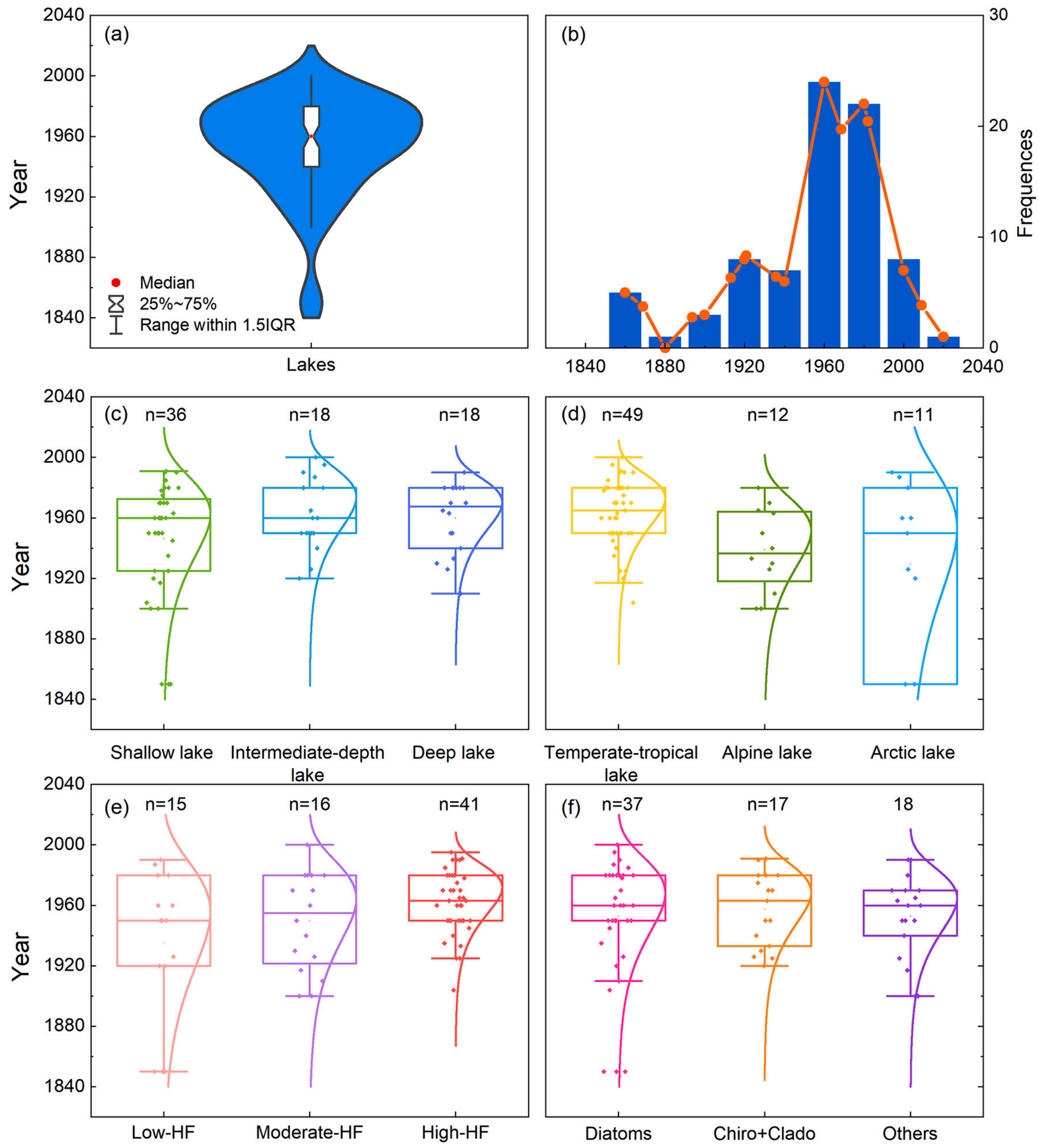

Fig. 2. Comparison of the timing of abrupt ecological changes. The comparisons were performed across 72 lakes (a) with a frequency distribution of the timing of abrupt changes (b), and lakes with different water-depth (c), distinct geographic regions (d), and variant human pressure (e), and the timing of lake abrupt changes based on the different proxies (f). In (b), the column graph (blue) indicates the statistical frequency of the timing of lake abrupt changes, whereas orange line with symbols presents the frequency of that using the bootstrapping procedure *SMOTE* to eliminate the effects of imbalanced data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

regional scales (Moorhouse et al., 2018). For instance, regional synthesis from Canada shallow prairie lakes revealed the onset of eutrophication varied by a century and was not coherent (Maheaux et al., 2016), and abrupt shifts of lake ecosystems were also found to be not coherent across China over the last century (Zhang et al., 2018a).

