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INTERFACE OF LANDSCAPE ECOLOGY AND CLIMATE CHANGE (B ZUCKERBERG, SECTION EDITOR)

Evidence for the Combined Impacts of Climate and Landscape Change on Freshwater Biodiversity in Real-World Environments: State of Knowledge, Research Gaps and Field Study Design Recommendations

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Abstract

Purpose of Review Multiple stressor studies conducted in real-world environments play an important role in discovering how stressor pathways may vary relative to ecological complexity and study scale. We reviewed the evidence for climate and landscape change impacts on freshwater biodiversity in real-world ecosystems at the global scale. Using our compiled database of 150 studies, we asked (1) what are the study characteristics within the available evidence base and (2) what are the main knowledge gaps and recommendations for future research?

Recent Findings Most studies employed an observational design and examined climatic and landscape change trends over a broad regional spatial scale (median = 97 sites/study). Ecological complexity was well represented in studies with a median of 11 predictor variables that characterized the relevant climate, landscape condition, and many other environmental attributes. Community-level metrics were common response types across all biota including larger, more mobile organisms such as fish that are challenging to examine in an ecologically-relevant context within controlled laboratory settings.

Summary We identified several knowledge gaps including the need for more published time-series data, particularly with respect to understanding climate change impacts. Other opportunities for improved future research included incorporating more stressor and biological interactions, examining potential climate stressors over multiple seasons and streamlining methods for dealing with the pervasive challenges of multicollinearity in real-world systems. We emphasize the unique role of 'natural experiments' in validating experimental findings and provide a suite of recommendations for creating more strategic field studies to inform conservation efforts.

Keywords Multiple stressors · Land use · In situ · Aquatic · Interactions · Ecological context

Introduction

Global freshwater biodiversity is in crisis as a result of many persistent and emerging threats [1, 2••], prompting the development of an emergency action plan [3]. In most regions of the world, landscape change due to rapid human population growth and development remains the leading driver of freshwater biodiversity loss [4]. However, these impacts are being increasingly exacerbated by concurrent climate change effects acting on similar pathways [2••]. In response to the deepening biodiversity crisis, there is a growing, substantial body of research dedicated to understanding

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drivers of freshwater biodiversity change, including syntheses of the overall evidence base [5, 6]. However, translating this growing knowledge base into meaningful conservation action remains a significant challenge in part due to the vast complexity and diversity of real-world ecosystems [7].

Recent multiple stressor syntheses and meta-analyses have provided valuable insight into how different combinations of stressors influence freshwater biodiversity [5, 6, 8, 9••]. Notably, many multiple stressor syntheses in varying ecosystems have focused on fully factorial experimental studies conducted in controlled laboratory settings or outdoor mesocosms, facilitating a more direct understanding of causal relationships [6, 10–12]. Some emerging key trends include the prevalence of interactive effects between multiple stressors, how diverse communities may be more resilient to stressors than individual populations and the possible mediating role of warming when combined with a second stressor in freshwater ecosystems [6, 10, 11]. However, another common emerging theme is how the effects of multiple stressors often remain unpredictable and in fact may vary considerably depending on the specific ecological context including ecosystem type, geographical region, biological response and study design [6, 10, 12, 13]. These discrepancies highlight the need for studies that focus on understanding underlying stressor mechanisms and how they may be altered with varying context [14•].

While controlled experimental studies are critical for understanding stressor mechanisms, complementary research in real-world ecosystems can be used to validate findings within more realistic settings where numerous ecological factors may be at play [15, 16]. Stressor pathways have been shown to vary depending on the ecological context including the spatial or temporal scale, the regional biodiversity or the presence of additional stressors or important environmental covariates [9••, 16–19]. Climate change may be particularly important to examine in situ in order to capture complex indirect and interactive effects as well as impacts from major climatic events like 100-year storms or drought [20, 21]. Further, climate studies that use a space-for-time study design inherently require a large study area to capture trends and filter out finer scale effects [22, 23]. With respect to landscape change, larger study scales may also translate into longer stressor gradients, possibly leading to improved recognition of disproportionately vulnerable ecosystems [9••]. Although observational field studies can inevitably lead to more 'noise' or unexplained environmental variability, they may also provide important insight into the role of numerous stressors, biological interactions and other important ecological context that would be difficult or even impossible to replicate using laboratory experiments.

Our study objective was to understand what evidence exists on the combined effects of climate and landscape change on freshwater biodiversity in real-world ecosystems. We have intentionally adopted the term 'real-world' to differentiate our review from others that have included relatively artificial laboratory studies or simulated responses of ecosystems. Further, we prefer to describe ecosystems as 'real-world' as opposed to 'natural' to emphasize the dynamic state of our world's ecosystems amid global environmental change. To achieve our objective, we conducted a literature review and compiled an evidence base of 150 studies at the global scale. Evidence base synthesis is a valuable tool for providing a comprehensive overview of a specific research area and can be used to identify knowledge clusters (i.e. subtopics of interest that may support and guide future evidence synthesis endeavours) and knowledge gaps [24, 25]. Our review scope specifically focused on the collation of real-world studies which included large, observational field studies as well as smaller outdoor mesocosms or field experiments that approach more realistic conditions with direct relevance for conservation management and planning. With our review database, we aimed to answer two questions: (1) what are the characteristics of studies focusing on the combined impacts of climate and landscape change on freshwater biodiversity in real-world environments and (2) what are the main knowledge gaps and recommendations for conducting future research?

Methods

Search Strategy

We performed a three-step nested search for relevant studies using ISI Web of Science (Appendix 1). The search results were bounded within a ten-year period from September 22, 2011 to September 22, 2021. To test our search strategy, we had one coauthor (C. Mantyka-Pringle) independently identify nine benchmark studies that were expected to be within the search results based on their expert judgement (Appendix 1). Eight of the nine identified benchmark studies were found within the search results, verifying our chosen search terms.

