Integrated Environmental Assessment and Management — Volume 20, Number 2—pp. 359–366
Received: 7 July 2023 | Revised: 7 December 2023 | Accepted: 11 December 2023

Special Series

Incorporating climate change model projections into ecological risk assessments to help inform risk management and adaptation strategies: Synthesis of a SETAC Pellston Workshop®

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EDITOR'S NOTE:

This article is part of the special series "Integrating Global Climate Change into Ecological Risk Assessment: Strategies, Methods and Examples." The papers were generated from a SETAC Pellston Workshop held at Oscarsborg Fortress near Oslo, Norway, June 2022. The international workshop included climate change modelers, risk assessors, toxicologists, and other specialists with a diversity of backgrounds and experience. The findings of the series demonstrate that climate change can successfully be incorporated as an integral part of risk assessment for a wide range of environments, to address the issues of long-term, adaptive environmental management.

Abstract

The impacts of global climate change are not yet well integrated with the estimates of the impacts of chemicals on the environment. This is evidenced by the lack of consideration in national or international reports that evaluate the impacts of climate change and chemicals on ecosystems and the relatively few peer-reviewed publications that have focused on this interaction. In response, a 2011 Pellston Workshop® was held on this issue and resulted in seven publications in *Environmental Toxicology and Chemistry*. Yet, these publications did not move the field toward climate change and chemicals as important factors together in research or policy-making. Here, we summarize the outcomes of a second Pellston Workshop® on this topic held in 2022 that included climate scientists, environmental toxicologists, chemists, and ecological risk assessors from 14 countries and various sectors. Participants were charged with assessing where climate models can be applied to evaluating potential exposure and ecological effects at geographical and temporal scales suitable for ecological risk assessment, and thereby be incorporated into adaptive risk management strategies. We highlight results from the workshop's five publications included in the special series "Incorporating Global Climate Change into Ecological Risk Assessments: Strategies, Methods and Examples." We end this summary with the overall conclusions and recommendations from participants. *Integr Environ Assess Manag* 2024;20:359–366. © 2023 The Authors. *Integrated Environmental Assessment and Management* published by Wiley Periodicals LLC on behalf of Society of Environmental Toxicology & Chemistry (SETAC).

KEYWORDS: Bayesian network; Chemical management; Climate change; Ecological risk assessment; Environmental management cycles of chemicals and climate change

This article contains online-only Supporting Information.
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Published 21 December 2023 on wileyonlinelibrary.com/journal/ieam.

BACKGROUND

Climate change and its impacts on humans and ecosystems are recognized as an existential threat to life on this planet (Adeniyi, 2016; Intergovernmental Panel on Climate Change [IPCC], 2022). The combined effects of chemicals and climate change on ecosystems remain an issue rarely discussed in national and international reports, in our experience. Previous efforts related to climate change by the Society of Environmental Toxicology and Chemistry (SETAC) include a SETAC Pellston Workshop® in 2011, which examined the influence of climate change on the foundation and practice of environmental toxicology and chemistry (Balbus et al., 2013; Gouin et al., 2013; Hooper et al., 2013; Landis et al., 2013; Moe et al., 2013; Stahl et al., 2013). While since the 2011 workshop there has been increased focus on the interaction of climate change with chemicals (Landis et al., 2014; Stahl et al., 2017; Wenning et al., 2010), in our view, it has not yet been sufficiently incorporated into risk assessment (Moe et al., 2023) and management (Cains et al., 2023).

The original calls to action and for greater involvement by environmental chemists, toxicologists, and risk assessors (Wenning et al., 2010) were driven by the lack of consideration by various national climate change assessments (e.g., US Global Change Research Program, 2018) of the potential harm to humans and the environment caused by exposure to legacy and new chemicals or other stressors in combination with climate change. Examples of publications illustrate the potential severity of climate change and interactions with legacy chemicals at contaminated sites, sensitive polar and marine tropical environments (Latola & Savela, 2016), and the proximity of climate-related environmental changes to potential irreversible tipping points (Pearce, 2019).

