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Global historical trends and drivers of submerged aquatic vegetation quantities in lakes

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Abstract

Submerged aquatic vegetation (SAV) in lake littoral zones is an inland water wetland type that provides numerous essential ecosystem services, such as supplying food and habitat for fauna, regulating nutrient fluxes, stabilizing sediments, and maintaining a clear water state. However, little is known on how inland SAV quantities are changing globally in response to human activities, where loss threatens the provisioning of these ecosystem services. In this study, we generate a comprehensive global synthesis of trends in SAV quantities using time series (>10 years) in lakes and identify their main drivers. We compiled trends across methods and metrics, integrating both observational and paleolimnological approaches as well as diverse measures of SAV quantities, including areal extent, density, or abundance classes. The compilation revealed that knowledge on SAV is mostly derived from temperate regions, with major gaps in tropical, boreal, and mountainous lake-rich regions. Similar to other wetland types, we found that 41% of SAV times series are largely decreasing mostly due to land use change and resulting eutrophication. SAV is, however, increasing in 28% of cases, primarily since the 1980s. We show that trends and drivers of SAV quantities vary regionally, with increases in Europe explained mainly by management, decreases in Asia due to eutrophication and land use change, and variable trends in North America consistent with invasive species arrival. By providing a quantitative portrait of trends in SAV quantities worldwide, we identify knowledge gaps and future SAV research priorities. By considering the drivers of different trends, we also offer insight to future lake management related to climate, positive restoration actions, and change in community structure on SAV quantities.

KEYWORDS
drivers, inland water, lake, littoral, quantities, submerged aquatic vegetation, submerged macrophyte, trends, wetland, world

Tendances et facteurs globaux déterminant les quantités de végétation aquatique submergée dans les lacs

La végétation aquatique submergée (VAS) dans la zone littorale des lacs fait partie des milieux humides des eaux continentales et soutient plusieurs services écologiques, tels que fournir un habitat pour la faune, réguler les flux de nutriments et stabiliser les sédiments. Cependant, comment les changements des quantités de VAS varient mondialement en réponse aux activités humaines demeurent peu connu, alors que leur perte menace le maintien de ces services écologiques. Dans cette étude, nous avons généré une synthèse globale des séries temporelles des quantités de VAS dans les lacs et avons identifié leurs tendances et leurs facteurs explicatifs. Nous avons compilé les tendances à travers les méthodes et les métriques, intégrant à la fois les approches observationnelles et paléolimnologiques ainsi que des mesures diverses de quantité de VAS, telles que la superficie de couverture, la densité et les classes d'abondance. La compilation a révélé que les connaissances sur la VAS proviennent surtout des régions tempérées, avec peu d'information dans les régions boréales, tropicales et montagneuses riches en lacs. Comme pour les autres types de milieux humides, nous avons trouvé que la VAS est largement en déclin, tel que reporté dans 41% des séries temporelles principalement à cause des changements d'utilisation du territoire et de l'eutrophisation. La VAS est cependant en augmentation dans 28 % des cas, surtout depuis les années 1980. Nous montrons que les tendances de la VAS et les facteurs explicatifs varient par région. En Europe, les augmentations sont expliquées principalement par la gestion, en Asie, le déclin est fonction de l'eutrophisation et des changements d'utilisation du territoire, alors qu'en Amérique du Nord les tendances variables sont associées à l'arrivée de nouvelles espèces. En fournissant un portrait quantitatif des tendances de VAS à travers le monde, nous indiquons des lacunes dans les connaissances et les futures priorités de recherche. En se penchant sur les facteurs explicatifs, nous offrons des informations sur l'influence du climat, des actions de restauration positives et du changement de la structure des communautés sur la VAS qui pourront informer les gestionnaires des lacs.

1 | INTRODUCTION

Inland wetlands are ecosystems with among the highest rates of global decline, which given their social and ecological value, has led to a wide range of conservation and restoration initiatives worldwide (MEA, 2005; Rattan et al., 2021). These wetlands include peatlands, marshes, and swamps, but also the underwater vegetated zones surrounding lakes and rivers. Submerged aquatic vegetation (SAV) creates a typically unrecognized and understudied wetland type located within the littoral zones of many aquatic ecosystems, which is distinctive from open-water habitats (Gopal, 2016; Vander Zanden & Vadeboncoeur, 2020). In some shallow lakes, where sunlight reaches the deepest point, the littoral zone can cover the entire ecosystem. The littoral zone can also be a smaller areal proportion of an aquatic ecosystem (<30%), but even in the world largest lakes it is disproportionally valuable given that it harbors the majority (93%) of lake species (Vadeboncoeur et al., 2011). Much like the representative plants of other wetland types, SAV is a foundational habitat that supports a vast and unique biodiversity. Indeed, SAV modifies the functioning of inland waters, delivering high-value ecosystem services such as providing food, promoting water clarity through particle settling, and stabilizing sediments, which strongly regulates nutrient and carbon cycling (Janssen et al., 2021; Jeppesen et al., 1998; Orth et al., 2017).

Despite its importance, global assessments of inland water SAV littoral quantities and trends through time are lacking. The underwater nature of SAV has conceptually and practically hampered these assessments. Wetland classification schemes are limited to emergent vegetation, and typically lump SAV with open-water habitats more generally (e.g., Federal Geographic Data Committee (FGDC), 2013; Gopal, 2016; Ramsar Convention, 2012). Furthermore, limnologists that study inland waters have traditionally focused research on the pelagic zone and have tended to neglect littoral areas (Vander Zanden & Vadeboncoeur, 2020). Mapping inland SAV is a challenge that has restricted global assessments as airborne or satellite remote sensing cannot detect plant canopies deeper than a few meters in turbid waters (Rowan & Kalacska, 2021). Additionally, the one reported global littoral assessment has lumped SAV with marsh-type, emergent, and floating aquatic plants (Zhang, Jeppesen, et al., 2017). Given that broad scale assessments of inland waters do not distinguish littoral from open-water areas or SAV from other aquatic plants (Davidson, 2014; Hu et al., 2017; Lehner & Döll, 2004; Zhang, Jeppesen, et al., 2017), our understanding of how SAV in inland littoral zones is changing in response to human activities remains fragmented.

In contrast to inland SAV, thorough compilations of changing aerial extents exist for seagrass meadows, their underwater marine counterpart, and are linked to various anthropogenic drivers (Dunic et al., 2021; Waycott et al., 2009). In freshwaters, aerial extents compiled for all aquatic plant types, including emergent and floating, are found to be declining (Zhang, Jeppesen, et al., 2017). This is in contrast to individual studies monitoring inland SAV quantities that suggest, similar to reports on seagrasses, that temporal changes are dynamic and vary according to location. Some show widespread regional declines (Korner, 2002; Sand-Jensen et al., 2000) whereas others observe increases (Vermaire & Gregory-Eaves, 2008), which may include successful restoration of lost habitats (Hilt et al., 2018). The contrast could be due to the distinct plant groups considered, differences among methods and periods assessed, or a bias in aquatic plant records toward temperate regions and China. To increase the number of SAV time series and widen the geographic range, one possibility is to consider the different metrics used to measure SAV quantities, as and they can be reported as areal extent (e.g., Wang et al., 2019), percent volume inhabited (or "infested"—PVI, e.g., Hanlon et al., 2000), ordered abundance class (e.g., Beklioglu & Altinayar, 2006), or density (e.g., Xiao & Liu, 2013). Additionally in lakes, SAV changes can be reconstructed from sediment archives using paleolimnological techniques (e.g., Ayres et al., 2008; Davidson et al., 2005). Although the latter provides a longer time frame than direct observational methods, the two can overlap at the decadal scale (e.g., Kornijów et al., 2016; Madgwick et al., 2011; Smol, 1992). The challenge is then to find a way to compare the results among these different methods and metrics to determine worldwide spatiotemporal patterns in inland water SAV quantities.