Screening Process

The search resulted in an initial 1015 articles that were screened using detailed inclusion/exclusion criteria (Fig. S1 and Table S1 in Appendix 2). We additionally added one benchmark study that was omitted due to a missing term from the second search step [26•], for a total of 1016. Our study inclusion criteria terminology followed the standardized terms outlined in the Collaboration for Environmental Evidence guidelines [24]. Inclusion criteria details were grouped into six sections which included the study population, the intervention or impact variables, the outcome or response variables, the comparator (i.e. the use of controls, alternative interventions or other comparative methods), study design and language (Table S1). Studies that met the detailed inclusion and exclusion criteria for all six sections were screened into our review for data collection. Review articles and book chapters identified within our search results were also checked for relevant studies using a snowball approach where additional reviews of interest were subsequently added to the screening list. A list of all excluded articles with accompanying reasons for exclusion is provided in Appendix 3. Two main reviewers performed the screening with an agreement rate of 85% and a Kappa statistic of 0.58 based on a joint screening of 103 articles. The main source of disagreement was due to the secondary reviewer being overly inclusive relative to the detailed inclusion/exclusion criteria (Appendix 2), which accounted for 13 of the 15 disagreements.

Data Extraction

Following screening, a total of 154 studies were included in initial data extraction. Upon further assessment, four studies were removed due to the joint use of datasets and analyses, resulting in a final database of 150 studies (Fig. S1). In these cases of replication, we selected the most comprehensive study for inclusion in the database. For each screened-in study, we collected information relating to the general study set-up (location, ecosystem type, study type), the intervention types (climate and landscape change variable information), the biological response variables (biological level, organism type, response type) and study design (comparator types, unit of analysis, study scale, number of predictor variables, methods for testing multicollinearity).

Although our screening targeted a specific set of climate and landscape change predictors (Table S1), we classified all relevant variables in retained studies following the definitions provided in Table 1. For example, streamflow metrics were commonly used as study predictors, representing a diverse range of effects from natural variability to landscape change to climate. To help focus our review, streamflow metrics were only used as an inclusion criterion when the study specified flow as an indicator or proxy of climate. However, we recognize that streamflow variables are often linked to climate and therefore all flow-related variables were classified under the climate heading 'hydrology' in retained studies. Despite the default classifications outlined in Table 1, we

Table 1 Classification of climate and landscape change variables included in our review

Environmental variables	Definition
Climate variables	
Air temperature	Annual, seasonal, monthly, and daily air temperature values; growing degree-days, air temperature variability or seasonality, season length
Water temperature[a]	Annual, seasonal, monthly, and daily water temperature values; water temperature variability or seasonality
Precipitation	Annual, seasonal, and monthly precipitation values; precipitation variability or seasonality
Hydrology[a]	Measurements of streamflow (velocity, discharge) and drought
Largescale climate oscillations	Largescale climate oscillations (e.g. NAO, ENSO)
Other	Other climate-related variables including measurements of light (e.g. radiation, diurnal period), humidity, evaporation, and wind
Landscape change variables	
Land use and land cover[a]	Areal coverage of anthropogenic land use and natural land cover classifications within a catchment; measurements of natural vegetation cover in the catchment or riparian zone as a proxy of landscape change; other measurements of land use intensity such as livestock density, number of mines or hydropower plants
Road presence and density	Road crossing density or presence in study area
Water quality degradation[a]	Water quality degradation from point or diffuse-source pollution (e.g. wastewater effluent, fertilizer/pesticide use, nutrient loading from catchment runoff)
Sedimentation[a]	Measurements of sedimentation as a proxy of land use (e.g. sediment addition, fine substrate deposition, turbidity)
Hydrological alteration and fragmentation[a]	Presence, densities, or proximity to dams, reservoirs/impoundments, and canals; water withdrawals/abstraction; measurements of habitat fragmentation
Habitat loss	Experimental alteration of aquatic habitat size
Indirect proxies of human impact	Indirect proxies of human impact including population density, gross domestic product, industrial and agricultural output; trace metals in paleolimnological studies

[a]Predictors that may be influenced by climate, landscape change or a combination of these pathways depending on the specific study

acknowledge that several predictor variables including water temperature, hydrology, land use and land cover, water quality degradation, sedimentation and hydrological alteration and fragmentation may be influenced by climate, landscape change or a combination of these pathways depending on the specific study context.

Our final database of studies used for data collection and supplementary coding information is provided in Appendix 4. Our findings in the following sections are all reported with respect to either the number of studies or the number of cases, with the latter indicating the more specific number of examples (i.e. model combinations) found within each study. Descriptions of select codes used in data extraction and detailed in Appendix 4 are repeated here to aid in results interpretation. First, we classified study spatial scale into five categories: global, continental, regional, local or waterbody-level. We generally defined a regional study area to be either greater than 100 sites or spanning more than 100 km in length. When calculating the total number of units in a study (e.g. number of site replicates or years of data collection), there was often a range of values depending on the specific model. To provide conservative estimates, we used minimum values in all reported results. Last, we examined each study for a hypothesis or prediction statement and classified the results as either yes, partial or none. Studies that achieved a 'yes' supplied a priori predictions between the biological response and every predictor variable tested, whereas studies that were assigned a 'partial' had justification given for the inclusion of at least one predictor variable.

Results and Discussion

Study Characteristics

Study Location and Type

We identified 150 real-world studies that examined some combination of climate and landscape change impacts on freshwater biota. Studies spanned over 40 countries and were mainly concentrated in the continental and temperate climatic zones (39 and 56% of studies, respectively), with relatively lower coverage in arid (19%), tropical (9%), subarctic (9%) and polar and alpine regions (3%; Fig. S2). River ecosystems including streams were by far the most common ecosystem type under analysis (77%), followed by lake ecosystems (17%), ponds (7%) and wetlands (4%).

