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Citation for the original published paper (version of record):
Cains, M., Desrousseau, A., Boxall, A. et al (2024). Environmental Management Cycles for Chemicals and Climate Change, EMC4: A new conceptual framework contextualizing climate and chemical risk assessment and management. Integrated environmental assessment and management, 20(2): 433-453. http://dx.doi.org/10.1002/ieam.4872

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Received: 21 July 2023 | Revised: 24 October 2023 | Accepted: 6 November 2023

Environmental Management

Environmental management cycles for chemicals and climate change, EMC^4: A new conceptual framework contextualizing climate and chemical risk assessment and management

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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 environmental management cycles for chemicals and climate change (EMC^4) is a suggested conceptual framework for integrating climate change aspects into chemical risk management. The interaction of climate change and chemical risk brings together complex systems that are imperfectly understood by science. Making management decisions in this context is therefore difficult and often exacerbated by a lack of data. The consequences of poor decision-making can be significant for both environmental and human health. This article reflects on the ways in which existing chemicals management systems consider climate change and proposes the EMC^4 conceptual framework, which is a tool for decision-makers operating at different spatial scales. Also presented are key questions raised by the tool to help the decision-maker identify chemical risks from climate change, management options, and, importantly, the different types of actors that are instrumental in managing that risk. Case studies showing decision-making at different spatial scales are also presented highlighting the conceptual framework's applicability to multiple scales. The United Nations Environment Programme's development of an intergovernmental Science Policy Panel on Chemicals and Waste has presented an opportunity to promote and generate research highlighting the impacts of chemicals and climate change interlinkages. *Integr Environ Assess Manag* 2023;00:1–21.

KEYWORDS: Chemicals management; Climate change; Ecological risk assessment; Management implementation; Regulatory approaches

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Published 4 December 2023 on wileyonlinelibrary.com/journal/ieam.

INTRODUCTION

Introduction to chemical pollution

In 2022, it was estimated that the value of global production, shipping, and trade in chemicals was US $5.7 trillion, with Asia-Pacific, Europe, and North America accounting for the bulk of this figure (American Chemistry

Council, 2023). While the chemicals industry has brought large benefits to modern lives (e.g., advances in the development of medicines, detergents, lubricants, and cosmetics), the use of chemicals has the potential to negatively impact the natural environment and human health (Fuller et al., 2022). Examples of known negative impacts include persistent perfluorinated compounds causing liver damage in rodents (Costello et al., 2022); toxic pesticides contributing to global insect declines (Forister et al., 2019; Sánchez-Bayo & Wyckhuys, 2019); endocrine disruptors (e.g., oral contraceptive pills, bisphenol A) causing feminization and potential infertility of fish populations, even in sites far from urban areas (Harris et al., 2011; Jarque et al., 2015); anti-inflammatory pharmaceuticals devastating populations of vulture species in areas of India and Pakistan (Oaks et al., 2004); and nonpoint-source agricultural pollution contributing to eutrophication of waterbodies (European Environment Agency [EEA], 2018; Grizzetti et al., 2017).

Global policy analysis studies highlight that the historical and current chemical production and use burdens the earth's physical capacity for chemical pollution and outpaces our technical capacity for chemical and toxicological analyses, thus threatening ecosystems and human viability (Diamond et al., 2015; MacLeod et al., 2014; Persson et al., 2022). Therefore, it is imperative that the effects of climate change on chemical pollution, toxicity, and ultimately risk are assessed to understand the global, regional, and local actions necessary for the management of chemical risk in a changing climate.

Landscape of chemicals management systems

Multiple chemicals management systems exist to limit and manage chemical pollution, including regulatory, policy, and voluntary systems. At the world scale, the Inter-Organization Programme for the Sound Management of Chemicals (IOMC) attempts to strengthen international cooperation on chemicals issues and supports national decision-making through the IOMC toolkit (Inter-Organization Programme for the Sound Management of Chemicals, 2021; World Health Organization [WHO], 2023), the Stockholm Convention regulates persistent organic pollutants (Stockholm Convention, 2001), the Rotterdam Convention (1998) promotes prior informed consent for exporting listed chemicals, and the Minamata Convention regulates mercury (WHO, 2021). Examples at the regional scale to legislate the manufacture, import, distribution, use, and disposal of various types of chemicals include the European Union (EU) Registration, Evaluation, and Authorization of Chemicals legislation (European Parliament, 2023) and in the United States, the Toxic Substances Control Act (TSCA; USEPA, 2020). Systems are also in place for specific types of substances and pollution issues on a national scale, for example, a series of United Kingdom contaminated land regulations identify and remediate chemicals on land in the UK. Through voluntary mechanisms, various organizations and company groups establish agreements and systems to control the manufacture and use of chemicals. For example, the Antimicrobial Resistance Industry Alliance (AMRIA) promotes responsible antibiotic manufacturing to reduce environmental contamination from these substances and help suppress the selection of antimicrobial resistance (AMR Industry Alliance, 2022).

These are a few examples from the complex landscape of chemicals management approaches that have been developed over the last century (Christensen et al., 2011; Lönngren, 1992; Teran et al., 2012). Table 1 presents a nonexhaustive list of these systems, providing examples at different ranges of legal coverage, chemicals targeted, and geographic reach, all aimed at meeting their respective protection goals vis-à-vis potential effects of chemicals.