We are now experiencing a warming earth and lack of substantive work by governments to reduce emissions that stimulate climate change (IPCC, 2022; Voosen, 2019). There are still major knowledge gaps contributing to the difficulty in predicting the interactions between climate change's impacts and contaminants. These gaps include the effects of environment (pH, temperature, dissolved oxygen, food resources, and landscape) on the exposure and response to chemicals at the individual, population, and community scales for a diversity of species. A scenario where climate-forcing emissions continue at current or higher levels, increasing global warming, coupled with exposure to new and legacy chemicals, will ultimately result in even greater stress on the environment.

Over the past 10 years, improvements have been made to the data sets and climate models that underpin the now sixth-generation representative concentration pathways (Stahl et al., 2017) (Durack & Taylor, 2019) and the linked shared socioeconomic pathways (IPCC, 2022). In addition, more advanced methods for regional downscaling are available to make climate projections more relevant for incorporation into ecological risk assessments and adaptation management at regional and local scales (Han et al., 2018). These developments gave the impetus for organizing a second Pellston Workshop® in 2022, which resulted in this special series, "Incorporating Global Climate Change into Ecological Risk Assessments: Strategies, Methods and Examples."

The purpose of this introductory paper is to present the background, objectives, organization, and main outcomes of the workshop. The following sections will present (1) the workshop objectives and organization; (2) the main outcomes from five papers addressing risk assessment methodology (Moe et al., 2023), case studies (Landis et al., 2023; Mentzel et al., 2023; Oldenkamp et al., 2023), and risk management (Cains et al., 2023); and (3) conclusions based on the scientific papers and on the workshop objectives.

WORKSHOP OBJECTIVES AND ORGANIZATION

The 2022 workshop was designed to address the issue of incorporating climate model projections into ecological risk estimates, understanding that to do so requires the ability to make those projections at spatial and temporal scales relevant to the habitats and assessment endpoints of interest (Harris et al., 2014; Root, 1993). Previously, climate models operated at spatial and temporal scales that were not suitable for incorporation into regional or local ecological risk assessments.

The overall goal of this workshop was to explore novel approaches for incorporating climate scenarios and model projections into ecological risk assessments to support the evaluation of potential harm from physical, chemical, and biological stressors in marine and freshwater ecosystems.

The specific objectives of the workshop were to:

1) Bring together experts from multiple scientific disciplines, including climate modeling and catchment modeling, hydrology, biogeochemistry, environmental chemistry, ecotoxicology, biology, and ecological risk assessment, to build working relationships across the diverse scientific communities.
2) Build upon and further develop existing methods for incorporating climate model projections into ecological risk assessment frameworks to ensure that they address current and potential future risk.
3) Communicate the conclusions from the workshop to key stakeholders including the IPCC, national and international governmental organizations, and researchers.

The SETAC Pellston Workshop® on integrating climate model projections into ecological risk assessments to inform risk management and adaptation strategies was held on 20–24 June, 2022 at the Oscarsborg Fortress, on the small island of Håøya in the Inner Oslo Fjord, Norway. Due to continued concerns with COVID-19, and the potential for travel restrictions, this workshop was held in a hybrid format: most participants joined in person, while some joined virtually. The 25 participants in this workshop were invited to represent expertise in climate science and modeling, ecotoxicology, exposure assessment, risk assessment, and policy-making, among others. The participants represented 14 countries, different career stages from PhD students to retired scientists, and various sectors (academia, business, government, and research organizations) (Figure 1). Participants were initially divided into three working groups (WGs), focusing on (1) problem formulation and exposure