The majority of studies made inferences based on observational data (93%). In contrast, we identified ten studies that performed experimental manipulations, with nine studies conducted in outdoor mesocosms and one completed in situ. We note that our strong focus on observational field studies remains relatively unique within the literature, as past multiple stressor reviews and meta-analyses of marine and freshwater ecosystems have often focused on evidence

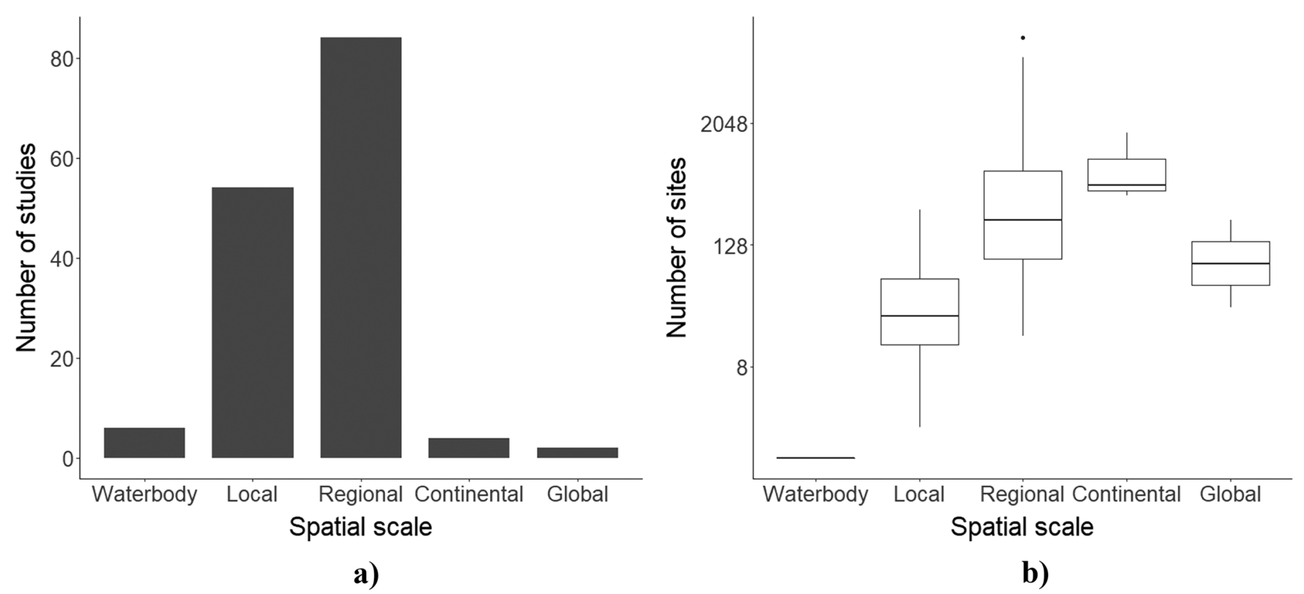

Fig. 1 **a** Number of studies and **b** number of sites by spatial scale for 150 studies within our review database. Please note that the y-axis for panel b has been reformatted to the logarithmic scale

from laboratory or small mesocosm experiments [e.g. 6, 10–12; but see 5, 8, 9••].

Study Scale

Most studies included spatial replicate units (93%), with temporal data less commonly used (21%). Studies that incorporated both spatial and temporal variability were the rarest study type (13%; e.g. 27•, 28].

Many studies were conducted across an extensive spatial scale, with a median number of 97 site replicates over all spatial scale types combined (Fig. 1). Most studies had sites spanning a regional study area (56%), with a median of 227 sites. Local studies were the next most prominent spatial scale (36%), with a median of 26 sites. Studies conducted at the continental, global and waterbody scales each represented approximately 1– 4% of all studies.

The choice of spatial scale has been shown to influence study results, with expected trade-offs between ecological complexity and model performance [9••, 29, 30]. However, larger spatial scales may be advantageous in certain scenarios, for example when examining species that are highly mobile such as migratory fish that require multiple, intact habitats with reliable connectivity. Further, broader spatial scales are often required for capturing a sufficient climate gradient in space-for-time climate studies [31]. Another good example comes from Birk et al. [9••], where greater interactive stressor effects were only found when examining larger spatial scales in river ecosystems. Ultimately, the selected spatial scale should be carefully considered with respect to the species and ecosystems under study, as well as the potential relevance for conservation and management planning [29].

Although less common, temporal studies often had a substantial number of years of data collected, with a median temporal scale of 9 years. Given rapid climate change, the need for time-series data has perhaps never been more urgent due to unevenly shifting baselines [32]. Temporal studies in our review were able to capture the before-after effects of major climate events such as drought and El Nino years [33, 34•], as well as examine more long-term climate-driven trends [26•, 35, 36]. Some other noted benefits to longer study periods include the heightened ability to identify chronic long-term effects, or delayed stressor impacts and potential recoveries following behavioural shifts or community succession [13, 16, 37].

Climate and Landscape Change Variables

Most studies included at least one temperature variable type (90%), with air temperature and water temperature predictor variables being equally represented in around half of all studies. Precipitation effects were also examined in approximately half of all studies (51%). Although we did not specifically target hydrological variables within our search terms, flow-related indices including drought were identified in 40% of studies. Climate variable types that were less commonly observed included large-scale climate oscillations, measurements of light, wind speed and moisture.

As environmental drivers of biodiversity may vary seasonally, we analysed how frequently studies included climate seasonality within their models. We found that seasonal climate variables were examined in approximately 30% of studies, with results revealing how climate in different seasons may combine and sometimes interact to influence local biodiversity [38–40]. Some of these studies elucidated climate effects on biodiversity with impressive datasets spanning over multiple seasons and years [38].