Depending on the protection goals of each management system or framework, chemicals are evaluated, characterized, and handled in different ways and at different lifecycle stages of a chemical. The evaluation process relies on existing information and toxicological and ecotoxicological data regarding chemical characteristics, toxicity, and exposure. If research suggests that a substance's hazard or risk will affect the protection goal of a system, then the substance's environmental risks or hazards will be managed in the manner outlined by the system and/or framework. There is, however, a factor of growing importance largely ignored within these chemicals management systems that affects the management and impacts of chemicals at every stage of a product's life cycle, namely, climate change.

Lack of climate change inclusion in chemicals management systems

Climate change and chemical emissions are tightly intertwined. Climate change, for example, is likely to cause increases in cardiovascular disease and respiratory illnesses, with corresponding increases in pharmaceutical usage (Redshaw et al., 2013). Wastewater treatment plants will see more demand for the reuse of their wastewater, the need to cope with increased flooding, sewer overflows, and a lack of freshwater for dilution (Zouboulis & Tolkou, 2014). Similarly, chemical technology development, production, usage, and consumption increase ozone depletion, increase carbon dioxide emissions, and alter environmental services (McKenzie et al., 2011; Naidu et al., 2021; Thonemann, 2020). The interactions between climate change and chemical emissions are further explained in the section "Implications of climate change for chemicals management."

Even though concerns over the links between climate change and chemical risk are being highlighted by researchers, conventions and strategic initiatives around climate and chemicals are siloed. For example, the UN Framework Convention on Climate Change tends to ignore implications for chemical pollution, while the voluntary Strategic Approach to International Chemicals Management (SAICM) overlooks the impacts of climate on chemical risks (Strategic Approach to International Chemicals Management, 2019). The same is true for the sixth and most recent Intergovernmental Panel on Climate Change assessment report and its predecessors (Intergovernmental Panel on Climate Change [IPCC], 2021,

TABLE 1 Curated list of chemicals management scenarios and corresponding compliance characteristics

Management scenarios	Management systems	Responsible agency	Compliance commitment	Chemicals and/or pollutants covered	Protection goal and approach	Implementation scale
Management of global chemical pollution	Stockholm Convention (2001)	United Nations Environment Programme (UNEP)	Regulatory; legally binding	Persistent organic pollutants (POPs)	Reduce global pollution of persistent organic chemicals by helping parties to phase-out production and products with POPs	Global scale
	Basel Convention (1989)	UNEP	Regulatory; legally binding	Hazardous chemicals and hazardous waste	Control on trades of hazardous chemicals between countries and the promotion of environmentally friendly chemicals	Global scale
	Rotterdam Convention (1998)	UNEP	Advisory and facilitation service; legally binding	Pesticides and industrial chemicals that have been banned or severely restricted	Facilitate government decision-making with the promotion of information exchange (prior informed consent) for listed hazardous chemicals	Global scale
	Minamata Convention (WHO, 2021)	UNEP	Regulatory; legally binding	Mercury	Places controls on or bans all uses of mercury during production, use, and disposal	Global scale
	Strategic Approach to International Chemicals Management (International Conference on Chemicals Management [SAICM; ICCM], 2006). Beyond 2020 framework	UNEP	Advisory and facilitation service; voluntary	POPs, plastics pollutants, metals, emerging policy issues, chemicals of concern, highly hazardous pesticides, etc.	Agrees targets and provides guidance for signatories to minimize harm from chemicals during production, use, and disposal	Global scale
	Chemicals Road Map (WHO, 2017)	World Health Organization (WHO)	Advisory; road map guidance	All chemicals and waste	Provides roadmap of actions where the health sector plays a role in the multisector management of chemicals	Global and multiscale
	International Code of Conduct on Pesticide Management (WHO, 2014)	Food and Agriculture Organization (FAO); WHO	Advisory guidelines; voluntary	Pesticides	Provides guidelines (including criteria for identifying highly hazardous pesticides) for governments, industry, and civil society on best practices to reduce health and environmental impacts around a life-cycle approach	Global scale

(*Continued*)

DOI: 10.1002/ieam.4872

TABLE 1 (*Continued*)

Management scenarios	Management systems	Responsible agency	Compliance commitment	Chemicals and/or pollutants covered	Protection goal and approach	Implementation scale
	Inter-Organization Programme for the Sound Management of Chemicals (IOMC; WHO, 2023)	Rotating agency lead	Advisory; roadmap guidance	All chemicals and waste	A nine United Nations Agency that provides facilitating, coordinating, and capacity building on the sound management of chemicals	Global scale
	Global Assessment of Air Pollution Legislation (GAAPL; UNEP], 2021)	UNEP	Legislation	Air pollutants	Provides recommendations to strengthen air quality governance as well as guides countries to effectively address air pollution	Global scale
Management of regional pollution EU	Mediterranean Action Plan (MAP; UNEP, 2023)	UNEP	Advisory and facilitation service	Harmful chemicals and waste	Protect the Mediterranean Sea from pollution and obtain a clean and sustainable Mediterranean Sea environment	Mediterranean countries
	Registration, Evaluation, Authorization and Restriction of Chemicals (REACH; European Parliament, 2023)	European Union (EU) member countries competent authorities	Legislation	Industrial chemicals	To protect human health and the environment by the registration, evaluation, authorization, and restriction of chemicals prior to entering the market	EU countries
	Toxic Substances Control Act (TSCA; USEPA, 2020)	Environmental Protection Agency (EPA)	Legislation	Multiple types of chemicals	To protect the public from unreasonable risk of injury to health or the environment by the regulation of the manufacture, import, distribution, use, and disposal of new and existing chemicals in US commerce	USA
	Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA; USEPA, 2023b)	EPA	Legislation	Insecticides, fungicides, rodenticides	To ensure that pesticides will not cause unreasonable risk to human health or the environment by the governance of the registration, distribution, sale, and use of pesticides	USA
	European Chemicals Agency (ECHA; European Chemicals Agency, 2023)	EU Commission	Regulatory	Multiple types of chemicals	For the safe use of chemicals to benefit human health, the environment and innovation	EU countries