The ecological responses of different biological proxies from multiple aquatic trophic levels to environmental forcing might be distinct, and could exhibit temporal asynchrony across one lake (González Sagrario et al., 2020). However, the discussion about the varied timing of ecological responses among aquatic species at multiple trophic levels could also depend upon the examined timescales. Aquatic communities could show distinct responses to the same stressor at daily, weekly, and even yearly scales, due to their various generation time and specific own traits (Jackson et al., 2021). However, at multi-decadal and centennial scales, the timing of response at multiple trophic levels could exhibit less differences (Lin et al., 2019; Monchamp et al., 2021; Su et al., 2020). As our results revealed, there was no significant influence on the general pattern of the timing of lake transitions worldwide during the last two centuries evidenced by the shift timings of different biological proxies (Fig. 2f, Fig. S2, and Table 1).

In addition, the detection approach of abrupt change in the original studies may be a potential factor that influenced the synthesis result. Increasingly statistical detection methods of abrupt change in the mean or variance have been applied on the long-term paleolimnological time-series (Ives and Dakos, 2012; Taranu et al., 2018). Furthermore, cross-validations of different methods complemented with other auxiliary techniques (e.g., early warning signals) were used to identify the nature of the transitions (Beck et al., 2018; Taranu et al., 2018). An evaluation