Land use and land cover (LULC) effects were the dominant landscape change variable type examined, with related variables present in 80% of studies. The most common LULC predictors were proportions of anthropogenic and natural land use cover within the study area catchment. Hydrological alteration and fragmentation effects were examined in 21% of studies, representing a mix of potential impacts due to widespread damming, impoundments and other hydrological barriers. Water quality and sedimentation impacts were tested in 18% and 8% of studies, respectively. Of note was one Arctic study that performed nitrogen additions to disentangle the cumulative effects of direct warming and warming-induced landscape change [41]. Other landscape change variables identified in our review included road-related effects (8%), and more indirect proxies of human disturbance such as nearby population density (12%). We note that the majority of landscape change predictor variables were continuous (~85%) and therefore represented wide, real-world disturbance gradients that would be challenging to create in an experimental setting, especially over prolonged periods.

Biological Responses

Community-level metrics including diversity, composition and abundance were used as biological response variables in 69% of all studies. Species-level metrics such as distribution and abundance were included in approximately one third of all studies, whereas population and individual-level metrics were found in less than 10% of studies. Although several studies examined multiple biological levels, organisms and response types, the majority maintained a limited focus with only one or two response metrics (Fig. 2a). Further, biological interactions were only assessed in a small proportion of studies (16%). Biological interactions most commonly represented the effect of an invasive species, but also included other biological effects from native species providing potential food sources, competition, predation or habitat [42–44].

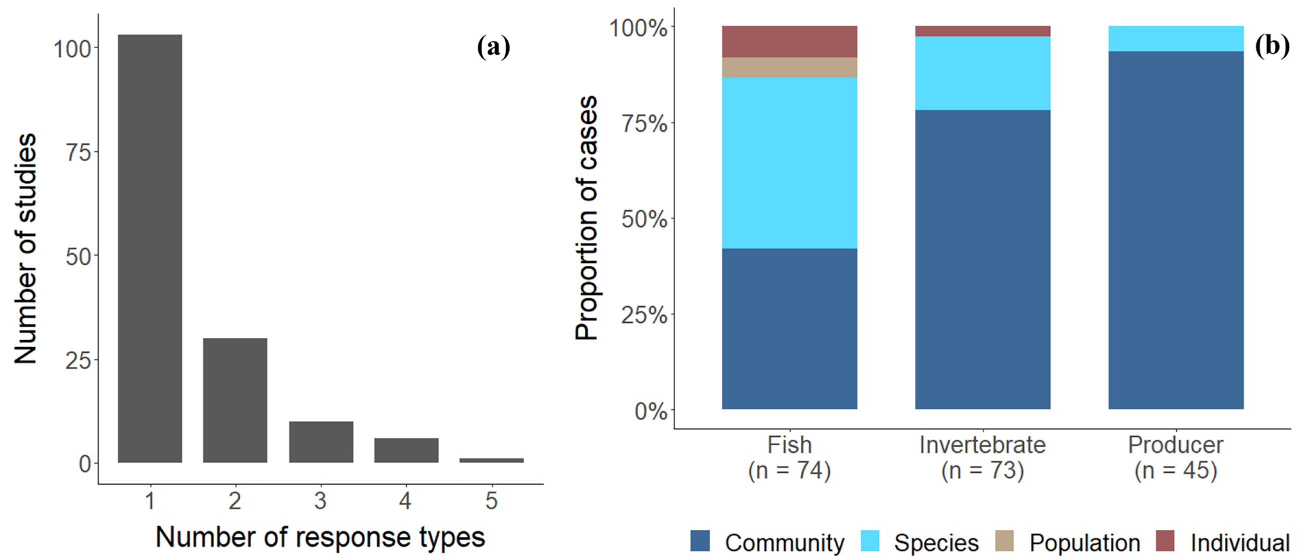

Fig. 2 **a** Number of response types included in our study analyses, and **b** biological organization level by organism type. Number of cases by organism type are indicated in brackets. Invertebrates included macroinvertebrates and zooplankton, whereas Producers included all primary producers such as algae, phytoplankton, diatoms and macrophytes

The biological level examined differed by organism type, with community-level metrics most commonly used for invertebrates and primary producers (78 and 93% of cases, respectively; Fig. 2b). In contrast, fish were more likely to be examined at the species level (45% of cases), although community-level metrics were a close second (42% of cases; Fig. 2). We note that the relatively high number of studies that focused on fish communities here is in stark contrast to a review conducted by Matthaei and Lange [12], where they found that fish communities were barely represented (8%) within their review focused on fully factorial multiple stressor experiments on freshwater fish. This difference in results underscores the importance of evidence synthesis from larger in situ studies that may be more suited for organisms that undergo complex biological interactions over large spatial and temporal scales. Further, in our review, fish community data collected over large spatial scales was commonly used for developing numerous species distribution models, with some studies developing upwards of 50 individual species models within a single study [30, 45, 46].

Study Design Complexity

We found that studies using true comparators were rare given the high number of observational studies in our database. Instead, the majority of studies examined climate and landscape change trends over space and/or time. However, approximately 20% of studies did examine climate change effects using time-series data, allowing for relative comparisons over time [e.g. 26•, 28, 47]. A small subset of studies used experimental controls or approximated a more controlled comparative study design using observational data. For example, six studies using observational climate data included a before-after approach where the same sites were repeatedly measured before and after a major climatic event such as drought [e.g. 33, 34•]. For landscape change variation, ten studies used experimental controls and treatment levels [41, 48, 49], and another seven used an observational study design that included either a before-after or control-impact approach [e.g. 34•, 50, 51]. We note that studies that employed more strategic study design comparators were often conducted at relatively small, local

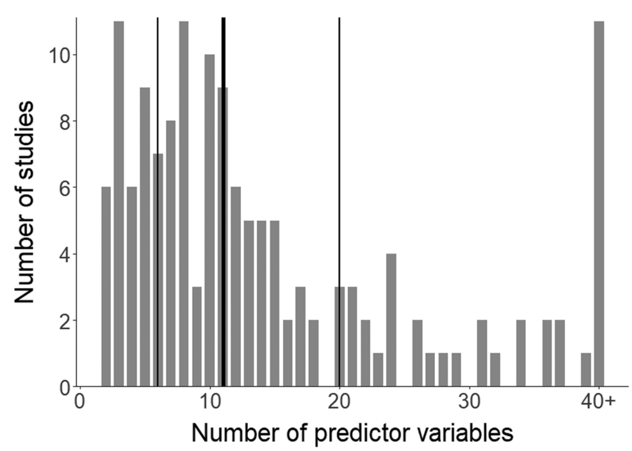

Fig. 3 Number of predictor variables included in study analyses. Black lines indicate the median value (thicker black line) and the two quartiles (thinner black lines)

study scales in contrast to studies that examined trends over broader spatial scales.