(*Continued*)

TABLE 1 (*Continued*)

Management scenarios	Management systems	Responsible agency	Compliance commitment	Chemicals and/or pollutants covered	Protection goal and approach	Implementation scale
					and competitiveness in Europe by legislation	
	Convention for the Protection of the Marine Environment of the North-East Atlantic (1992 OSPAR Convention, 2007)	OSPAR Commission	Legislation	Hazardous substances	To protect the marine environment of the North-East Atlantic by the adoption of decisions, which are legally binding on the contracting parties, recommendations, and other agreements	Marine environment of the North-East Atlantic
	EU Ambient Air Quality Directives (European Commission, 2023a)	EU Commission	Legislation	Air pollutants	To protect human health and the environment from the harmful effects of air pollution	EU countries
Management of local pollution	EU Water Framework Directive (European Parliament, 2000)	EU Commission	Legislation	Multiple types of chemicals (in total 45 priority chemicals)	To achieve good status for all waterbodies. This comprises the objectives of good ecological and chemical status for surface waters and good quantitative and chemical status for groundwater	EU countries
Management of contaminated sites (domestic and regional regulations)	Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA; USEPA, 2017); Resource Conservation and Recovery Act (RCRA; USEPA, 2023a)	EPA	Legislation	Solid waste and hazardous waste, and remediation of contaminated sites	For the proper management of hazardous and nonhazardous solid waste by law and by the waste management program, and remediation of contaminated sites	USA
	EU Soil Strategy (European Parliament, 2021)	EU Commission	Legislation	All chemicals and waste	To protect and sustain use of soil by preventing further soil degradation, preserving its functions, and restoring degraded soils to a level of functionality consistent at least with current and intended use, thus also considering the cost implications of the restoration of soil	EU countries

(*Continued*)

TABLE 1 (*Continued*)

Management scenarios	Management systems	Responsible agency	Compliance commitment	Chemicals and/or pollutants covered	Protection goal and approach	Implementation scale
Management of water quality in a catchment	Domestic and regional regulations (e.g., EU Water Framework Directive)	EU Commission	Legislation	Currently 45 chemicals (metals, pesticides, pharmaceuticals)	To ensure good ecological status of aquatic systems by regulatory controls and the development of diverse programs for river restoration for the removal of barriers to fish migration or for the reduction of diffuse pollution	EU countries
Environmental impact assessment/strategic environmental assessment (SEA) of new developments	EU Environmental Impact Assessment (EIA; European Parliament, 2014) and Strategic Environmental Assessment (SEA; European Parliament, 2018) Directives	EU Commission	Legislation	Certain public and private projects (airports, nuclear installations, railways, roads, waste disposal installations, wastewater treatment plants, etc.)	To ensure that projects that are likely to have a significant impact on the environment are identified and assessed, within an appraisal process, before these projects proceed to development	EU countries
Management strategies by Industry	Antimicrobial Resistance Industry Alliance (AMRIA) Safe Manufacturing Framework (AMR Industry Alliance, 2022)	AMRIA	Advisory	Antibiotics, pesticides, industrial chemicals	To promote responsible antibiotic manufacturing	Industry
Management of agricultural pollution	Nitrate Directive (European Parliament, 1991)	EU Commission	Legislation	Nitrate	To reduce nitrate used in agriculture by establishing codes of good agricultural practices and developing measures to prevent and reduce water pollution	EU countries

2023). If we are to continue to benefit from the use of chemicals under a changing climate while not harming the natural environment, climate change should be explicitly factored into chemical risk assessment and management practices to evaluate and manage the interlinkages between chemicals and a changing climate and environment.

Aim

The aim of this article, therefore, is to explore the implications of climate change for different chemicals management practices. It also provides recommendations on how these practices could and should be adapted moving forward to ensure sustainable use of chemicals into the future. We present a discussion on how climate change impacts can be incorporated into chemicals management. A conceptual framework is presented to guide the reader through understanding the causal pathway integrations with risk assessment and risk management. This article also provides three case studies of where a changing climate will impact the stated goals of chemicals management frameworks. The presented framework also offers a structure to help decision-makers incorporate climate science into their decision-making. Where tools and techniques exist to support this process, these are highlighted. Where gaps exist in the tools needed to support decision-makers, these are similarly highlighted along with suggestions on how these could be filled.