Because global trends in SAV quantities are unresolved, we also know little about the drivers of changes in SAV habitat at broader scales. Indeed, various human activities impacting nutrient inputs, water levels, and trophic community structure can have a negative effect on SAV. However, SAV ecology and the main drivers controlling their quantities over time have been mostly described locally, particularly in shallow lakes. A central conceptual framework in SAV ecology is the alternative stable state theory that highlights the key role of light and its interaction with nutrient inputs, water level, and trophic interactions in regulating SAV quantities (Scheffer et al., 1993). In this framework, the temporal variability in long-term SAV quantities is a function of eutrophication history where an increase in nutrients favors high phytoplankton biomass or the proliferation of epiphytes that shade SAV, eventually leading to their collapse. The few regional assessments of changes in SAV quantities have been largely attributed to this eutrophication effect or to its reversal (e.g., Hilt et al., 2018; Korner, 2002; Sand-Jensen et al., 2000; Vermaire et al., 2012; Vermaire & Gregory-Eaves, 2008). However, there is evidence of a unimodal relationship with eutrophication, where a moderate increase in nutrients in pristine ecosystems stimulates SAV growth before having a negative effect. Furthermore, the alternative stable state theory indicates that a reduction in water levels tends to promote SAV expansion through greater light exposure to bottom sediment, while a change in community structure could lead to a decline when the new species promotes higher turbidity, like benthivorous fish that resuspend sediments (Scheffer et al., 1993). In contrast, new species can facilitate SAV growth when they favor clear water, like the addition of piscivorous fish that can indirectly regulate phytoplankton quantities through a trophic cascade. These top-down effects can also control SAV quantities through the modification of macroinvertebrate grazers and epiphytes (Phillips et al., 2016). Although the mechanisms of how these individual factors control SAV are known and we are learning about the effect of combined stressors (e.g., Vijayaraj et al., 2022), how human activities shape these environmental factors across space and time is yet to be determined.

Therefore, our objective is to characterize how SAV quantities in lakes have changed globally in response to human activities at longer term time scales. To do so, we synthesize trends, measurement methods, and metrics of time series on SAV quantities, and report the global distribution of trend types and the main drivers of those changes. As we were interested in human influences on SAV in inland waters, time series from 1850 onward, where anthropogenic activities have more significantly impacted the planet, were used (i.e., the Anthropocene, Steffen et al., 2015). As a preliminary survey showed that most SAV studies were conducted in lakes rather than lotic ecosystems, our study focuses on lakes. This finding is consistent with a recent review on macrophyte macroecology (Alahuhta et al., 2021) and earlier development of theories on eutrophication and alternative stable states where SAV plays a central role, compared to their more recent application in rivers (Hilt, 2015; O'Hare et al., 2018). By applying a novel trend typology approach, we synthesized information from observational and paleolimnological studies from 431 lakes, creating the most comprehensive spatial dataset on freshwater SAV time series trends and main drivers of change to date.

2 | METHODS

Using a literature search, we compiled a dataset describing time series of SAV quantities from lakes and reservoirs at the decadal time scale, synthesizing trends across observational and paleolimnological methods (Figure 1). Inspired by similar work on seagrasses (Waycott et al., 2009), references on SAV time series were identified using a keyword search on Scopus in November 2018 of the following terms describing SAV (macrophyte* or hydrophyte* or "submer*e* aquatic vegetation" or "submer*e* plant*" or "aquatic plant*"), lentic water bodies (lake* or pond or billabong or reservoir), and potential changes (cover or map or paleolimnology or "remote sensing" or "aerial photograph*" OR biomass or area or trend or long-term or historical or change or proliferation or increase or gain or decline or loss or recovery or stability or dynamic or impact). To restrict the search, we excluded terms in reference to marine, riparian, or riverine habitats (not (seagrass* or tidal or marsh or riparian or river or marine)). This resulted in 2197 bibliographic records that were

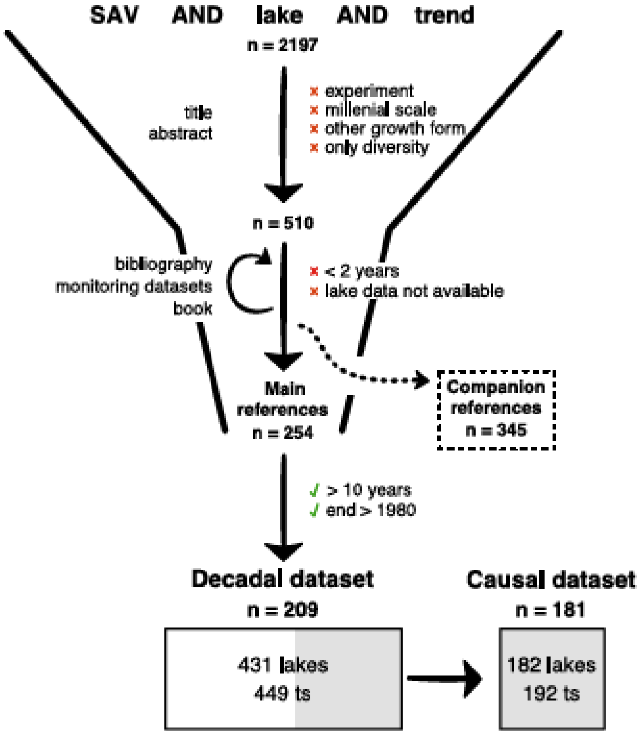

FIGURE 1 Filtering process during literature search and reference selection for the creation of the decadal scale and associated causal datasets describing SAV quantities time series. The grey area in the decadal dataset represents the subset of the causal dataset. Ts, time series.

exported to EndNote and first screened using titles and abstracts. To compare observational and paleolimnological approaches, we used titles and abstracts to remove either longer term millennial studies describing Holocene dynamics where data after AD 1850 could not be distinguished, or short-term studies lasting less than a year, concentrating on those that covered decadal time frames. We also removed studies when results were from experimental assays, models, or describing other types of aquatic plants (emergent and floating) or organisms.

The full texts of the remaining 510 documents were screened a second time to extract trend information. For this detailed data extraction, references were removed using similar criteria as for the first screening as well as when SAV changes focused on diversity only, when a single invasive SAV was described without including the whole community changes, or when SAV could not be distinguished from other plant growth forms. Reference bibliographies were also scanned. Two documents were examined in detail for additional SAV trends as they were peer-reviewed syntheses on SAV restoration (Hilt et al., 2018), and aquatic vegetation extent changes in lakes (Zhang, Jeppesen, et al., 2017), with references from the gray literature. These syntheses provided valuable information for lakes located in Germany, Denmark, England, the Netherlands, and China. When documents cited in the syntheses were not available due to either a language barrier or limited accessibility to gray literature, trends were extracted directly from the synthesis. A book chapter (Scheffer, 2004) reviewing SAV stories in lakes, was also instrumental in identifying SAV time series. We also accessed regional SAV monitoring datasets from the North Temperate Lakes LTER (Long Term Ecological Research network, Magnuson et al., 2016a, 2016b; Nichols, 2021), the New Zealand NIWA (National Institute of Water and Atmospheric Research, de Winton, 2018), and the United Kingdom Broads Authority (Broads Authority, 2013; Tomlinson et al., 2019). Several references were identified that were promising, but data on SAV trends were not accessible (Text S1).

From the identified references, we compiled information on lake location and characteristics, trends in SAV quantities, methods, and measurement metrics as well as causes of observed trends. When a given lake had a SAV time series reported in multiple references, all were used in extracting pertinent information. For lake identification and to avoid duplication, lake coordinates were extracted from Google Map from any geographic information available in the original references. Any information on lake shape, watersheds, and contemporary trophic status were also noted from the texts. For a number of lakes, information on lake mean depth ($n = 132$), lake area ($n = 73$), and watershed area ($n = 189$) were derived from the HydroLAKES dataset (Messager et al., 2016) using the select by location option in QGIS (QGIS.org, 2019).