Studies in our review included a relatively substantial number of predictor variables (median = 11; Fig. 3). In contrast, several past marine and freshwater multiple stressor reviews have focused primarily on fully factorial studies with 2–3 stressors maximum [e.g. 5, 10, 11], and have highlighted the need for extrapolating findings into real-world ecosystems where numerous environmental factors may be at play [52]. However, we note that interactive effects between climate and landscape change variables were only tested in approximately one-quarter of all studies in our database, which may in part reflect the inherent challenges in examining interactive effects in situ. We identified a wide range of variable types used in studies including various anthropogenic stressors, indices of climate and other important environmental covariates. After climate and landscape change variables, predictors representing habitat quality such as elevation, slope, water and sediment quality and characteristics of the surrounding vegetation were the most common variable types. Many studies also included variables representing habitat size, such as river basin area, waterbody area or wetted depth and width in flowing systems. This added ecological complexity allowed studies to demonstrate how stressor impacts varied depending on a range of factors including ecosystem size and type, historical and current climate conditions and interactions with invasive species [19, 40, 42, 53].

Due to the high number of predictor variables tested, possible multicollinearity among predictor variables was addressed in approximately half of studies. Within these discussions, the most common strategy was to pose a multicollinearity threshold cut-off value using either pairwise correlation coefficients (between 0.6 and 0.8) or variance inflation factors (ranging widely from 2 to 20). Approximately 25% of studies removed variables using a cut-off value but did not provide any statistical or ecological justification for why certain variables were eliminated over others. A smaller subset of studies (10%) provided more specific justification for variable choice [e.g. 54, 55], and a handful of studies (3%) ran alternative models to support final variable inclusion [e.g. 26•, 52]. In contrast, approximately one-quarter of studies with relevant statistical methods (e.g. multiple linear regression, GLM, Bayesian network models) did not discuss the issue of possible multicollinearity.

We found that only a small number of studies (15%) provided detailed hypotheses or predictions outlining each predictor variable's expected relationship with a biotic response [e.g. 37, 54, 56]. Approximately 30% of studies provided some justification for a subset of predictor variables tested (classified as 'partial' under the hypotheses/predictions coding). In contrast, the majority of studies (56%) did not provide hypotheses or ecological justification to support the inclusion of predictor variables within analytical models. Many of these studies lacking hypotheses tested a high number of predictor variables, with a median value of 12 variables.

Experimental vs. Observational Studies

The ten identified mesocosms and outdoor experimental studies within our database demonstrated unique characteristics that highlighted their valuable and complementary role in understanding stressor mechanisms. Notably, these studies were much more likely to test for climate-landscape change stressor interactions (7/10 studies), as well as outline hypotheses (7/10 studies) in comparison to observational field studies [e.g. 37, 48, 57]. Further, these studies employed fully factorial stressor treatments and controls, providing much stronger evidence for how stressors were influencing freshwater biota in real-world systems. However, there were also clear trade-offs when comparing other characteristics of experimental studies to observational field studies. For example, experimental studies were conducted at smaller, local scales with fewer replicates (median of 36 sites) and low temporal resolution (median study duration of less than one year; e.g. 41, 58, 59). Further, these studies tested less predictors (median of 3 predictors) relative to observational studies (median of 11 predictors).

Knowledge Gaps and Study Design Recommendations

Our review identified several knowledge gaps relating to study scale, organism type, ecological complexity, location and season. We found that temporal data use in studies was limited, despite the noted importance of time-series data for disentangling the effects of climate change [20]. Primary producers such as algae and macrophytes were the most underrepresented group in our review and were the focal group in approximately 1/3 of studies. In comparison, fish and invertebrates were examined in 45% and 46% of all studies, respectively. Studies that incorporated additional ecological complexity into models, either in the form of testing for stressor or biological interactions, were also in the minority. With respect to study location, we found that very few studies were conducted in tropical, subarctic or polar and alpine climatic regions, underscoring the need for future studies within these climatic zones. Studies were also not well-represented across freshwater ecosystem types, with lakes, ponds and wetlands being the most underrepresented groups. Finally, most studies examined climate-related effects during a single spring or summer season, hence not considering the possible cumulative effects of climate over multiple seasons including during the autumn or winter period.

We noted several landscape change stressors that were underrepresented in our review. In particular, studies that examined direct habitat loss and alteration were relatively rare (< 25% of all studies). Examples of commonly observed habitat alterations in our database included dams, water abstraction, impoundments and reservoirs in the study area. A small number of studies incorporated direct measurements of habitat size or fragmentation into their analyses, providing further insight into how multiple stressor impacts may vary depending on habitat connectivity and patch size [58, 60]. Other landscape change stressors that were less frequently represented in our database included road-related impacts, sedimentation and pollution. However, we note that these results are reflective of our refined search terms which did not include these specific stressors.