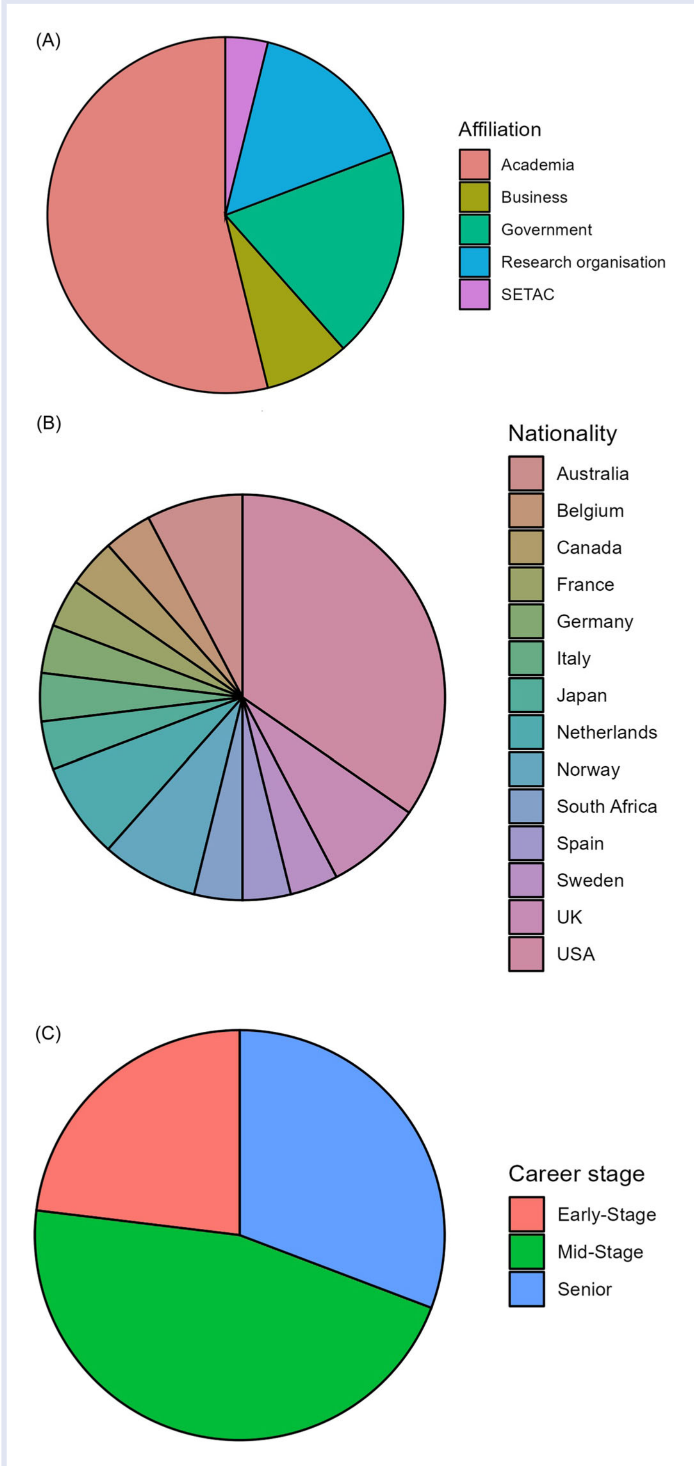

FIGURE 1 Overview of the workshop participants categorized by (A) affiliation, (B) nationality, and (C) career stage

characterization, (2) effects and risk characterization, and (3) risk management to help inform adaptation strategies.

A series of online meetings was organized during the months before the workshop, starting with a virtual kick-off meeting in October 2021. During these meetings, the participants identified and discussed examples of ecosystems where environmental risks of chemicals are known or likely to be influenced by climate change (see Supporting Information). Three of these examples were selected as case studies (Table 1) to focus the discussions and to help develop and explore a common risk modeling approach across WG1 and WG2. The case study selection criteria were as

TABLE 1 Overview of the case studies (after Moe et al., 2023)

No.	Location and geographic region	Ecosystem type	Chemical stressors and other stressors	Relevant climate change variables	Risk assessment endpoint	References
1	Skuterud, Viken, Southeast Norway	Stream	Pesticides	Precipitation, temperature	Risk quotient: ratio of environmental concentrations to effect threshold concentration	Oldenkamp et al. (2023)
2	Great Barrier Reef, Northeast Australia	Nearshore coastal	Herbicides, nutrients, sediments, biological interactions	Precipitation, temperature, cyclones	Hard corals' demographic rates and indicators (mortality, bleaching, cover)	Mentzel et al. (2023)
3	Yakima River, Cascadia, Washington, Northwest USA	River	Pesticides, water quality (hypoxia)	Temperature	Chinook salmon demographic rates and population size	Landis et al. (2023)

follows: (1) different geographic regions, (2) different types of ecosystems, (3) good knowledge of the ecosystem including chemical stressors and endpoints, and (4) an existing risk assessment model and/or sufficient information to build one. The resulting case studies represent three different types of aquatic ecosystems: streams, rivers, and inshore coastal waters.