We define SAV quantity as the amount or extent of the total plant community, which may be measured and recorded in different ways. We were inclusive in this regard and all methods and metrics encountered were considered, and we classified these in our compilation to determine any effects or bias on the trends reported. Time series of SAV quantities were largely reported from repeated field surveys, remote sensing, or from paleolimnological records. Surveys included the assessment of SAV from planned sampling using either visual estimation of cover or from plant harvest. Remote sensing included any plant detection from a sensor at a distance, either optical or acoustic. Paleolimnology referred to the evaluation of SAV from fossils in the sediment archives. Sometimes, however, the information on SAV was from oral reports or old photographs and these were classified as "historical knowledge." For others, the method could not be determined and was classified as "unknown." This sometimes occurred when the reference was in a language other than English, French or Spanish, that is, languages known by the authors. Many paleolimnological studies combined direct methods (survey, remote sensing, historical knowledge) with sediment archives and were classified as "paleo+." Regardless of methods, we also noted the scale within the lake at which SAV quantities were reported. Scale was noted as either "global" or "local" or both as SAV was typically measured over the entire lake and/or only within the littoral zone. The metric types were classified as "cover" when SAV extent was reported as areas and proportion of the lake with SAV or as maximum colonization depth. "Abundance" referred to SAV quantities reported using classes (e.g., low, medium, high), relative abundance, abundance scores, or frequency of occurrence, while "density" referred to biomass measurements, and "fossil" represented sedimentary indicators of SAV (e.g., diatoms, benthic macroinvertebrates, SAV remains) used in paleolimnology.

We characterized SAV trends as how their quantities were changing through time using a visual classification of six possible trend types (Figure 2). These trend categories were determined during data extraction as we observed that the simple increasing, decreasing, and stable trends did not capture time series with inflection points and more complex trajectories, such as unimodal, recovery, and oscillating trends. As we were interested in relating changes in SAV to their drivers, we characterized and compared the shape of SAV trajectories, not just end points and rates of changes. To decide whether a time series had a directional change in SAV and was not stable, we looked for high magnitude differences between data points of SAV quantity. For example, a trend was considered an oscillation not only when quantities were noticeably increasing and decreasing, but also when shifts were very abrupt, that is, going from almost no vegetation to sudden high quantities. These were usually indicated by the study authors. For paleolimnological data, trend types were determined from inferred SAV quantities or the proxies interpreted by the study authors to reflect SAV quantities. The inferred quantities included abundance classes and percent coverage within a lake (e.g., Bjerring et al., 2008; Vermaire et al., 2012), while proxies were most often the abundance of fauna and flora associated with SAV (e.g., benthic diatoms, benthic invertebrates), SAV remains, or both. The metrics used to extract the trends from paleolimnological studies were clearly identified by the author as an indicator of changes in SAV quantities, which could be characterized as habitat when the proxies were SAV-associated fauna or flora. A given trend was also typically extracted from a single core from a deep site that was assumed to integrate information across the whole lake or a substantial part of a lake (e.g., a bay in a large lake). Trends were most often obvious and directly extracted from the original reference, either from the text or figures. In datasets that we needed to directly process in R (R Core Team, 2020), to visualize yearly maximum colonization depth for example (de Winton, 2018; Nichols, 2021), changing trends were assigned when interannual variations were at least 1 m, which seemed reasonable given the typical colonization depth of 3 m. Trends were also characterized by noting the start, end, and number of years of observations. Intra-annual seasonal variation was not considered as typically, one yearly summertime observation of SAV quantities was reported by authors (e.g., Bresciani et al., 2012; Hilt et al., 2018; Hobbs et al., 2012; Périllon et al., 2018). In one case where the seasonal variation was reported over 21 consecutive years (Wang et al., 2019), the long-term trend was similar regardless of the moment of sampling, suggesting that within year variation does not mask decadal trends.

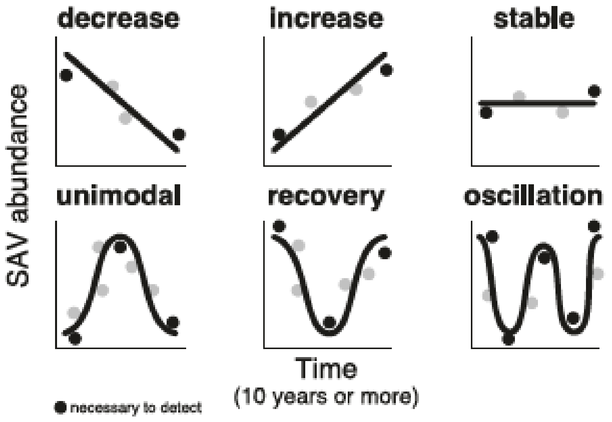

FIGURE 2 Typologies of SAV trends and minimal number of observations for their classification at the decadal scale.

Trend causes were determined from the abstract and main text. Various causes were identified and classified into broad categories to facilitate interpretation as a root cause rather than a precise environmental variable. For example, many studies reported changing nutrient levels (environmental variable) resulting in eutrophication and a change in SAV quantities (process). Eutrophication was typically related to increased agricultural or urban areas within watersheds, and as such we categorized the driver of change as "land use" (root cause). Land use also included water use and further divided in more specific subcategories describing the process impacting SAV (e.g., "browning," "siltation," "eutrophication") or use directly in the lake resulting in increased turbidity ("aquaculture," "navigation"). Other categories of root causes were "management," "biotic," "climate," and "geomorphology." Management included any deliberate human modifications to the lake with the goal of controlling SAV. Management aiming at reducing SAV always occurred within lakes (e.g., using herbicide or harvest), while efforts attempting to restore SAV involved management actions both in the lake and within its watershed, and these were classified in different subcategories (SAV reduction, restoration internal, and external). Changes in SAV driven by invasive alien species or a change in community structure were categorized as biotic. These were subdivided by feeding behavior ("filter feeder," "piscivore," "planktivore," "benthivore," "herbivore") or biological kingdom ("plant") or a characteristic unrelated to foraging ("guano"). Climate referred to causes related to variation in general long-term weather conditions and were subdivided into environmental drivers ("water level," "temperature") or specific climate events and processes (e.g., "North Atlantic Oscillation," "event," "browning"). Finally, geomorphology encompassed any modifications to lake and watershed shape and associated water flow. This was subdivided as "drainage system" (mainly dams), "embankment," "land reclamation," and "drawdown." For individual time series, up to three drivers could be identified.

The search resulted in 599 references on 665 SAV time series in 627 lakes. Some references reported the same time series, while others provided additional information. To clarify what information was extracted from each reference, we separated the references into "main reference" and "companion information." We identified 254 main references that included SAV time series and associated trend types used for this study. Each lake typically had one time series that came from one reference where the complete information was available ($n_{\text{time series}} = 581$, $n_{\text{reference}} = 182$), but an individual reference could also contain information on many lakes. Additionally, time series were sometimes determined based on multiple documents that had continuous, nonoverlapping, and comparable data given the similar metrics for SAV quantities used. When lakes had multiple time series with metrics that could not be compared (e.g., biomass vs. colonization depth), they were recorded as distinct time series, and these typically had limited time overlap. Some large lakes (e.g., the Great Lakes) had multiple time series at different locations within their shoreline (e.g., in basins or bays). The companion information dataset included 345 documents that either had trend information that was similar but on a shorter time scale than the associated main references, or additional information on lakes and SAV-related environmental variables. To limit duplicate entries and errors, all data were integrated in a relational database framework using PostgreSQL and are openly available (Botrel & Maranger, 2022). This dataset does not include information on SAV species as this information was fragmented and difficult to summarize. However, in the table summarizing all the reference used, we did note the type of data included in each study, notably species information. This overall global metadata of SAV time series includes time series beyond those used in this study as we provide all the information that was found with a minimum of two observations over 2 years. The intention is to share and grow it over time to serve future research.