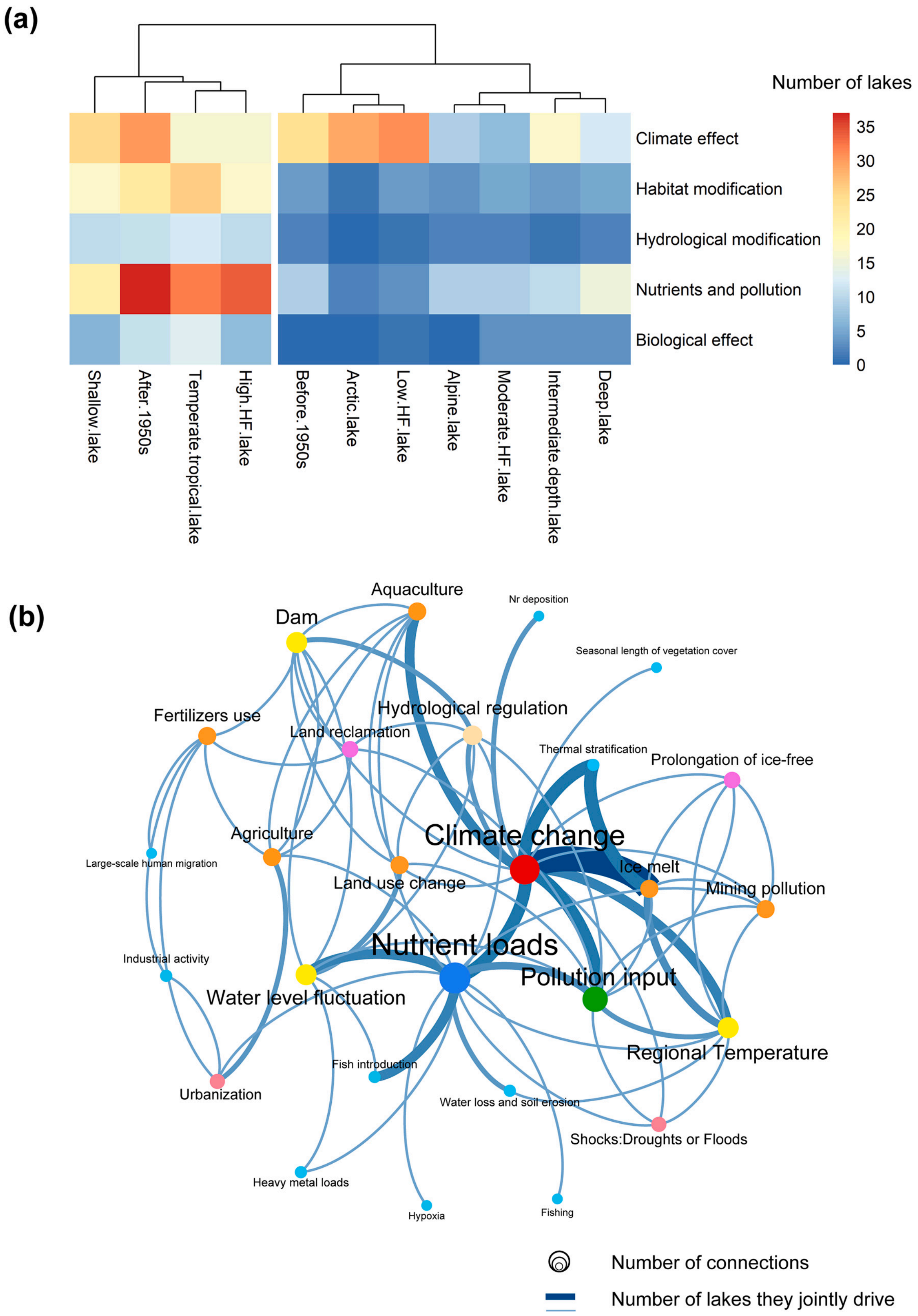

Fig. 3. Analyses of drivers for abrupt lake ecological changes. (a) Categories of drivers underpinning abrupt changes of per lake type. The color scale indicates the number of lakes driven by each driver category. Hierarchical clustering based on Euclidean distances revealed the similar lakes share the similar driver categories. (b) Co-occurrence network of drivers ($N = 30$) connected by the lakes ($N = 72$) they drive. The node size depends on the number of driver nodes that they jointly act based on the degree of the network (Fig. S4, Supplementary File 2). The same degree was presented with the same color and node size. The width of links corresponds to the frequency of two co-occurrence drivers, which is the number of lakes they jointly drive.

of our result showed that one-quarter of case studies in our synthesis have used at least two detection approaches or combined with early warning indicators (e.g., autocorrelation, standard deviation, rates of change, etc.), and their detection results based on different detection methods were basically consistent (Bunting et al., 2016; Klamt et al., 2019; Wang et al., 2012; Zhang et al., 2018a). Moreover, the determination of the most lake change points was discussed in combination with the other sedimentary proxies and environmental historical archives and/or modern monitoring records. In our synthesis, the responses of biological proxies at the multi-decadal and centennial scales and their detection approaches of abrupt changes applied in the original references have little influence on the general pattern of global lake ecological shifts during the Anthropocene (Table 1). Increasing regional and local environmental forcing played the most significant roles in lake shifts worldwide in our meta-analysis.

Although the timing of abrupt changes is not identical, the increasing frequency of abrupt changes since the 1950s identified among lakes is remarkable. This finding indicates a general pattern of abrupt change exists at a broad systemic level, embedded within the background of local variability, which is also supported by the trend analysis that demonstrated abrupt changes around the 1950s for all synthesized paleoecological data (Fig. 4a). This corresponds well to the Great Acceleration as a fundamental shift in the state and function of the Earth system (Steffen et al., 2015) (Fig. 4). The increasing abrupt changes have led to quick and severe degradation of lake ecosystems across the globe over recent decades, such as widespread algae blooms (Ho et al., 2019) and homogenization of lake biological communities (Monchamp et al., 2018). Our findings provide a global evolutionary perspective that abrupt changes in lake ecosystems are becoming more frequent under increasing anthropogenic and climatic pressures in the near future.

4.2. Multiple drivers of abrupt ecological change

Global warming, which has become prevalent especially after the Second Industrial Revolution (Fig. 4b), is one of the most frequent co-occurrence drivers in our simulated network (Fig. 3b). The great effects of climate warming have been recorded early in arctic lakes, where widespread composition shifts and ecological reorganizations in algae and invertebrate communities occurred after the mid-19th century (Smol et al., 2005). For the high latitude and high altitude lakes, longer growing season, and more available habitats for aquatic communities promoted lake primary productivity, changed the limnological conditions (e.g., trophic status and thermal stratification) and structural complexity of the lake ecosystem (Douglas and Smol, 1999; Douglas et al., 1994; Rühland et al., 2003). Ultimately, abrupt ecological shifts towards new states occurred. Recent anthropogenic climate change has accelerated after the Great Acceleration of the mid-20th century (Fig. 4b). The warming spillovers, including increasing surface water temperatures and longer seasonal stratification (O'Beirne et al., 2017), have been documented in our dataset, the effect of which not only limited to arctic and alpine lakes, but also lakes at middle and low latitudes (North et al., 2014; Rühland et al., 2008). However, these impacts on lake ecosystems may be blurred in temperate and subtropical regions, where interactions of multiple stressors including regional and local human disturbances can mask or even override climatic signals (Rühland et al., 2008; Smol, 2008).