This article is part of a series (Landis et al., forthcoming; Mentzel et al., forthcoming; Moe et al., forthcoming; Oldenkamp et al., 2023; Stahl et al., forthcoming) produced at a Society of Environmental Toxicology and Chemistry Pellston® workshop in June 2022. The workshop goal and, more specifically, this article was to address the concern that potential environmental and ecological impacts associated with a changing climate were not being considered in national or international chemicals management processes.

IMPLICATIONS OF CLIMATE CHANGE FOR CHEMICALS MANAGEMENT

Climate change and associated adaptation approaches will affect how chemicals are emitted and behave in the environment as well as the characteristics of receiving environments and the sensitivity of receptors to exposures. These effects have been reviewed in detail in a range of publications (e.g., Balbus et al., 2013; Boxall et al., 2009; Hader et al., 2022).

Reductions of chemical risks due to climate change can be foreseen. For example, a move away from fossil fuels, in response to climate change, will result in a reduction in emissions of hydrocarbons from spills and combustion processes. The associated decline in the availability of oil-based feedstocks is already resulting in a move toward more biologically based chemicals in products produced by different sectors, which may be less toxic to receptors, and more research is needed to fully understand toxicity. Additionally, increases in temperature may reduce the persistence of some chemicals within the environment under certain conditions (e.g., pesticide degradation in warmer conditions; Bailey, 2004). Conversely, warmer conditions could negative affect microbiological communities needed for chemical biodegradation (Bogdal & Scheringer, 2011).

Most changes, however, will increase chemical risk. In terms of chemical use, several scenarios can be foreseen. For example, increases in plant, animal, and human disease pressures will require increased use of pesticides, veterinary medicines, and pharmaceuticals (e.g., Boxall et al., 2009; Redshaw et al., 2013). Increasing dry and hot periods, which are predicted to increase under climate change (IPCC, 2021, 2023), may result in increased emissions and ecotoxicity of chemicals used in personal care products, such as chemical sunscreens interacting with higher-salinity water (Diffey, 2003; Neale et al., 2023). Additionally, the dilution of effluents and runoff will be reduced, thus increasing chemical concentrations, while increase of precipitation and/or intensity of rainfall events in some regions could provide higher nutrients loadings in certain catchment areas, which, together with an increase in temperature, could trigger eutrophication processes. In forested areas, increases in fires will result in an increase in volatile organic compound emissions and particulate matter (Jaffe et al., 2020) and the release of polyfluoroalkyl substances (PFAS) from use of fire suppression foams and wetting agents (Mejia-Avendaño et al., 2017). Increases in temperature will also alter the bioaccumulation, persistence, and volatility of chemicals (Bailey, 2004; Tao et al., 2017).

Flooding events, sea-level rise, and increased erosion will mobilize contaminants, such as metals and persistent organic compounds contained in dump sites and other contaminated sites, in turn establishing new pathways by which they can affect biological receptors (Brand et al., 2018). Existing wastewater treatment infrastructure will not be able to cope with the large volumes of surface runoff from extreme rainfall events, resulting in an increase in untreated emissions from combined sewer overflows (Esteve-Selma et al., 2016).

These alterations will have important implications for chemical risk managers working at the global, national, local, and site-specific scales. In Table 2, we select previously described chemicals management scenarios and highlight some climate-driven changes that are likely to be relevant for that scenario. We also consider the potential implications of a selection of adaptive and mitigation responses to climate and explore the impacts of these on chemical risks in the environment. The take-home message from Table 2 is that if we are to protect ecological and human health in the future:

1. those responsible for chemical risk management need to incorporate climate change into their assessment frameworks and ask the question, "Will climate change alter the use, emissions, fate, exposure, and effects of chemicals in the system I am managing?"; and
2. those responsible for policies to mitigate and adapt to climate change need to consider chemical risk in their decision-making processes and ask the question "will the mitigation/adaptation approach that I am evaluating or proposing have any unforeseen consequences in terms of chemical risks to the environment?"

TABLE 2 Implications of climate change for global through to highly localized environmental management scenarios from a chemical impacts perspective

Management scenarios	Scale	Approach used	Implications of and responses to climate change from a chemical impact perspective	References
Minamata Convention	Global	• Ban on new mercury mines, the phase-out of existing ones, the phase-out and phase-down of mercury use in a number of products and processes. • Emissions to air, land, and water are controlled. • Regulations of artisanal and small-scale gold mining. • Considers interim storage and disposal of mercury and sites contaminated by mercury.	• The speciation of mercury at a site will be altered due to increases in the incidence of flood events and sea-level rise. • The connectivity of key ecological and human receptors to sources of mercury will alter due to extreme events (e.g., natural disasters, industrial accidents).	World Health Organization (2021)
Development of a contaminated land register for a country	National	• Data on previous site use, used to identify whether a site is potentially contaminated. • Monitoring of sites performed to determine level of contamination and these data compared to threshold values or to assess risks to controlled waters.	• Increase in frequency and magnitude of flood events or sea-level rise, resulting from climate change, could create new pathways to aquatic systems and require classification of sites to be reconsidered.	Hypothetical scenario
Development of a national policy to move away from fossil fuels toward a renewable source of energy	National	• Driven by national targets on greenhouse gas emissions as well as air quality targets and political drivers (e.g., Russo-Ukrainian War). • Country typically sets targets to reduce use within certain time scales. • A range of options used, including move toward renewables. • Other than traditional air quality indicators, chemicals not considered.	• Move away from oil results in fewer hydrocarbon emissions from spills and combustion. • Move toward plant-based industrial feedstocks results in new chemistries in household and other products. • Replacement sources of energy, such as photovoltaics, nuclear, wind, and biofuels results in new sources of chemical emissions and increases the emissions of some chemical types. • Electrification of vehicles increases the emissions of metals and tire particles in local low-emission zones.	European Commission (2021)
Evaluation of a new pesticide as part of the marketing authorization process	National	• Data on application rate, use characteristics, and environmental fate used in models alongside scenarios of weather, soil characteristics to estimate exposure concentrations. • Data from ecotoxicity studies used alongside safety factors to establish a "safe" concentration for the pesticide (e.g., a PNEC). • Exposure concentrations are compared with "safe" concentrations to assess whether use is acceptable or not.	• Scenarios for weather, soil properties, and soil parameters will be different from current scenarios. • Climate change will alter the fate characteristics (e.g., biodegradation rate) of the pesticide. • Transport pathways not currently considered, for example, flooding, will become more important. • Sensitivity of receptors to the pesticide will be altered due to changes in temperature.	Hader et al. (2022)