2.1 | Statistical analysis

For this study, we focus on information from decadal scale time series (hereafter named the decadal dataset) that includes a time span of 10 years or greater, ending after 1985 (209 main references, 449 time series in 431 lakes, Figure 1). In a subset of time series, hereafter named the causal dataset, causes for trend patterns were identified (181 main references, 192 time series across 182 lakes). Significant differences among quantitative variables (e.g., time span, start year) among categories (e.g., trend types, drivers) were assessed using Kruskal–Wallis tests, and pairwise differences using Wilcoxon tests with Holms corrected *p*-values calculated from the R package ggpubr (Alboukadel, 2020). To analyze contingency tables and assess associations between two categorical variables (e.g., trend types against regions), χ^2 goodness-of-fit tests were used. Prior to testing, categories with fewer than 10 observations were removed. For graphical representation of association, we only represent X^2 residuals under −1 or above 1.

3 | RESULTS

3.1 | Global distribution of trends

By compiling time series that spanned 10 years or more to classify trend types of SAV quantities, we found that decreasing and unimodal trends, were the most common, accounting for 41% of time series overall (Figure 3a). The remaining two thirds were equally divided between those that increased and recovered, and those with no clear directionality (stable, oscillation). Trend types covered different time frames (Figure 3b). This was more a function of start year (Figure 3a), as the median end year of 2006 was similar across all trend types ($p = .15$). Decreasing and stable trends started around 1950, while increasing trends started later, around 1980 ($p < .01$). As a result, time series of decreasing and stable trends tended to be almost twice longer compared to increasing ones with a median time span of 46 and 28 years, respectively. Recovery and oscillation trends, which included two types of monotonic changes (increasing and decreasing), lasted ~32 years and started in ~1977. As expected, trends also had a different number of observational years, where simpler trends (decrease, increase, stable) typically had fewer observations compared to those with inflection points. Unimodal and recovery had 8–9 observations, oscillation up to 16 ($p < .01$, Figure S1). However, simple increasing trends had significantly more observations (median = 5) than decreasing and stable ones (median = 2).

Trends were derived from predominantly small and shallow lakes. For the lakes where we could find this information, the median area and mean depth were 0.6 km^2 and 2.6 m, respectively (of the 431 lakes in this study, 103 and 206 did not report information on area, and mean depth, respectively, Table S1). Our dataset, however, also covered large lakes up to 3753 km^2 (Poyang Lake, China), and bays in four of the Great Lakes (except Lake Superior). Two third of the lakes with time series where we could identify contemporary trophic status ($n = 299$, n missing $= 150$) were classified as eutrophic or hypereutrophic, while 21% were mesotrophic and 9% oligotrophic. The majority of aquatic ecosystems used in this synthesis were natural freshwater lakes. Artificial lakes constituted 15% (68) of the total, and were mostly infilled excavation ponds from peat mining or polder lakes (in the Netherlands). Other ecosystem types included 15 reservoirs and five saline lakes, with the latter ones being enclosed coastal lakes with some seawater intrusion.

SAV time series were also not uniformly distributed in space (Figure 4). Only two lakes where time series could be compiled were from South America and seven from Africa, while the remaining lakes were mostly from OECD (Organization for Economic Co-operation and Development) countries, including those from Europe, Oceania, and the United States (Figure 4a). Within these general areas, sampled lakes were also clustered into specific countries or states. In Europe, lakes were particularly abundant in Italy, Great Britain, Germany, Denmark, and the Netherlands, whereas in North America, lakes were mostly from the temperate lake regions of Wisconsin, Minnesota, New York (USA), and southern Quebec (CA). In Oceania, lakes were mostly from the northern New Zealand island, while lakes from Australia were all along the Murray–Darling river. Lakes in Asia were predominantly from the China Changjiang (Yangtze) river basin or the southern Yunnan Province. In addition to the clustered spatial distribution, the trend types were associated with specific geographic regions and were

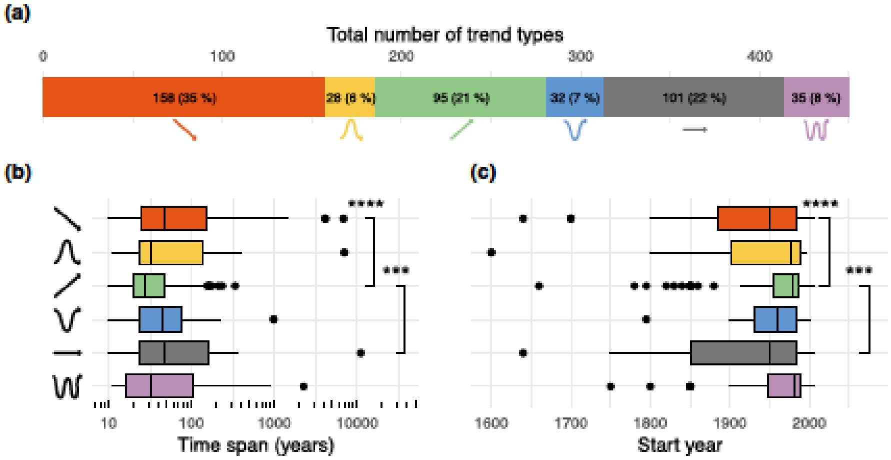

FIGURE 3 Proportion of trend types and their temporal distribution showing (a) total number of time series per trend type and their proportional distribution, (b) length and range of time series, and (c) start year per trend type. (c) The *x*-axis was truncated at 1500 for clarity (nine time series started before 1500). Vertical bars within boxes indicate median value, box boundaries represent 25th and 75th percentile and whiskers range from 10th to 90th percentiles. $^{***}p < .001$, $^{****}p < .0001$.