One notable gap in our review was the lack of studies that focused on Indigenous knowledge and wisdom either on its own or bridged with western science. Indigenous knowledge can strengthen numerous stages of study development including identifying relevant stressors, site selection, and conceptual model development [61, 62]. A two-eyed seeing approach (or other similar approaches [63]) that involve bringing together Indigenous knowledge and Western science [64] can be a particularly effective means for facilitating knowledge co-production or co-assessment to directly inform meaningful conservation actions [65]. Further, we note that a two-eyed seeing approach may be particularly well suited for observational field studies that may better complement the wide breadth of local knowledge spanning large territories and multiple generations. Indigenous knowledge may also help connect local observations to other influences that may be overlooked or unmeasurable in the study design such as broader environmental or biological changes and Indigenous relationships to water [66, 67]. Future reviews may consider a broader review scope in order to capture studies that examine climate and landscape change impacts with an Indigenous lens. For example, with more expansive inclusion criteria, our review would have included a study by Mantyka-Pringle et al. [61] that bridged Indigenous and western scientific knowledge in a two-eyed seeing approach. The study authors included broad indices of climate and landscape change including water quality and quantity to understand multiple stressor effects on ecosystem health; however, these indices did not meet our more focused definitions as stressors outlined in our review inclusion criteria.

Three Key Recommendations for Conducting 'Natural Experiments'

Based on our review, we compiled a list of three key considerations for researchers planning and executing strategic field surveys or 'natural experiments' that examine combined climate and landscape change impacts on freshwater biodiversity (Fig. 4). These considerations aim to leverage the unique characteristics of field studies while also avoiding the common pitfalls.

1. Select sites that capture landscape and climate gradients at a relevant scale

   In an ideal scenario, the first step in planning a strategic field study involves selecting sites that capture a wide, representative landscape change gradient relevant for conservation management and planning. Within this pre-defined gradient, identifying pseudo 'control' sites that maintain zero or relatively low disturbance levels can greatly strengthen the study design by facilitating a control-impact or reference-condition approach. For example, Esselman et al. [68] defined least-disturbed reference sites within their national fish survey database using a pre-developed reference-condition approach. However, we note that the benchmark for lower disturbance or 'control' sites may shift considerably higher in more developed regions [e.g. 69, 70]. In contrast, finding disturbed sites in more remote, northern regions may present a challenge particularly as many areas lack detailed disturbance mapping.

   Following the identification of the landscape change gradient, researchers will need to determine their approach for including climate variation. Although temporal studies are the gold standard for examining climate change effects, carefully crafted space-for-time studies spanning broad spatial scales can complement time-series datasets or provide unique insights in lieu of more rare temporal datasets [e.g. 71–73]. If using a space-for-time approach, researchers may need to circle back and expand their initial site selection to ensure that sufficient landscape change and climate gradients are both included. If possible, we recommend that researchers consider a study design that incorporates both repeated sampling over time, as well as a broad range of climatic conditions over space in order to effectively disentangle climate change pathways that may vary depending on local conditions. Within our database, we noted a few good examples of studies that fell within this category including some that applied their empirical datasets for weighing different land use management scenarios under future climate conditions [74, 75].

Site Selection Challenges and Potential Solutions

As field studies are often challenged by limited resources and unpredictable conditions, creative solutions may be required to approximate an ideal study design. In particular, incorporating climate variation