(Continued)

TABLE 2 (*Continued*)

Management scenarios	Scale	Approach used	Implications of and responses to climate change from a chemical impact perspective	References
Meeting the requirements of the nitrates directive	National	• Identifying waterbodies affected by nitrates pollution from agricultural origin. • Monitoring nitrate concentration in those waterbodies. • Designating as vulnerable those areas in which drainage leads to nitrate pollution. • Developing action measures regarding agricultural activities, for example, applying regulations regarding fertilizer application, including manure from livestock.	• Nitrate loads and/or concentrations might increase: waterbodies ecological status and water quality for consumption threatened. • Vulnerable areas might change and alter exposure. • Uncertainty about future fertilizer use, which will ultimately depend on the socioeconomic pathway followed: might increase (market-driven agriculture) or decrease (agriculture for nature).	European Parliament (1991), Molina-Navarro et al. (2018)
Development of a river basin management plan to achieve good status and/or potential in waterbodies as part of the WFD	Catchment	• Monitoring of biological, hydromorphological, and chemical indicators to determine status. • Identification of pressures and mitigation approaches to achieve good status. • Implementation of measures.	• Changes in land use and chemical use in response to climate change will affect chemical emissions into the catchment. • Changes in temperature and hydrology will affect the transport and fate of chemicals in the catchment and subsequent exposure to chemicals. • Changes in community structure will affect the sensitivity of communities in the catchment to chemicals exposure. • Interactions of chemicals with co-stressors will become more important (e.g., pesticide exposure and habitat alterations). Changes in water demand for multiple uses will affect the chemical processes in the catchment and the exposure of ecosystems and human targets.	European Parliament (2000), EEA (2018), Molina-Navarro et al. (2014), Mack et al. (2019), Molina-Navarro et al. (2020)
Development of city policy to meet zero carbon	Local	• Multiple options, such as a move to renewable energy sources, electrification of transport, and insulation of buildings.	• Emissions of polycyclic hydrocarbons, nitrogen oxides, particulates reduced in the city. • Increase in traffic, due to electrification of vehicles, in areas currently designated as low-emission zones will result in higher emissions of tire particles and metals. • Lithium mining to produce vehicle batteries will cause wider impacts in areas not currently affected by pollution.	Pineda et al. (2020)

(*Continued*)

TABLE 2 (*Continued*)

Management scenarios	Scale	Approach used	Implications of and responses to climate change from a chemical impact perspective	References
Selection of treatment methods for antibiotics emissions from a factory as part of AMRIA good management practice	Site-specific	• Target values are set for an antibiotic based on tests with bacteria and cyanobacteria. • Information on production volumes, cleaning, and so forth used to calculate emissions to the environment, which are then combined with flow data to estimate exposure. • Results are used to inform mitigation options.	• Changes in flow resulting from climate change will alter exposure concentrations. • Changes in environmental conditions could affect the sensitivity of microbes to antibiotics.	AMR Industry Alliance (2022)
Performance of an EIA procedure for a new municipal landfill	Site-specific	• Data on ecology, hydrology, hydrogeology, pedology, geomorphology, and current and future receptors (humans, ecosystems, crops and livestock, heritage) used to assess whether the proposed site is likely to cause impacts or not. • Impact mitigation measures proposal and designing of a monitoring program to prevent and/or correct eventual pollution events.	• Increase in frequency and magnitude of flood events or sea-level rise, resulting from climate change, could increase exposure of receptors. • Human receptors could become more sensitive to the chemical exposure due to interactions with other stressors (e.g., temperature). • Sensitivity of ecological receptors could be altered due to changes in temperature.	European Parliament (2012), European Parliament (2014), Granero Castro et al. (2015)

Abbreviations: AMRIA, Antimicrobial Resistance Industry Alliance; EIA, Environmental Impact Assessment; PNEC, predicted no-effect concentration; WFD, Water Framework Directive.

3. both groups need to consider the fundamental material connections between petroleum exploitation for use in the energy system, the use of petroleum-derived products as feedstock for the production of chemicals, and the role played by resulting emissions in worsening climate change.