The online meetings in this preparatory phase also addressed interdisciplinary topics such as relevant concepts and terminology (listed in Moe et al. [2023]), definitions and interpretation of risk, conceptual models, quantitative modeling methods, and communication with stakeholders. For example, participants presented approaches to risk analysis from the fields of climate modeling, climate policy, hydrology, and engineering, which could contribute to the advancement of chemical risk analysis. Following these discussions, it was agreed to use a common modeling technique across the case studies, and to collaborate on the case studies across WG1 and WG2.

WORKSHOP OUTCOMES: SUMMARY AND HIGHLIGHTS

Modeling approach

A key message from climate scientists participating in the workshop was that a large number of global climate models can be run in ensembles to generate future projections of a range of climate variables. The outcome of ensemble model runs will be more robust than projections from individual climate models, and can subsequently be aggregated and characterized by the main statistical properties (Moe et al., 2022). This derived climate information can in turn be used to generate probability distributions as input for chemical exposure modeling, effects modeling, and other types of impact modeling. Moe et al. (2023) describe and explore a modeling approach for integrating climate model projections into the assessment of near- and long-term ecological risks in this way, developed in close collaboration with the participating climate and environmental scientists. Their paper presents a probabilistic modeling approach, Bayesian networks (BN), aiming to evaluate the uncertainties associated with global and downscaled climate models in conjunction with the uncertainties of the traditional risk assessment pathways. We draw upon three cases studies of risk assessments (Table 1) that utilized the BN methodology for incorporation of climate model projections and represented advances in the science for their applications, for better prediction of future risks to ecosystems. The modeling approach developed here aims to contribute toward better assessment and management of risks from chemical stressors in a changing climate, taking into consideration society's multifaceted responses to these changes.

Case studies: Use of climate model projections in ecological risk assessment

A brief overview of the case studies is presented in Table 1, while more details are provided in the three case study papers (Landis et al., 2023; Mentzel et al., 2023; Oldenkamp et al., 2023) and in summary tables (Moe et al., 2023).

Case study 1: Pesticides in streams (Norway). In Northern Europe, climate change is expected to result in increased temperature and precipitation, which can in turn increase the occurrence of crop pests. This case study from agricultural fields in Norway was based on a BN model that predicts the probability distribution of risk quotients (ratio of exposure to effect thresholds), informed by a series of pesticide monitoring data (Mentzel et al., 2022). A statistical model was developed by Oldenkamp et al. (2023) to estimate a functional relationship between monthly precipitation patterns and pesticide run-off, which can provide a link from future climate projections to the exposure and risk characterization. For this case study, expertise on climate and hydrological modeling played a crucial role in developing a time-weighted precipitation index for bridging climate variables to chemical exposure. A BN was used to explore alternative scenarios of pesticide application, ranging from worst case (+50% emission as a response to climate-related increases in pest pressure) to best case (−50% emission to comply with the European Union's Zero Pollution Action Plan).

Case study 2: Great Barrier Reef (Australia). Mentzel et al. (2023) developed an adverse outcome pathway (AOP) network to conceptually delineate the combined effects of climate variables and the herbicide diuron on the in-shore coral reefs of the Mackay area of the Great Barrier Reef, Australia. Climate projections were derived from an ensemble of 16 downscaled models encompassing current and future conditions based on multiple emission scenarios for two 30-year periods. A BN was created to demonstrate how risk may be predicted for multiple stressors including temperature, ocean acidification, cyclones, sediments, macroalgal competition, crown of thorns starfish predation, and chemical stressors such as nitrogen and herbicide exposure. Participants with expertise on climate and hydrological modeling derived conditional probability distributions of the physical and chemical stressors for the different climate scenarios. The qualitative AOP model, developed by ecotoxicologists based on literature searches, informed the development of a BN to quantitatively compare the effects of historic (1975–2005) and future projected climate on inshore hard coral bleaching, mortality, and cover. It was found that both climate- and catchment-related stressors pose a risk to these ecosystems, with projected increases in coral bleaching and coral mortality under all future climate scenarios. This modeling exercise can support the identification of risk drivers for the prioritization of management interventions to build future resilient reefs.