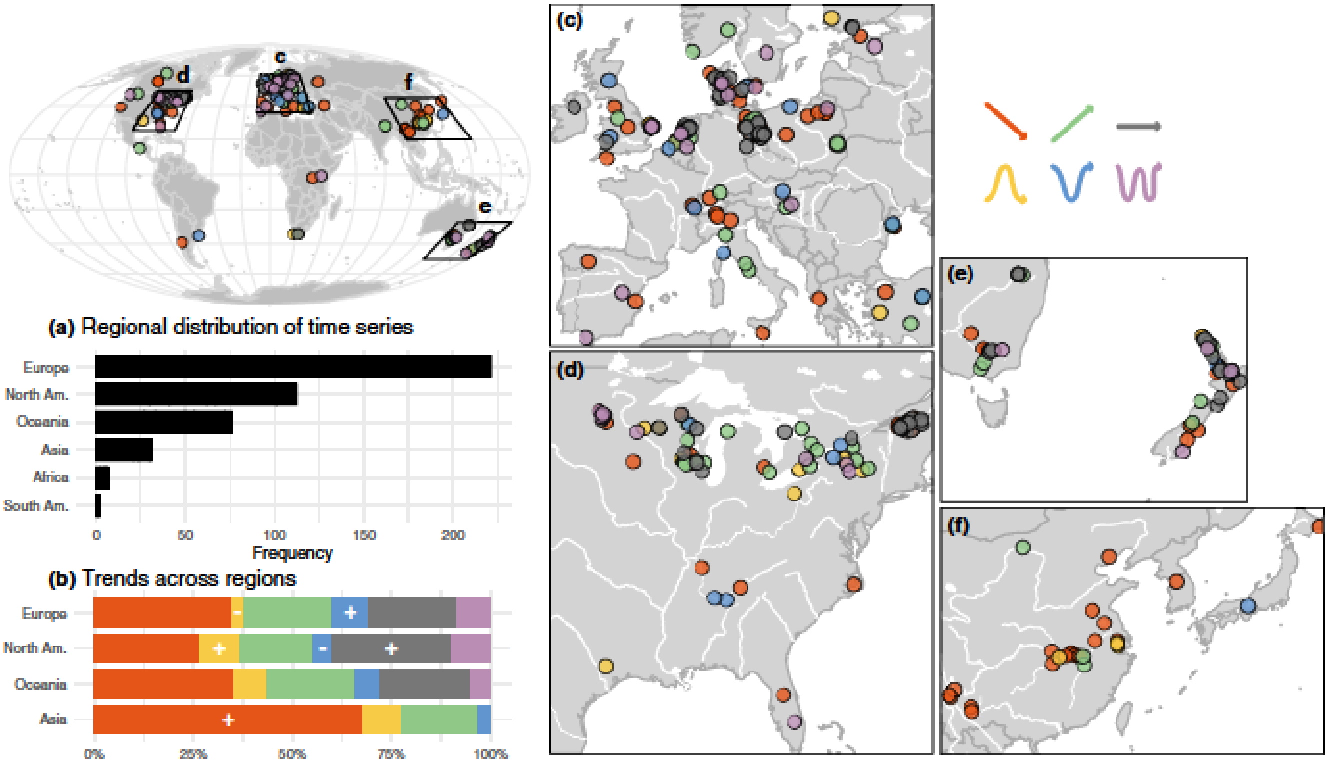

FIGURE 4 Geographic distribution of SAV time series showing (a) regional distribution of time series, (b) comparison of trend types across regions, and (c–f) location of time series and their associated trend types. + and − indicate if proportion of trend type is more or less than expected compared to other continental regions and is shown for X^2 residual < −1 and >1. Map dark gray lines delineate study areas and do not necessarily depict accepted national boundaries.

not randomly distributed ($X^2(df = 15, n = 449) = 36.9, p = .001$, Figure 4b, Figure S2). In particular, Asia had twice more declining trends (68%) than expected compared to other continents and had no stable or oscillating trends recorded, exceptionally contributing to the X^2 score (51%). In contrast, trend types were more evenly distributed in North America with more stable (30%) and unimodal trend types (10%) that were counterbalanced by a reduced number of decreasing trends (27%). Recoveries were overrepresented only in Europe (9%) and were compensated by fewer unimodal trends in that region.

3.2 | Drivers of SAV trends

The subset of time series for which SAV drivers could be identified had a similar spatial distribution to the time series of the decadal dataset (Figure 5, Figure S3), except for Oceania where associated drivers were rarely reported. Over the causal dataset, land use was the dominant driver in SAV change (41%), followed by management (25%), biotic (13%), climate (12%), and geomorphology (9%, Figure 5a). These drivers of trends in SAV quantities differed in space with regionally specific associations ($X^2(df = 12,$

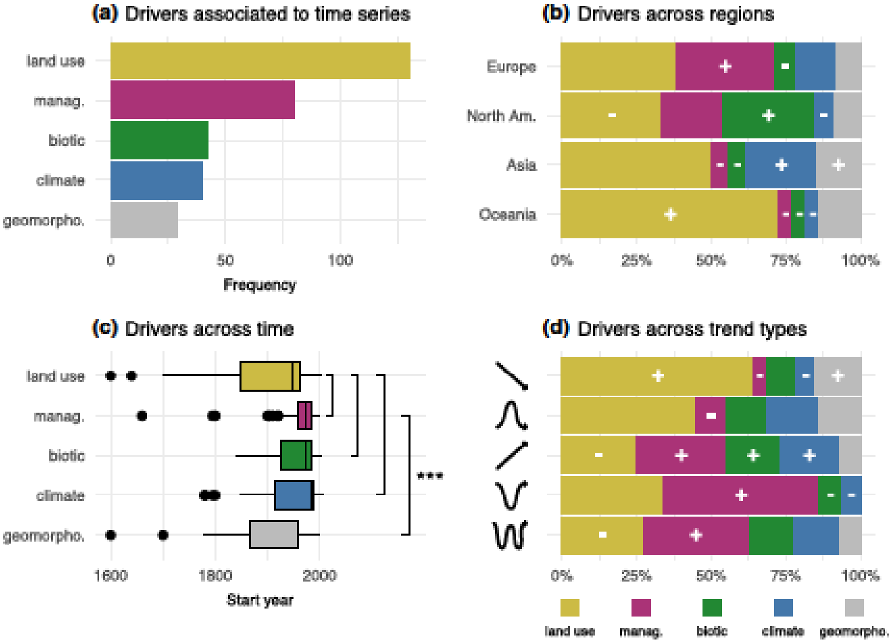

FIGURE 5 Drivers associated with time series. (a) Frequency of occurrence, (b) distribution across regions, (c) distribution across time represented as start year of time series, and (d) comparison of drivers associated with specific trend types. For each time series, up to three drivers could be identified. For clarity in (c) the x-axis was truncated to represent start year after 1500. Manag., management; geomorpho., Geomorphology; North Am., North America. + and − indicate if proportion of is more or less than expected compared to other regions or trend types and is shown for X^2 residual < −1 and >1. ***$p < .001$.

$n = 323$) $= 56.9$, $p < .0001$, Figure 5b). In Europe, impacts of management were observed more frequently than expected (33%), and were counterbalanced by fewer impacts associated with biotic drivers. The latter was overrepresented in North America that had almost three times more time series associated with biotic drivers than expected (31%), contributing the most to the X^2 score (35%). This more dominant regional effect resulted in a reduced impact from the influence of land use and climate on SAV time series. In Oceania, land use was the dominant driver, while in Asia, although land use was the predominant cause, climate and geomorphology were more important as compared to other regions. Within regions there seemed to be coherent patterns in which drivers most influenced SAV time series (Figures S4 and S5). In Europe, management was mostly in central Europe while climate drivers occurred with greater frequency in the Northern and Southern range of sampled lakes. In North America, time series associated with biotic drivers were all within or close to the Great Lakes. In Asia and Oceania, land use and geomorphology were observed across individual river basins, while climate impacts were observed in lakes sampled toward the East.

In addition to differences in space, drivers emerged over different time scales. Time series associated with land use and geomorphology had a longer time span (median 70–56 years) because of an earlier start in tracking (median 1934–1959) and presumed influence of these drivers on SAV (Figure 5c, Figure S6, median end 2005–2012). Management, biotic, and climate started later, around 1973–1980, and as a result spanned ~30–36 years, half as long as time series associated with land use change. Given these temporal and spatially uneven distributions, specific trend types were more associated with particular drivers (X^2[$df = 16$, $n = 323$] $= 83.5$, $p < .0001$, Figure 5d). About half of decreasing trends were associated with land use change and 15% with geomorphological alteration, contributing strongly to the X^2 score (21%). Decreases were also rarely explained by management and climate. Unimodal trends had similar associations than decreasing trends but with a larger number of time series explained by drivers other than land use or geomorphology. In contrast, increasing trends were explained by management, biotic, and climate drivers, which were not associated with decreases. The more complex trends of recovery and oscillation were more associated with management.