Mounting evidence indicated that most of the new lake ecological states were fingerprints of human activities especially after the 1950s (Bannister et al., 2019; Randsalu-Wendrup et al., 2016). Our dataset showed that anthropogenic alterations to land-use, nutrient supply, and hydrological fluctuations have contributed significantly to reshaping aquatic communities and widespread lake shifts. The exponential population growth (Fig. 4c) and increasing food demand during the past ~150 years have brought about a rapid and large expansion of agricultural land, which led to the global booming consumption of nitrogen and phosphorus fertilizers (Fig. 4d). Moreover, accelerated urbanization along with effluent discharge has been conducive to the eutrophication of lakes along the urban-rural gradient (Cao et al., 2020). Consequently, allochthonous nutrient and pollutant inputs from multiple anthropogenic sources have caused surprising lake ecological shifts and water quality degradation in a costly, even irreversible manner especially after the 1950s (Fig. 3). Meanwhile, urgent demand for flood control, hydropower, water storage and irrigation has promoted the global construction of large dams (Fig. 4e), leading to water level variations far from natural hydrological regimes, with potential negative effects on aquatic vegetation communities (Huang et al., 2021), and reducing the recovery potential of a turbid lake to a clear state (Adamczuk et al., 2020; O'Farrell et al., 2010).

The single, intense and well-characterized driver can not only act alone to dominate lake ecological responses, but also interact with each other to shift ecosystem status (Birk et al., 2020; Turner et al., 2020). Interactions of multiple stressors are increasingly recognized as a major concern to shape aquatic communities and yield complex socio-ecological consequences (Birk et al., 2020; Ormerod et al., 2010). Our analyses show that the majority of abrupt lake changes were mainly raised by interactions among multiple drivers (Fig. 3). Most abrupt changes before the 1950s were dominated by climate warming and its spillover effects, whereas various anthropogenic drivers interacting with climate change caused the most of post-1950s shifts. These interactions can be additive and even synergistic, which have been increasingly reported (Birk et al., 2020; Lin et al., 2021; Su et al., 2020; Verbeek et al., 2018). Similarly, our findings highlight the increasing co-occurrence of anthropogenic and climatic impacts was responsible for most lake abrupt changes on a global scale. For instance, the synergistic impacts of nutrient enrichment and climate change have accelerated the recent eutrophication and harmful cyanobacterial blooms in a large shallow lake (Taihu Lake) in China (Lin et al., 2021). Moreover, eutrophication can interact with climate warming to exacerbate water quality degradation, biodiversity and habitat loss (Meerhoff et al., 2022; Richardson et al., 2019), and consequently produce and maintain a turbid algae-dominated lake regime. Land use and land cover change can amplify the effects of climate change through terrestrial-atmospheric positive feedback, and thus alter the likelihood of ecosystem regime shifts (Turner et al., 2020). The revealed and other potential mechanisms are increasingly dominating the processes underlying the accelerated pace of abrupt changes across global lake ecosystems.

Our results complement previous findings by offering a wide spectrum of causal hypotheses about how abrupt changes can occur in global lakes through time (Spears et al., 2017). Under the future change, local pressure reduction could help to limit the occurrence of shifts, but without global coherent collaboration, as climate warming continues, more lake shifts could be expected. For instance, recent studies indicated that climate effects have overwhelmed human activities in highly degraded lakes for algae blooming (Capo et al., 2017; Lin et al., 2021), which poses great threats for future sustainable management.

4.3. New evidence for characterizing the Anthropocene

The start of the Anthropocene has been under intense debate among scientists from different disciplines (Chin et al., 2017). The Anthropocene Working Group (AWG) recently determined to officially define the beginning of the Anthropocene Epoch around the 1950s (Subramanian, 2019), which was also supported by many researches (Rose, 2015; Syvitski et al., 2020; Waters et al., 2018). Recently scholars proposed that the Anthropocene should be defined as a geological event, rather than a formal epoch (Gibbard et al., 2021), because the geological events could recognize the heterogeneity of space and time, and incorporate a broader range of anthropogenic transformative practices. However, most of these relevant studies are based on finding physical evidence, such as radionuclides, spherical carbonaceous particles in the sedimentary records (Dong et al., 2021; Rose, 2015). While identifying "golden spikes" in stratigraphy is critical, others suggested that more