Case study 3: Chinook Salmon, Yakima River, USA. Landis et al. (2023) incorporated climate model projections downscaled to the Cascade region, information on pesticide application, and population modeling to predict risk to the protected Chinook salmon population in the Yakima River basin. The BN from Mitchell et al. (2021) was adapted by adding a climate change pathway for the region to predict changes in the 2050 and 2080 time ranges. The network's structure and input node values (pesticides, dissolved oxygen, temperature) were modified by a risk assessment and a BN analyst using domain expertise from a hydrologist and a climate change scenario expert. The three experts jointly identified the information sources and processing methods that best matched the case study region. This combination of modeling and domain expertise is important for BN structure development. Scenarios of pesticide application also considered a potential introduction of new pest species. Pesticide effects were modeled by the use of an acetylcholinesterase AOP built into the BN. An age-structured population model describing the metapopulation dynamics of the salmon was used to predict the abundance under different scenarios. The management goal for the Chinook population was to have net loss from the current abundance. The key driver in the model turned out to be the increase in temperature from climate change, with a lower contribution from the pesticide pathway. This study demonstrates the feasibility of incorporating direct effects of climate change and pesticide use to predict risk and to identify efficient management alternatives.

Chemicals management

Cains et al. (2023) discuss existing chemical management programs and introduce the conceptual framework of Environmental Management Cycles of Chemicals and Climate Change (EMC^4), a conceptual framework for the EMC^4. The framework considers that chemical management programs such as those under the United Nations Environment Program, among others, do not appear to consider the influence of climate change on the fate and effects of chemicals. They argue that explicit inclusion of climate change stressors can now be addressed, particularly given that the results from this workshop provide the tools to incorporate climate model projections into ecological risk assessments (e.g., Landis et al., 2023; Mentzel et al., 2023; Oldenkamp et al., 2023). Additionally, the EMC^4 highlights the roles and influence of interface and implementation actors, that is, decision-makers with a combination of motivation and means, to change, or reduce the production, emission, and/or exposure to chemicals of concern. The word *actor* is used here to underscore that *action* is needed to implement management strategies and policies.

The conceptual framework offers eight guiding assessment and management questions to help decision-makers identify chemical risks from climate change, management options, and, importantly, the different types of actors that are instrumental in managing that risk. Cains et al. (2023) use three examples of risk management at different spatial scales to answer the eight questions and illustrate the utility of the framework:

 DOI: 10.1002/ieam.4883

1) Global scale: Strategic approach to international chemicals management and pollutants from the lifecycle of textiles (e.g., pesticides, detergents, microplastics). Regional scale: Water quality management in compliance with the European Union Water Framework Directive (e.g., nutrients pollution in a catchment)
2) National/state or more local level: Legacy contamination management in South River, West Virgina, USA (e.g., methyl mercury, polyaromatic hydrocarbons, organochlorine pesticides).

Managing chemicals under a changing climate is a dynamic and open system where no one framework or policy will be the silver bullet. Cains et al. (2023) underscore that a coordinated effort is needed to understand and explain the relationship between chemicals and climate change on a global scale down to the local scale. The EMC^4 framework and guiding questions help facilitate the problem-scoping phase of risk analysis (assessment, management, communication) to establish an understanding of stakeholders' priorities, decision-makers' capacity, and the relationship between chemicals and climate change.

CONCLUSION

Workshop outcomes

This paper has summarized and highlighted the main outcomes of the workshop: a conceptual framework for chemicals management problem-scoping and accounting for climate change (Cains et al., 2023), a refined modeling approach for integrating climate model projections with environmental risk modeling (Moe et al., 2023), and three case studies for exploring this approach (Landis et al., 2023; Mentzel et al., 2023; Oldenkamp et al., 2023). Our case study models build upon previous attempts and experiences for linking climate projections with impact assessment, for example, from geosciences, hydrology, and catchment modeling. Based on the workshop participants' development of the risk management framework, elaboration of the modeling approach, and experiences from applying this to the three case studies, we draw the following conclusions.