Both chemical policy developers and climate policy developers need to coordinate efforts to optimize the mutual benefits (i.e., co-benefits) of any adaptation or mitigation approaches in the chemical and climate policy areas and to ensure that there are no detriments for the other sector. In the section "Decision and implementation deficit," we propose an overarching conceptual framework that risk managers could use to consider climate change and chemical interactions for different management scenarios and illustrate the approach using three contrasting scenarios covering a range of scales and both a conceptualization of and framing chemical and climate change management and implementation.

Decision and implementation deficit

Both the climate and the way in which society uses chemicals are changing rapidly; thus, flexibility is needed in addressing climate and chemical issues. Chemicals management performed within a multilevel governance understanding (e.g., global, regional, national, and subnational; Geels, 2011), in addition to the combined challenges of climate and increasing production and resulting emissions, exposures, and effects of chemicals, requires management systems that can adapt to the challenges presented by changing technologies, ecosystems, and societal structures. As seen in Table 1, many management frameworks and strategies exist; yet, why are they not working? Where is action needed? Previous research highlights the lack of identification of actors (e.g., Persson, 2019). To address the impacts of climate change on chemicals management and chemicals on climate change, we need to move beyond decision-makers *initiating* actions such as strategies, policies, and standards to the identification and appointment of "*doers*" who will implement the identified mechanisms and follow up on outcomes of actions taken.

Conceptual framing for change and action implementation

We present a conceptual framework developed to guide chemical and climate change decision-makers on the implications of climate change for current chemicals management strategies such as those summarized in Table 1. This framework, environmental management cycles for chemicals and climate change (EMC^4), illustrates the flow of information and interactions between components of the assessment, management, and implementation processes (Figure 1) and builds on following existing management (nonanalytical) approaches such as

- Driver-Pressure-State-Impact-Response (DPSIR, environment focus; EEA, 1999; Patrício et al., 2016),
- the Driving force-Pressure-State-Exposure-Effect-Action (DPSEEA, environmental health focus; Corvalán et al., 1999; Edokpolo et al., 2019), and
- the adaptive management framework (Van den Brink et al., 2016; Cains & Henshel, 2021).

To strengthen and emphasize the monitoring and implementation needed to improve on current chemicals management, while highlighting the key chemicals and climate change actors (e.g., decision-makers), it is important to identify which actors are in a position to give the directive for developing, initiating, and physically implementing strategies and laws. The purpose of this conceptual framework (Figure 1) is to provide a tool to identify actors and options for chemicals management. Furthermore, it can lead to recommendations for different actors on how to incorporate monitoring and adaptive management approaches for sustainable design, production, use, and disposal of chemicals in the context of climate change. This conceptual framework is scalable and adaptable as it considers the different levels of chemicals management (e.g., global, national, regional, local) and the actors (e.g., intergovernmental organizations, governments, nongovernmental organizations, industry, academia) within these policy arenas.

Changes in externalities. From the perspective of an adaptive management cycle, externalities (i.e., contexts) are properties and characteristics of a system that are beyond the purview or scope of the decision-makers' or managers' governance. Some things cannot be changed or are perceived as being constant. For example, climate change is an external factor to the scope of impact for city-level governance; the sustainability management practices of one city or one chemical facility cannot directly affect climate change on a global scale but only provide a small contribution toward mitigation and adaptation. Thus, climate change is an externality of the environmental management cycles for any single actor. Building from the DPSEEA and DPSIR models, climate change is both an impact and driving force producing causes and giving effects that need considerations for chemical risk management strategies. Driving forces of climate change include but are not limited to emissions, technology, lifestyles, economics, social issues, political contexts, and institutional structures.

Risk assessment. To effectively manage chemicals risk, it is crucial to establish the link between risk assessment data and the implementation of risk management strategies. The process of risk assessment can help decision-makers and managers understand how externalities and driving forces are affecting their system of interest (e.g., chemical manufacturing, watershed, species in ecosystems). The problem formulation and scoping step of risk is foundational in establishing the scope, context, stressors, and criteria specific to the decision-makers' and risk managers' decision space (Cains & Henshel, 2021; Suter et al., 2003). Traditionally, risk assessments have focused on a single stressor, such as a