By looking at more details within driver subcategories, we observed that some had a more consistent influence on observed trend types, while for others, consequences on trends in SAV quantities were diverse depending on the variable at play. Land use and geomorphological alterations generally were associated with declines, mostly through eutrophication (Figure S7). In contrast, management from reduction of nutrient inputs to lakes (external restoration) was associated with clear SAV expansion (increasing, recovery) as compared to restoration actions within lakes that lead to more oscillating trends (Figure 6a). The effect of biotic drivers depended on the organism associated with the time series, with those promoting water clarity improving SAV (Figure 6b, Table S2). Among facilitating species were zebra and quagga mussels (*Dreissena*) that directly increased water transparency through filter feeding (e.g., Brooks et al., 2015; Ibelings et al., 2007; Zhu et al., 2006), but also illegal piscivorous fish stocking that reduced phytoplankton through a trophic cascade effect (Albright et al., 2004). In contrast, benthivores associated with SAV decline directly decreased transparency through uprooting and sediment resuspension (e.g., Maceda-Veiga et al., 2017; Titus et al., 2004; Volta et al., 2013), while planktivores increased phytoplankton abundance, also through a trophic cascade (Ramstack Hobbs et al., 2016). Increases in bird droppings (guano) were also associated with a SAV decline related to animal mediated eutrophication and reduction in light availability (Barker et al., 2008). Arrival of invasive plant species (*Egeria densia, Elodea canadensis, Hydrilla verticillata*) was associated with increasing SAV (e.g., Mjelde et al., 2012; Rejmánková et al., 2018), while decreases sometimes co-occurred with arrival of various herbivores (birds,

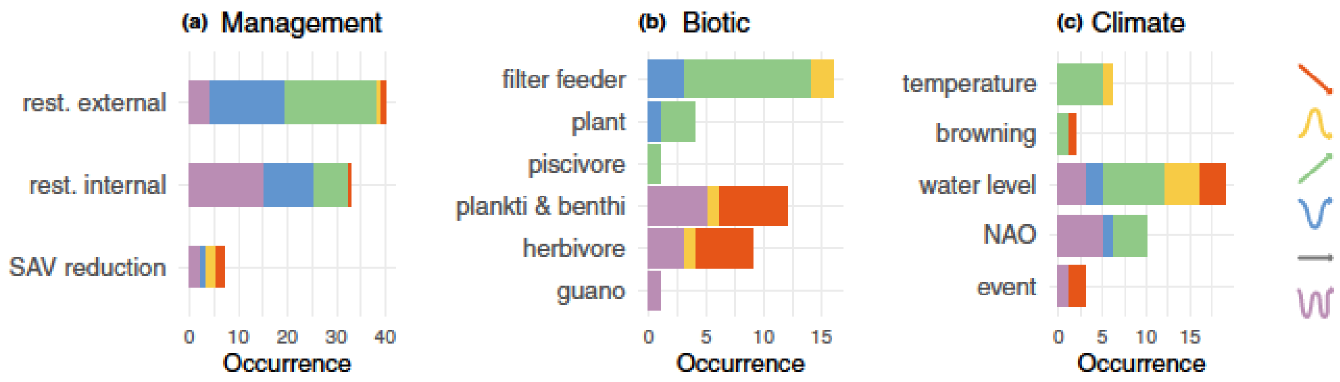

FIGURE 6 Drivers and associated trend types showed by detailed subcategories. (a) Restoration, (b) biotic, (c) climate. Rest., restoration; SAV, submerged aquatic vegetation; plankti and benthi, planktivore and benthivore; NAO, North Atlantic Oscillation.

insects, crayfish, fish) directly removing SAV (e.g., Caires et al., 2013; Dodds et al., 2012; Johnson et al., 2000).

Changes brought by climate depended on the specific environmental variable involved (Figure 6c). Increases in temperature were associated with an increase in SAV, where warmer conditions and a longer growing season favored SAV range expansion (e.g., of *Ranunculus trichophyllus* Chaix. in the Himalayas above 4000 m.a.s.l.; Lacoul & Freedman, 2006). Storm events were more associated with SAV decreases through increasing water levels and turbidity (e.g., Kelly & Jellyman, 2007; Klamt et al., 2017). Indeed, the most frequent climate effect was water level change, where outcomes in SAV directionality varied depending on whether water level was increasing or decreasing. Generally, decreasing levels were associated with increasing SAV (e.g., Churchill et al., 2016; Kowalewski et al., 2016; Yadav et al., 2017), although this was not always the case (e.g., Rejmánková et al., 2018; Zhang, Yang, et al., 2017). Changes were also often the result of broad climate patterns, like the North Atlantic Oscillation (NAO), that resulted in SAV trends following these cycles through the influence of a variety of associated variables. For example, in Swedish lake Tåkern, SAV had a 3-year lag with negative phase NAO causing harsh winter conditions that induced major fish kills, which subsequently increased SAV biomass (Hargeby et al., 2006). In the English Broad lakes, increases in temperature and the number of sunny days were related to higher SAV coverage (Phillips et al., 2015), while in a Spanish karst lake (Lagunillo del Tejo), positive NAO phase where associated with drought and drying up of the outer ring of SAV (López-Blanco et al., 2012). Finally, the effect of browning seemed to depend on initial trophic state and was positive in an oligotrophic lake through increasing nutrient inputs associated with colored dissolved organic matter or negative in cases where there was an increased loss of light (Ejankowski & Lenard, 2015; Spierenburg et al., 2010).

4 | DISCUSSION

In this study, we synthesized information on time series of SAV quantities and their worldwide distribution. Compiling time series was a challenge given the diversity of methods and metrics used to measure SAV, but these were successfully compared by creating a simple SAV trend typology. Similar to other wetland types, SAV decline was prominent globally, and declining trends were mostly due to eutrophication from anthropogenic activities, occurring either in the lake, its catchment, or in both. However, recorded changes in SAV quantities were dynamic both through time and across space, where some regions exhibited consistent declines (Asia) while others observed more increasing trends (Europe), particularly in recent decades. In the last 40 years, more frequently reported increasing trends were associated with regional changes in management, climate, and community structure. Given the patchy and limited distribution of SAV time series across the globe, current knowledge is biased toward temperate areas in Europe and North America, with more recent reports from China and New Zealand. As such, it is unclear whether patterns in trend types and associated drivers represent change in SAV quantities in unmonitored lakes, and other regions of the world. Nevertheless, existing information provides guidance on knowledge gaps and potential effective lake management practices. This includes management actions related to positive trends, the effects of changes in community structure, and the synergistic influence of climate that can be used to better inform restoration efforts.

4.1 | Geographic bias of SAV time series

Our compilation of SAV time series included lakes from six of the seven aquatic plant biogeographical regions, with Europe, North America, South-East Asia, and Oceania being more represented than others (Chambers et al., 2008). Within these four regions, lakes tended to be concentrated in subregions (Figure 4). The geographic distribution of SAV time series also matched the one for a combined aquatic plant assessment (Zhang, Jeppesen, et al., 2017), albeit our approach allowed for a better overall representation, especially in Oceania. The same geographic bias was also found in a review of global distribution and diversity of aquatic plants (Alahuhta et al., 2021). SAV compositional changes are not evaluated in our study of SAV quantities, as although that would have been interesting, full species information related to our trends was highly fragmented, and often unreported.

When comparing these SAV time series with the global distribution of lakes (Messager et al., 2016), large information gaps exist in many lake-rich regions, and there is a near absence of information in saline lakes that constitute half of global lake volume. In particular, very few lakes were monitored in the richest lake region of the Boreal (Canadian Boreal Shield, Scandinavia, and Siberia), and in mountainous lake regions (Andes, Rockies, Himalaya). Although the accepted distribution range of SAV is said to be between 80° N and 60°S (Chambers et al., 2008), some information gaps might be due to the limited presence of SAV at higher altitudes and latitudes (Short et al., 2016). In colder regions like the Arctic, lake littoral zones are typically colonized by microbial mats and reported to be devoid of vascular plants (Rautio et al., 2011). However, climate change and prolonged growing season might widen SAV distribution, as observed in the Himalayas, and may warrant monitoring at the northern and altitudinal edge of SAV ranges. Large information gaps were also observed in the tropics where SAV may be less dominant given the typical turbid state of the waters at lower nutrient levels, and the presence of floating leave macrophytes that can outcompete SAV for light (Feuchtmayr et al., 2009; Kosten et al., 2009; Netten et al., 2010). Additionally, some studies in the tropics were not considered because we could not distinguish trends in SAV quantities from other aquatic plant growth forms (floating, emergent), or only species information and not quantities were reported. Overall, these gaps highlight our poor understanding of inland SAV geographic distribution, including potential compositional changes, with most current knowledge on quantities concentrated in temperate regions of the northern hemisphere.