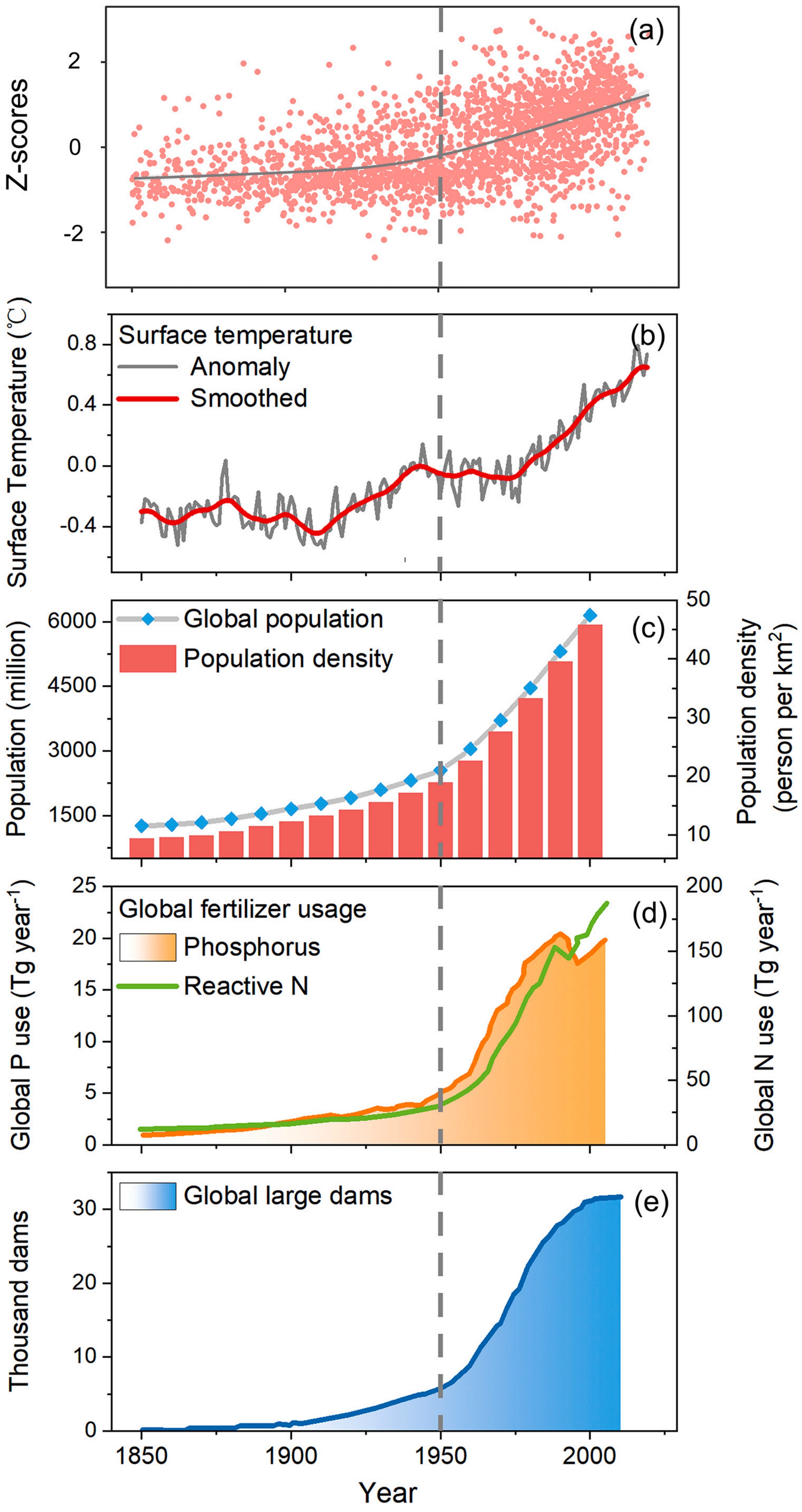

Fig. 4. Long-term trajectory of abrupt lake ecological change during the Anthropocene and global drivers. (a) The integrated trend of abrupt ecological shifts based on *Z*-scores transformed values of the digitalized paleo-ecological records from examined lakes in our synthesis using GAMs ($R^2 = 0.36$, $p < 0.01$). Shadow area represents the 95% confidence limits (Cls) of the fitted GAMs. 7 out of 72 lakes' paleoecological time-series were not extracted and digitized due to depicted paleo-ecological series with depth rather than through time in the original references. However, there were the marked timing of significant chang points in their figures and individual complex age-depth models, which was of great significance for our analyses of lake ecological shifts worldwide. (b) Global surface temperature anomaly (combined land and ocean observations, 20 year Gaussian smoothed). (c) Global population data (data are plotted as decadal points). (d) Global usage of phosphorus and reactive nitrogen (N) fertilizer referring to biologically available (Anderson et al., 2020; Galloway et al., 2008; Smil, 2000). (e) The number of global existing large dams (≥15 m height above foundation). Data sources for b, c, and d were detailed in Supplementary File 2.

attention should be paid to the changes in fundamental biophysical structure caused by anthropogenic impacts (Waters et al., 2016; Waters et al., 2018; Zalasiewicz et al., 2021). For instance, bio-stratigraphic records of the Anthropocene Epoch include fossils of megafauna, crop pollen, and domesticated animals (Waters et al., 2014). Here, we proposed that abrupt ecological changes in aquatic ecosystems worldwide could be regarded as a complementary indicator of the unprecedented human impacts during the Anthropocene, which provided new insights and empirical evidence for characterizing the Anthropocene Epoch/ Event from a global lake perspective. The increasing frequency of shifted lakes around the 1950s indicates that many lakes, with various geographical and environmental settings, have been fundamentally altered since then, potentially into a new normal with a new configuration (Zhang et al., 2016). The striking prevalence of lake abrupt changes around the 1950s coincides with the time proposed by the Anthropocene Working Group and others (Subramanian, 2019; Syvitski et al., 2020; Zalasiewicz et al., 2015, 2017). Meanwhile, it needs to be mentioned that many lakes worldwide are still in relatively good condition without abrupt shift, and more studies are needed to examine the dynamic patterns of these lakes through time, to draw a more comprehensive picture of global lake dynamics.