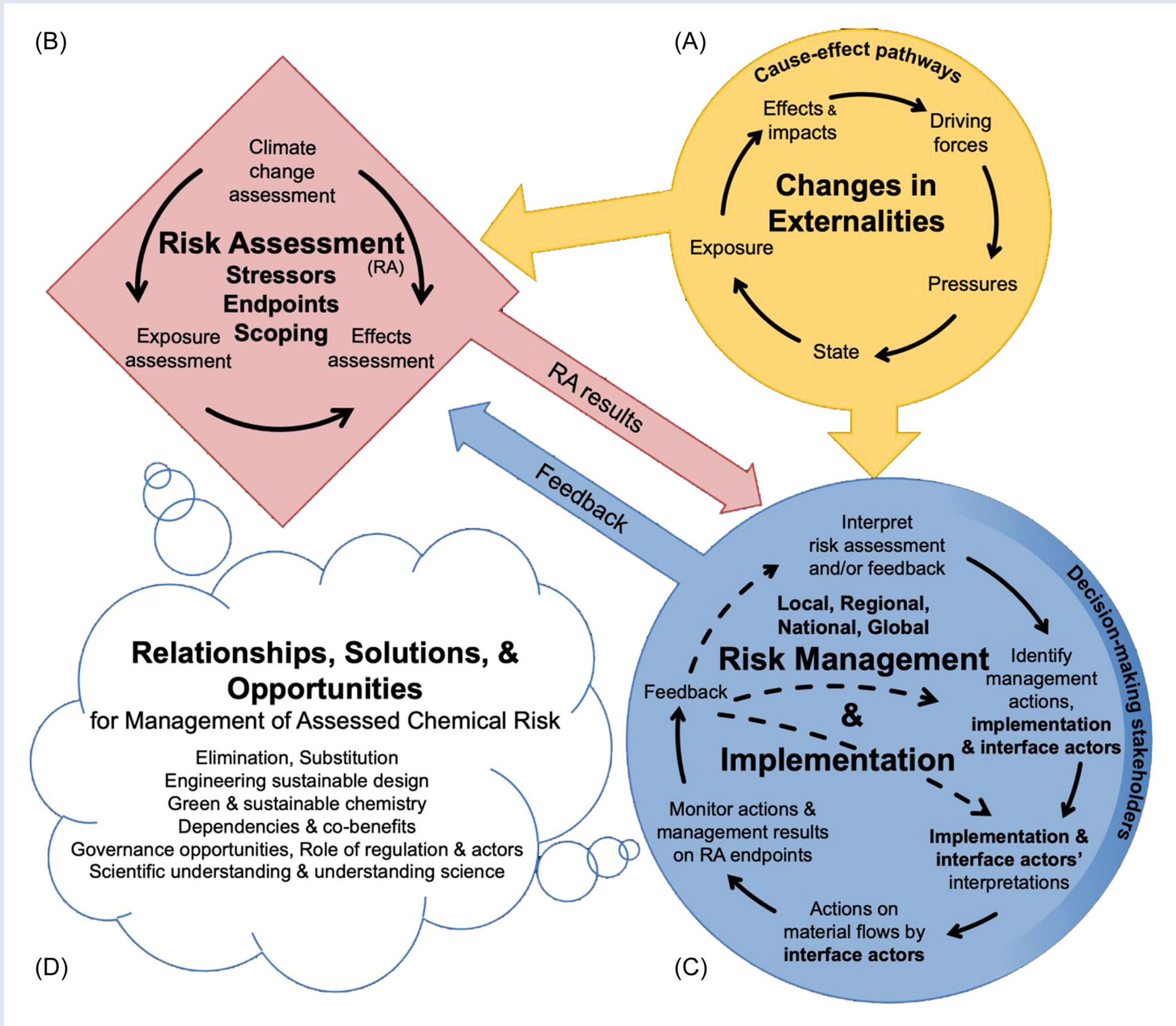

FIGURE 1 Environmental management cycles for chemicals and climate change (EMC[4]): The framework includes several feedback cycles, and linkages between and within subsystems, since learning and adaptation are key processes for the actors involved. The EMC[4] framework connects (A) changes in externalities for climate and chemicals; (B) risk assessment; (C) risk management and implementation; and (D) relationships, solutions, and opportunities. The solid arrows signify the flow of information from one stage to another. The dashed arrows in (C) signify the feedback of information into previous stages

chemical of interest (e.g., assessment under TSCA and FIFRA; National Research Council, 1983, 2009). However, such an approach limits the ability to understand the interaction between chemicals and climate change. Given that climate change is a "threat multiplier" (Goodman & Baudu, 2023), a multistressor risk assessment approach (not just multichemical) is suggested to characterize the multifaceted ways in which physical stressors caused by climate change can affect and have affected the physical, chemical, and toxicological characteristics of chemicals in the environment (e.g., Hering et al., 2015). In addition to interactions between climate change impacts and chemical properties, both types of stressors have the ability to increase the vulnerability of susceptible endpoints. For example, honeybee research has theorized increased susceptibility to compounding stressors due to climate change (Le Conte & Navajas, 2008). Research has found that some pesticides reduce colony survival, which can be further compounded by reduced queen bee fertility caused by temperature extremes (Cunningham et al., 2022).

Risk management and implementation. Risk management requires decision-makers and managers to interpret risk assessment results and transform them into actional management strategies. Risk management also needs to follow up on earlier actions and learn from experiences in a feed-back loop. The translation from assessment to management furthermore needs to be able to identify options and actors (e.g., decision-making and implementing stakeholders) in detail at each level. Such a process should identify various types of actors, together with their motivations and possibilities to act during various steps of implementation.

The suggested conceptual framework distinguishes between "decision-making stakeholders," "interface actors," and "implementation actors," while outlining their possible actions. The word *actor* is used here to underscore that *action* is needed to implement management strategies and policies, while the word *stakeholder* only conveys that someone has a *vested interest*. Interface actors and implementation actors are both decision-making stakeholders, but not all decision-making stakeholders are tasked with the responsibility or the ability to implement action. A key requirement of management strategies is the conceptualization of differences between actors regarding their capacity to perform actions, that is, actions that influence changes of relevance regarding the material flows (i.e., multistep process to transform raw materials into a final product; Brunner & Rechberger, 2016) leading to emissions and exposures. Not all actors can *de facto* change the material flow of concern. The ones who can do it we call "interface actors." They are the actors that have a combination of motivation and means, to change, or reduce, the particular material flow(s) of concern. It can be a question of closing a valve or buying and using a chemical substitute for a troublesome substance or to use less in a particular situation.