4.2 | Temporal and regional dynamics of trends and drivers of SAV quantities

We showed that trends in SAV quantities were spatially dynamic and associated with different drivers, with decreasing trends due to eutrophication caused by different anthropogenic activities being most common, and detected earlier. These findings are in agreement with early 20th century accounts from Europe and broad recognition of eutrophication as a driver of SAV loss in shallow lakes (Phillips et al., 2016). The overall decrease in SAV observed here is similar to a previous global aquatic plant study, although they did not distinguish SAV from other plant types or report drivers (Zhang, Jeppesen, et al., 2017). Our observations are also consistent with studies on aquatic plant metacommunities (reviewed in Alahuhta et al., 2021) where SAV quantities across lakes and scales are considered the result of environment filtering and dispersal. For aquatic plants, niche processes are typically thought to be more important than neutral processes, making SAV species composition an effective ecological indicator (Orth et al., 2017). This is coherent with our report of the importance of local context on trends in SAV quantities, and regional variations due to distinct environmental drivers.

Eutrophication as a driver was largely a function of land use change, including agricultural or urban development in catchments (e.g., Bennion et al., 2015; Rosińska & Gołdyn, 2018; Zhang et al., 2010), but also to within lake aquaculture (Kraska et al., 2013; Liang & Zhang, 2011) and boating activities (Bresciani et al., 2012; Garrison & Wakeman, 2000). Some regions were particularly affected by declines and eutrophication, like the Changjiang basin in China, which probably reflects the high population density and intense agriculture in the region. Eutrophication can also have a nonlinear effect on SAV quantities where oligo- to mesotrophic lakes might experience an increase in SAV with moderate nutrient additions followed by declines at higher trophic status (Korner, 2002; Vermaire & Gregory-Eaves, 2008). Indeed, we found that land use change was also associated with either unimodal or increasing trends. In fact, paleolimnological evidence from Danish lakes indicates that intensification of human activities created lush SAV beds during the Middle Ages, that collapsed with the ongoing eutrophication of the mid-20th century, with many lakes already having reduced SAV cover in the mid-19th (Bjerring et al., 2008; Johansson et al., 2005; Rasmussen & John Anderson, 2005). The prominence of SAV declines in our dataset was likely a function of a shift toward higher trophic status from the 1950s, the time when most SAV records started, to that of around 2006. SAV thus joins other wetland types in their worrying global decline (Davidson, 2014; MEA, 2005). Our work is very similar to reports on seagrass decline due to alteration of water quality, but, on a more positive note, are also increasing due to recent restoration efforts (Dunic et al., 2021). These similarities could foster interesting intercomparison of drivers, trends, and successful restoration practices across all SAV species whether located in littoral inland waters or coastal marine.

We do report a fair number of increasing SAV trends associated with active lake restoration, but also as a function of climate and alterations in community structure, including recolonization by invasive SAV species (Johnson et al., 2000; Newman & Biesboer, 2000). Management actions were observed in all regions with SAV time series, but they were much more widespread across Europe where strong regional policies for water conservation and restoration were actively put in place. Indeed, the European Water Framework Directive, adopted in December 2000, had the ambitious goal of achieving a minimum "good ecological status" for all European inland waterbodies by 2015 (European Union, 2000). However, not all restoration measures were successful and those carried out within the lake only, largely through biomanipulation, were mostly associated with oscillatory SAV trends and transient colonization (e.g., Hobbs et al., 2012; Søndergaard et al., 2017). This is consistent with a synthesis on SAV restoration showing that stable clear water conditions were largely obtained when external nutrient inputs were reduced or when combining both internal and external measures, while oscillation between states were associated with internal lake measures only (Hilt et al., 2018).

In comparison with restoration practices, SAV trends driven by climate were more complex and associated with all trend types, and observed across regions. As climate is a long-term feature of the Earth System, it is somewhat surprising that it has only been recently identified as a factor influencing changes in SAV quantities (>1970s). This may be due to the oscillatory and cyclical nature of climate that requires longer time series to disentangle climate from other confounding signals. The fact that climate controls multiple environmental variables simultaneously might also make it harder to detect. Additionally, the more recent attention may be due to climate change as a global priority (IPCC, 2018). Regardless, change in water levels was the most notable climatic influence, with reduction in levels predominantly leading to positive outcomes for SAV. This was likely a function of modest enough levels to increase light availability to bottom sediment, as opposed to complete drawdown that can be deleterious by creating conditions of SAV dry-out (Ersoy et al., 2020). How climate and eutrophication work synergistically to influence SAV quantities and species composition remains underexplored as influences may be antagonistic albeit up to a certain point, where other primary producers could outcompete SAV (Moss et al., 2011). Future research is needed to address the complex interactions of multiple stressors including climate on SAV, and how the responses vary regionally.

The arrival of invasive species or changes in biotic community structure were also associated with multiple trend types, but the response differed with organismal traits. Our findings are in agreement with a meta-analysis on the effect of invasive species on regime shifts from either a turbid to a clear state or vice versa, where the arrival of new plants and mollusks can favor SAV expansion, while crustaceans and fishes were linked to decreases in SAV (Reynolds & Aldridge, 2021). Interactions of invasive species with SAV should be included in regional restoration plans, as whether the goal is to increase SAV or control its proliferation, the potential invasive may help facilitate a desired response. For example, in decimated SAV beds, the arrival of invasive plant species that enhance water quality can facilitate recolonization of native SAV species, as was observed with *H. verticillata* in the freshwater portion of the Chesapeake Bay (Orth et al., 2017). In the case where invasive plants are a nuisance, herbivores could be used as biocontrol agents. For example, the insects that reduced SAV quantities (*Euhrychiopsis lecontei* and *Acentria ephemerella*) were native grazers of watermilfoil (*Myriophyllum spicatum*), an invasive SAV whose proliferation is perceived as a nuisance in North American temperate lakes (Johnson et al., 2000; Newman & Biesboer, 2000). Thus, in newly invaded areas within their range distribution, the efficiency of these herbivores to reduce milfoil quantities could be tested. We caution, however, that these manipulations must always be conducted within the natural or existing invasive species distribution range to avoid unintended consequences. This is exemplified by the Great Lakes that have been invaded by more than 145 alien species mostly from transoceanic ship ballast waters. Among these species are dreissenid mussels that dramatically modified the lakes functioning through a shift in energy production from the open pelagic to the benthos, advantaging SAV at the same time (Li et al., 2021; Ricciardi & MacIsaac, 2000). This explains why SAV time series associated with biotic drivers were primarily located in North America, around the Great Lakes, one of the world's major invasion corridors due to global trade.