Scientists and managers encounter a great challenge to manage the highly degraded lakes in the Anthropocene, especially lakes with the substantial abrupt ecological shifts. Though historical reference condition has been advocated as a principle for lake ecosystem restoration, others have proposed the Anthropocene baseline that fully considered the ecological and socioeconomic constraints (Kopf et al., 2015; Zhang et al., 2018b), and argued that many ecosystems cannot be restored to historical ranges of variability (Morse et al., 2014). For instance, as many lakes transit to turbid states, the positive feedback loops between algal community, sediment nutrient release, and the loss of macrophyte could further prevent the restoration, even the pressures are reversed far enough to mimic the conditions that maintain the historical baseline (McCrackin et al., 2017). Our findings of increasing shifts from a long-term perspective further highlight that new integrative approaches are needed to examine the Anthropocene baseline, in order to make realistic restoration targets for the highly degraded lakes globally.

5. Conclusion

Our study provides a global view of abrupt changes in lake ecosystems over the past ~200 years. The most striking result is the exceptional increasing frequency with a spatio-temporal coherence since the 1950s. This result provides further evidence of the unprecedented nature of anthropogenic impact in the context of the Anthropocene, potentially moving the global lakes out of safe operating spaces with compounding consequences. Furthermore, the analysis of drivers underpinning abrupt changes suggests that the magnitude and pace of anthropogenic activities are reshaping lake ecosystems, especially after the 1950s. We verify a long-standing concern over the multiple drivers, which was responsible for most abrupt changes and will be attributed to increasing the likelihood of abrupt shifts and even cascading shifts in lake ecosystems worldwide. While two-thirds of the drivers underpinning abrupt changes can be managed on local to regional scales, but without global collaboration, preventing undesired shifts is a difficult endeavor. Consequently, developing managerial strategies from a global perspective to reduce the risk of multiple drivers-induced shifts in lake ecosystems during the Anthropocene is necessary and emergency.

Data availability

All data generated or analyzed during this study are included in this published article (and its supplementary information files).

CRediT authorship contribution statement

Shixin Huang: Conceptualization, Investigation, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Ke Zhang:** Conceptualization, Methodology, Funding acquisition, Supervision, Writing – review & editing. **Qi Lin:** Methodology, Writing – review & editing. **JianBao Liu:** Writing – review & editing. **Ji Shen:** Funding acquisition, Supervision, Writing – review & editing.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

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