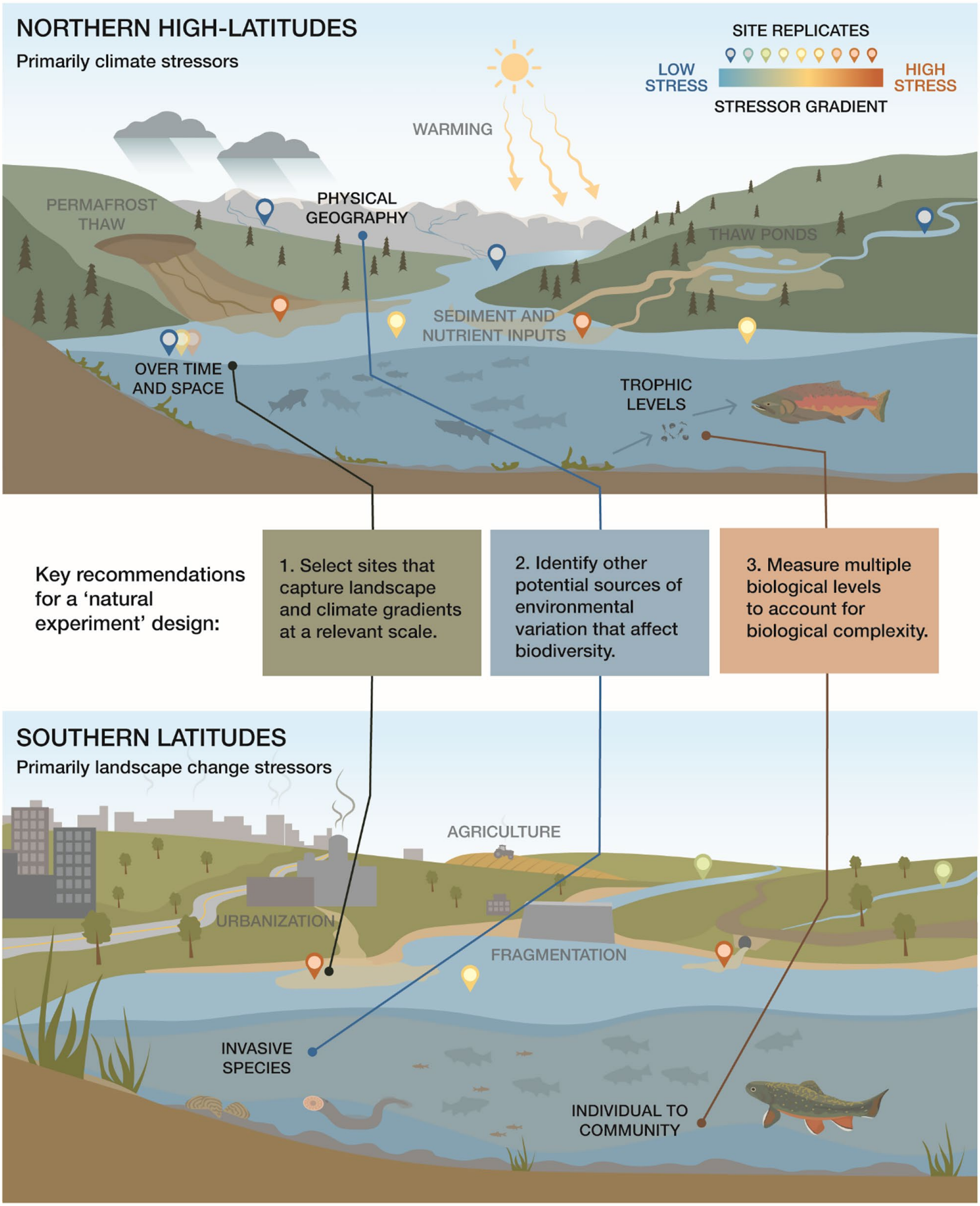

Fig. 4 Three key recommendations for conducting 'natural experiments.' Study design may differ depending on the primary stressor types and the complexity of ecological systems. For example, high-latitude ecosystems (top panel) may experience primarily climate-related stressors, whereas lower-latitude southern ecosystems (lower panel) may be dominated by landscape change stressors. The stressor gradient represents an index of cumulative climate and landscape change stressors occurring across each landscape

will be difficult for studies with more limited resources, and researchers will need to consider trade-offs between repeated sampling at fewer sites versus expanding the study area for a broader climate gradient over space. One potential solution may be to strategically incorporate current sampling programs with complementary pre-existing databases in the study area for greater coverage over space and/or time. Alternatively, some researchers have made exclusive use of large, pre-existing databases that contain data from field studies conducted by various monitoring and research programs [e.g. 40, 68]. In these cases, researchers may choose to ask research questions suited for the available stressor gradients. Alternatively, databases may be strategically subset with more specific research goals in mind. However, greater caution may be required when using multi-source datasets to ensure that any differences in study methods are carefully considered, mitigated where possible and clearly reported when interpreting the study findings.

We acknowledge that sampling challenges may be heightened for researchers working in remote, high-latitude regions associated with expensive fly-in costs, difficult environmental conditions and shorter seasonal windows for sampling. In these cases, researchers will need to carefully consider the minimum number of samples needed over space and time (including potential seasonal variation) to address their specific research questions with sufficient statistical power. If available, past knowledge collection efforts from diverse sources (e.g. Indigenous knowledge, grey literature, published studies) should be consulted to guide the planning process and identify potential opportunities and risks up front. Further, additional steps may be taken to help support sampling success such as budgeting for reconnaissance trips or Indigenous knowledge interviews during the planning process. Standardized monitoring programs used elsewhere may be consulted as a basis for developing new sampling programs but may need to be adapted due to limited resources and different environmental conditions. For example, lake fish community monitoring programs designed for ecosystems at lower latitudes may need to be modified to reduce mortality in high-latitude lakes that may be more vulnerable to exploitation [76].

One pervasive challenge for researchers conducting in situ climate and landscape change studies over broad spatial scales is the correlation of warmer temperatures with land use intensity or natural land cover [21, 77]. Where possible, we recommend that researchers aim to strategically sample landscape change gradients that are either unrelated to the surrounding climate or contained within a similar band of climatic conditions [e.g. 71, 78]. An even more advanced option would be to incorporate sites that span interactive effects levels between climate and landscape change (e.g. high disturbance with warmer vs. cooler climate, low disturbance with warmer vs. cooler climate, etc.).

2. Identify and account for other potential sources of environmental variation that affect biodiversity

One major strength of larger field-based studies is the ability to examine numerous variables representing important ecological context that are often not included in smaller experimental set-ups (Fig. 2a). Ideally, possible sources of environmental variation influencing biodiversity should be identified during the study planning stage (e.g. other anthropogenic stressors, physiography, hydrologic connectivity). Researchers can then decide which variables may be appropriate to test given their study resources, or alternatively they may choose to control for some variation using strategic site selection (e.g. all sites at the same elevation, or with no additional stressors). For example, Cuffney et al. [78] employed strategic site selection to represent a wide urbanization gradient within multiple distinct biogeographic regions of the conterminous USA. Another good example comes from Brucet et al. [31] where the authors identified and controlled for important natural covariates (e.g. elevation, lake size) prior to an in-depth examination of anthropogenic stressors on biodiversity.

Through our review, we observed several best practices for dealing with a high number of predictor variables that aimed to minimize issues with multicollinearity and interpreting correlative results. These best practises included (1) providing clear justification of all initially considered predictor variables as well as their hypothesized links with relevant biological responses; (2) where applicable, testing multicollinearity using well-referenced and repeatable analytical approaches; and (3) providing clear reasoning for final variable inclusion that considered both ecological and model performance. In the event that multiple models are considered equally viable, results from competing models may be assessed. Together, these best practises aim to help strengthen our collective understanding of stressor mechanisms while avoiding the common pitfalls of data dredging that may lead to erroneous study conclusions.

3. Measure multiple biological levels to account for biological complexity

Despite the huge opportunity for considering biological complexity in field-based studies, we found very few examples that examined more than one biological response category or directly assessed biological interactions (i.e. tested for the effect of distribution or abundance of one species on another). The most common modelling types within our review that incorporated biological interactions included multiple regression and ordination techniques such as redundancy analysis. Although introducing biological complexity into modelling can be challenging, examining interactions among biological groups within a multiple stressor framework can reveal critical insights that may otherwise go unnoticed or be spuriously attributed to environmental correlates. Some notable examples from our database included both direct and indirect analyses of biological interactions, such as the direct influence of an invasive species on trout population abundance, or even more subtle impacts of landscape change that were exposed by evaluating multiple biological levels in parallel [e.g. 18, 42]. Further, we encourage researchers to take advantage of rapidly developing technologies such as environmental DNA for incorporating biological complexity into future studies [79].