4.3 | Recommendation for future SAV studies

Our review of SAV quantities across metrics and methods allowed us to identify if their relative precision affected the detection of the different trend types (Text S2, Figures S8–S11), and provide recommendations for future studies. We found that metrics reporting SAV aerial coverage within lakes (maximum colonization depth, areal extent, or proportional SAV cover) were most effective at detecting more diverse trend types. We therefore recommend that aerial coverage metrics be used for conservation purposes given their higher sensitivity to detect changes, including loss, and set reasonable restoration targets. Compiling SAV areas is challenging as often only maximum colonization depth (Z_C) is reported, but the requisite lake bathymetric information is often not (e.g., Eigemann et al., 2016; Lachavanne et al., 1992; May & Carvalho, 2010). With bathymetric information, potential changes in SAV area estimated from depth limit could be modeled as a function of commonly measured secchi depth (Chambers & Kalff, 1985; Middelboe & Markager, 1997). Bathymetric information would also allow for the estimation of underwater slopes and suitable flat bottom areas for SAV development (Duarte & Kalff, 1990). However, SAV area estimated from Z_C and bathymetry has limitations since it relies primarily on light availability and does not consider unsuitable locations for SAV development such as coarse substrate (Barko et al., 1991; Duarte & Kalff, 1990). Epiphytes can further limit SAV growth even in cases where other conditions may appear suitable for their colonization (Sand-Jensen & Søndergaard, 1981). As Z_C and secchi are simple measurements to model SAV potential area, we recommend their continued reporting, especially when accompanied with bathymetric information and measured SAV areal extents.

The SAV changes we report were also primarily from long-term surveys, followed by paleolimnological records, and lastly from remote sensing. Future monitoring of SAV quantities should consider a more frequent use of faster, automated remote techniques. In clear lakes where light reflected by underwater canopies can be detected by airborne and satellite sensors (e.g., Bresciani et al., 2012; Brooks et al., 2015; Hargeby et al., 2006; Wang et al., 2019), SAV areal extent can be rapidly and well quantified. Because optical techniques have been available since the 1970s (e.g., for Landsat), these were the most common one used ($n = 54$) in the time series reported in our dataset, whereas hydroacoustics were only used for five (e.g., Depew et al., 2011; Hutorowicz et al., 2017; Zhu et al., 2006). Optical remote techniques will likely become more common in assessing SAV areas with the increase in hyperspectral capacity of new satellites, and greater accessibility of drones with improved sensors that could potentially be used in smaller lakes (Rowan & Kalacska, 2021). Hydroacoustics, however, have the advantage of being a tridimensional assessment of SAV quantities by reporting both SAV height and coverage across depths, thus simultaneously providing an estimation of SAV extent and biomass (Botrel et al., 2022; Duarte, 1987). Additionally, these techniques are best suited in turbid waters as in these conditions, only reasonable SAV detection is achieved from object-based image analysis and optic sensors are typically blind at only 1- or 2-m depth (de Grandpré et al., 2022; Krause et al., 2021; Rowan & Kalacska, 2021). Sonar technology is also becoming more accessible including the use of unmanned boats (e.g., Goulon et al., 2021), with improved recreational-grade sonars and automatic cloud-based postprocessing (Buscombe, 2017; Helminen et al., 2019; Howell & Richardson, 2019) that will allow for greater aerial coverage, faster sampling, and reduced cost. Both optical and acoustic remote techniques are increasingly being used for the monitoring of seagrass changes (Gumusay et al., 2019; Veettil et al., 2020), and learning from these practices may help fast-track their application to inland waters. We suggest that inland SAV researchers adopt approaches from the marine community more broadly, who recently launched a coordinated global effort to synthesize status and trends of seagrass worldwide (Coordinated Global Research Assessment of Seagrass System, C-GRASS, under the UN Environment Programme World Conservation Monitoring Centre, UNEP-WCMC). This includes application of standard protocols for seagrass studies (Phillips & McRoy, 1990; Short & Coles, 2001), that allow for the intercomparison of datasets that could easily be applied to inland waters and involve citizen science.

In contrast to monitoring efforts of coastal seagrass, paleolimnological approaches can provide changes in lake SAV over much longer time scales, and in unmonitored lakes. Indeed, and unsurprisingly, we found that the method used influenced the study time scale because of this inherent property of paleolimnological approaches (Figure S8). However, one challenge we found with paleolimnological assessments was the use of inconsistent proxies across studies, which were often difficult to interpret. Proxies ranged from SAV remains (generally poorly preserved) or spores (e.g., Klamt et al., 2017; Kowalewski et al., 2016; Volik et al., 2018) and associated flora (benthic diatoms, e.g., Davidson et al., 2013) or fauna (benthic cladocerans, chironomids, e.g., Ventelä et al., 2016; Zhang et al., 2010). SAV dynamics were also inferred in individual studies using SAV biomarkers (*n*-alcane, Das et al., 2009), sponge biogenic silica (Kenney et al., 2002), or sediment C:N ratio (Stephens et al., 2018). All these approaches were rarely used in combination. In contrast to reports using individual fossil proxies, the use of inference models to report SAV as quantities were rare. Only four paleolimnological studies reported SAV as either a semi-quantitative abundance estimate (Vermaire et al., 2012, 2013) or a quantitative areal cover (Bjerring et al., 2008; Johansson et al., 2005). Inference models in paleolimnology have been criticized (e.g., Juggins, 2013; Whitmore et al., 2015), however, they are useful as they simplify the complex multivariate relationship between organisms and their environment. The repeated association of benthic taxa to SAV assumed in the paleolimnological studies we collected, suggests that these indicators could be used for the development of new inference models. Indeed, more robust multiproxy approaches could provide more reliable reconstructions of inferred SAV trends across lakes (Jeppesen et al., 2001). Furthermore, DNA-based methods to track SAV species composition, which are currently lacking in the literature, could also be applied and provide more information related to diversity changes (Domaizon et al., 2017). A list of calibration sites for the future development of these inference models is provided through our synthesis.

5 | CONCLUSION

We have successfully synthesized information on time series of SAV quantities and provided a portrait of their trends, using different methods and metrics as well as the main drivers of change. Similar to other inland wetland types and coastal seagrasses, we found that SAV are globally declining due to human activities, primarily through catchment changes that influence water quality. We argue that vegetated littoral zones of lakes should be considered separately from pelagic areas in current wetland classification schemes as these essential wetlands are highly sensitive to anthropogenic change. We have also shown that both SAV quantities and associated drivers are very dynamic both in space and time. Declines are largely due to land use and associated influence of eutrophication and are currently the main trend in Asia. Recent increases in SAV were associated with restoration efforts in Europe, and changes in biotic communities, largely through species invasions in North America. By assessing the influence of different drivers, we have also provided information that could be used for SAV management to anticipate change. Future work should consider including information on SAV species composition together in quantitative assessments. Alterations in SAV species can point to earlier signs of environmental change. For example, characeans, mosses, and slow-growing vascular rosette species (i.e., isoetids) are the first to disappear with eutrophication (Blindow, 1992; Sand-Jensen et al., 2000). Furthermore, with the recent global effort to compile functional traits of aquatic plants (Iversen et al., 2022), understanding SAV compositional changes together with quantities would provide a more robust understanding of the influence on ecosystem functions and services.

Through this work we identified major knowledge gaps in SAV research. We found that SAV studies are biased toward North temperate regions with many unknowns about their quantities and trends at higher latitudes and altitudes, as well as in the tropics. It is possible that SAV is simply not dominant or present in some of these regions. Therefore, a basic biogeography of SAV is required to determine whether or not this is the case, which would also inform on their potential range expansion or reduction with climate change. Recent literature reports suggest this work is emerging with an increasing understanding of aquatic plant species distributions (Alahuhta et al., 2021), but information on quantities is lacking. Standard protocols for a better understanding of the status and trends in SAV quantities are needed. These developments include more systematic reporting of SAV areal coverage, but should also consider the collection of bathymetric information that is crucial in determining SAV colonization areas. The use of fast remote sensing technologies could facilitate monitoring and sedimentary archives should also be better exploited as they register lake histories and could reconstruct SAV long-term development in unmonitored lakes. Finally, we recommend that global approaches adopted in coastal seagrass research could serve as a template in developing a more robust global program to tracking inland SAV. As the shoreline of lakes is four times the length of the ocean's coast (Messager et al., 2016), inland SAV also needs to be considered in global restoration and conservation efforts.

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CONFLICT OF INTEREST

The authors declare no conflict of interest in this study.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.6502355.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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