1) We have proposed frameworks to build conceptual models and to calculate risk. Qualitative mechanistic information models such as AOPs can help refine conceptual models and causal pathways, to enable the development of more quantitative approaches.
2) Probabilistic methods such as BNs are promising for characterizing the outcome of climate models and for linking the resulting climate information to exposure, effect, and/or vulnerability of assessment endpoints. As a simpler approach, projected ranges of climate change with upper and lower limits can be compared to probability distribution functions or thresholds for effects to assess risks.
3) The development and comparison of the case studies have demonstrated that within the common modeling approach described by Moe et al. (2023), it is possible to incorporate climate model projections with associated uncertainty with multiple chemical and other environmental stressors, and multiple assessment endpoints, into different ecosystem types and under different climate and management scenarios.
4) Sensitivity analyses of the case studies have identified situations where climate change will be the major driver of risk to the selected assessment endpoint, overwhelming the signal from the effects of pesticides (Landis et al., 2023).
5) Society's adaptation to climate change is another potential driver of change in chemical exposure (e.g., increased use of pesticides), which may outweigh the direct effects of changed environmental processes (Oldenkamp et al., 2023). This driver will be difficult to quantify but can at least be considered in plausible scenarios.

Workshop objectives

The workshop successfully brought together experts from multiple scientific fields who contributed significantly to the developments presented here. Although some invited experts were hindered from on-site participation, their contributions were still enabled by the hybrid workshop format and the long preparatory phase. Combining expertise on climate modeling and impact assessment, such as this workshop, represents an important step towards breaking down the barriers to incorporating information on climate change into ecological risk assessments in national and international chemical management and climate adaptation programs.

Following this workshop, our approach to integrating climate and ecological risk has been improved with new insights from climate scientists, on aspects such as use of climate model ensembles, different approaches to downscaling, and further processing and use of climate information by statistical distributions. We conclude that traditional approaches to environmental toxicology and chemistry, developing regulations, and chemical management programs would benefit from such changes to account for the influence of climate change now and in the future.

In addition to this special series of papers and presentations in scientific meetings, the outcomes of this workshop have been disseminated to stakeholders such as national authorities (so far including Australia, Norway, United Kingdom, and the United States), IPCC lead authors, and the public through the recorded open SETAC Webinar, “Incorporating Climate Change Model Projections Into Ecological Risk Assessments to Help Inform Adaptive Risk Management Strategies” (https://vimeo.com/setac/review/877159519/fd4173a840).

AUTHOR CONTRIBUTION

Ralph G. Stahl, Jr.: Conceptualization; funding acquisition; project administration; writing—original draft; writing—review and editing. **Alistair B. A. Boxall**: Conceptualization; funding acquisition; writing—original draft. **Kevin V. Brix**: Conceptualization; funding acquisition; writing—original draft. **Wayne G. Landis**: Conceptualization; funding acquisition; writing—original draft; writing—review and editing. **Jenny L. Stauber**: Conceptualization; funding acquisition; writing—original draft; writing—review and editing. **S. Jannicke Moe**: Conceptualization; funding acquisition; project administration; visualization; writing—original draft; writing—review and editing.

ACKNOWLEDGMENT

The authors are indebted to our sponsors for contributing financial or in-kind support to the SETAC Pellston® Workshop, 20–24 June, 2022, at Oscarsborg Fortress near Oslo, Norway. The workshop was supported by the following companies and organizations: (1) BHP, (2) Chevron, (3) Corteva Agrisciences, (4) CSIRO, (5) International Copper Association, (5) NiPERA, (6) NIVA's Computational Toxicology Program, (7) Research Council of Norway, (8) Rio Tinto, (9) SETAC Asia/Pacific, (9) SETAC World Council, (10) Shell, (11) Teck Resources, and (12) the US Environmental Protection Agency. The authors also acknowledge the organizations who sponsored the travel costs and working time of the participants. The authors appreciate the practical support provided toward organizing the workshop by Oscarsborg Hotel & Resort, Strömberg & Sandell Audiovisual Solutions, and Samuel Welch. The authors also thank Sophie Mentzel for contributions to the figures, and Mariana Cains and John Carriger for comments on the manuscript.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

DISCLAIMER

The peer review for this article was managed by the Editorial Board without the involvement of S. Jannicke Moe.

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SUPPORTING INFORMATION

Examples of ecosystems with potential impacts of climate change on chemical risk, proposed by workshop participants.

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