Opportunities for Strengthening the Link to Freshwater Biodiversity Conservation

Due to the inherently multifaceted nature of real-world studies and their high implications for social-cultural values, we emphasize the need for inclusive research teams with diverse, multiple disciplinary expertise [80]. Further, multiple disciplinary approaches that adopt different perspectives and facilitate fair compromises among user groups can provide a powerful means for tackling complex conservation problems that are rooted in various ecological, social and political realms [81]. Although we did not explicitly test for a relationship between multiple disciplinary teams and conservation 'impact' in our review, we noted that studies with a more obvious and direct link to conservation actions often had authors with non-academic affiliations including government, environmental non-profit organizations and industry [e.g. 45, 74, 82, 83]. To promote an effective multiple disciplinary approach, we recommend that teams foster early and regular collaboration with decision-makers and other stakeholder and rightsholder groups to facilitate a stronger link to policy and on-the-ground conservation actions. Ideally, this is done in the context of a full co-production model that includes a shared and interactive process between academic and non-academics [65, 84]. As different partner groups may have varying project goals and capacity, we advise that studies are carefully designed to maximize 'success' in a meaningful way for all participants. For example, decision makers may be more interested in a smaller study area and compromises may be needed when discussing how that smaller study may be used to complement a larger one desired by another group (for example, by academic researchers).

Although there have been substantial efforts to find solutions for the biodiversity crisis, we are still in great need of forward-thinking and collaborative initiatives across sectors [4]. Some potential opportunities may be found by altering pre-existing (and emerging) large-scale monitoring programs to strategically sample climate and landscape change gradients (e.g. US Environmental Protection Agency's National Lake Assessment, Ontario's Broadscale Monitoring Program, the Conservation of Arctic Flora and Fauna's Circumpolar Biodiversity Monitoring program, Queensland's Ecosystem Health Monitoring Program—Freshwater). We note that there may also be significant opportunities in some regions to partner with industrial proponents undergoing baseline inventories and impact assessments as part of general regulatory activities. In some cases, large quantities of environmental data have been amassed as part of disparate development projects or government-led monitoring programs yet remain largely inaccessible to scientific researchers [85, 86]. Promoting data accessibility and collaboration across sectors could therefore provide valuable datasets to address research questions, particularly in more remote regions where scientific data remains relatively scarce [87]. Finally, opportunities to pair in situ experiments in facilities such as the Experimental Lakes Area (Canada) or the ExStream System (New Zealand) with larger 'natural experiments' could be explored to assess causal relationships and then to further validate those findings in real-world ecosystems [12, 16].

Review Limitations

Our review had some noted limitations that may have influenced our findings. We only had the resources to search one major database (ISI Web of Science (WOS)), which means that our results could be biased towards studies in specific countries or disciplines [88]. Although we screened some grey literature via WOS (e.g. theses, conference proceedings), our final database was lacking studies that may have been available had we made a general call for grey literature sources in our networks or spent time scanning other available databases. We also made decisions to narrow our search that undoubtedly impacted our results. For example, we used only the most recent 10-year period and we did not retain observational studies that included water quality variables as a proxy for landscape change. We also limited our search to studies that had indicated a cumulative, combined or interactive effect within the search fields. We acknowledge that this choice may have excluded many potentially relevant studies that assessed cumulative or combined effects without defining it as such (e.g. studies employing multiple regression models). To focus our review scope, an additional screening decision was made to use streamflow as an inclusion criteria variable only when a direct link between streamflow and climate was provided. As a result, our final database of studies aimed to provide more direct evidence of the independent and potentially interactive effects of climate and landscape changes on aquatic biota. Finally, the search was only conducted in English which limited our ability to locate and integrate evidence written in other languages. We recommend that future syntheses expand their search terms to include a wider diversity of potential studies representing climate and landscape change effects on freshwater biodiversity and to include additional languages beyond just English.

Conclusions

Our review highlights the unique contribution of field-based studies to the multiple stressor literature including broader ecological relevance and therefore potentially greater applicability to conservation planning and management in comparison to reviews focused on laboratory experiments. Most studies in our review were large, observational field surveys that incorporated long, realistic stressor gradients, numerous predictor variables, and the assessment of effects at higher biological levels that are difficult to replicate in laboratory settings. As a result, findings from these field-based studies may be more readily applicable for conservation managers seeking solutions for larger conservation management units that inherently incorporate more ecosystem complexity. However, observational studies also come with their own challenges such as increased unexplained variability, inconsistent sampling methods across large datasets, and the inability to isolate cause-effect relationships. To help overcome these challenges, we recommend that researchers conducting field-based studies focus on testing stressor mechanisms using clear hypotheses and strategic survey designs [12]. Further, we identified specific knowledge gaps within the literature that could benefit from future research including studies at the highest and lowest latitudes (i.e. the tropics and poles), studies that incorporate cumulative climate effects over multiple seasons and studies focusing on biodiversity in lentic or non-flowing waterbodies. Last, the establishment and maintenance of long-term monitoring sites, particularly in regions that have historically received less monitoring, remains a critical task for understanding and mitigating the mounting effects of climate change [87]. Ultimately, we emphasize the need for forward-thinking solutions by diverse, multiple disciplinary teams that can help facilitate a stronger connection between scientific knowledge and real-world conservation action.

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Author Contribution AM, CMP, and SJC conceived the research ideas; AM, DY, and CMP completed the article screening and data collection; AM led the writing of the manuscript. All authors contributed to sequential drafts and gave final approval for publication. We thank several anonymous referees for providing thoughtful input on the review manuscript.

Declarations

Conflict of Interest Alyssa Murdoch, Daniel Yip, Steven Cooke, and Chrystal Mantyka-Pringle declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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