We motivate the use of "interface actors" (following Wallin, 2014) by distinguishing specific actors that do have the capacity to take specific decisions and actions that affect the material's flow over the interface between the sociotechnical and ecological subsystems (i.e., human activities that affect the environment). A reason for thinking in terms of an interface between these two subsystems is that as long as substances (e.g., fluorinated compounds) and materials (e.g., crude oil) are within the sociotechnical subsystem, they can potentially be controlled by human actions (e.g., by circular material handling systems). When substances are emitted into the environment, this control is mostly completely lost, or at least drastically reduced. An example is contaminated soil, where earlier ways of disposal, like burying materials in the ground, or a sloppy use of substances at a site, have resulted in slow and long-time dispersal of contaminants into surrounding areas. These contaminations are sometimes possible but difficult and costly to retake control over.

Activities on various governmental or corporate levels do not directly change material flows but are intended to influence other actors in an often incomplete chain of actors and/or activities to reduce or in other ways change material flows with the final aim of reducing emissions and exposures, thus foregoing unwanted impacts on human health and the environment. "Implementation actors" are hardly able to make decisions that directly influence a material flow, but they might have possibilities to incentivize (or disincentivize) other actors within their own organization or even other organizations. Since human organizations mostly are hierarchical, several levels of organization may need to be involved to stepwise move information, motivations, and responsibilities, the whole way from implementation to interface actors. We foresee a rather detailed analysis to identify interface actors, together with mechanisms to influence their behavior. In conjunction with the implementation and interface actors, a wider set of "decision-making stakeholders" can be identified. In this group of actors, we may find industrial organizations, nongovernmental organizations, and media. In some cases, ordinary households also occur in this group, while they often can be regarded as "interface actors" having the direct influence over the release of substances into the environment.

Interface actors can occur at different levels in the organizations operating in product chains handling chemical substances, chemical mixtures, materials, and products that might find their way into the environment. Often, concerted actions within organizations are needed to change material flows and reduce emissions of particular substances. Furthermore, long-term activities (e.g., product design, design of industrial production systems, and the construction of supply chains) are important to achieve substantial emission reductions, even if indirectly related chemical production and use.

Relationships, solutions, and opportunities. A large set of background information regarding the relations between actors is of importance together with an extensive understanding of the relationships, solutions, and opportunities that exist regarding chemicals management and climate change. Basically, chemicals managers need to consider more deeply the interconnectedness between chemical production, use, and management decisions and their possible effects on climate change. Chemical production is reliant on feedstocks derived from petroleum, which is the common source for fossil fuels. Larger changes related to elimination, substitution, or changes regarding fuel production and feedstocks will have repercussions in the chemical industries and likewise, application of various engineering solutions, less toxic and sustainable chemistry insights will lead to changes of material flows and emissions.

Various dependencies (e.g., supply chain) and possible mutual benefits from changes in chemical production and use need consideration and will most likely influence what management options are seen as acceptable, given the numerous priorities influencing decision-making stakeholders (e.g., managers, producers, lawyers). The role of governance and potential opportunities for chemicals management also need a more holistic approach (e.g., managing the whole of an affected system rather than a stressor source) to make possible the larger changes in material flows that are needed to meet climate challenges. Furthermore, a scientific understanding of the various steps and information needs in designing effective chemicals management is crucial, as well as the interplay between science and management; thus, further development of panel actors is important and needed.

CASE STUDY APPLICATION OF EMC^4

We developed eight guiding assessment and management questions that risk assessors and risk managers should ask themselves to better understand how climate change will affect the assessment and management of environmental chemical risks (see Table 3). The three case studies of varying scale (e.g., global, regional, and local) are used to answer the eight questions and illustrate how the EMC^4 (Figure 1) can be used by risk assessors and risk managers to frame the integration of climate change into environmental risk assessments and identify decision-making stakeholders and actors. These case studies provide contrasting scenarios to show how there is no one answer or management solution that fits all scenarios.

For the "changes in externalities" and "risk assessment" component of EMC^4, the following questions should be addressed (adapted from DPSIR and DPSEEA):

1. *Driving forces*: What are the current chemical risks associated with your case study or context?
2. *Pressures*: How is the climate changing within the area and/or region of concern?
3. *State*: How will the physical stressors (e.g., precipitation extremes) induced by climate change affect the fate, transport, and toxicity of the chemical or the susceptibility of the exposed ecosystem and/or humans?
4. *Exposure*: How will climate change affect the use/release/bioaccumulation of the chemicals of interest?
5. *Effects and Impacts*: Are there evidence and data available to understand the relationship between the chemical risks and climate change impacts?For the "risk management and implementation" component of the EMC^4, the following questions should be addressed:
6. What stakeholders with decision-making powers and implementation and interface actors need to be involved in the assessment and management of these risks?
7. How can human behavior be modified to mitigate greenhouse gas emissions, chemical emissions, and climate change impacts at the same time?
8. What policy options are available to affect change while taking into consideration the pros and cons of each option?

Global case study: Integrating climate change into SAICM

The SAICM is a global chemicals management framework adopted by the United Nations in 2006. One of SAICM's stated functions was to identify and call for action on global emerging policy issues, such as the product life cycle of textiles. More than 1900 chemicals are used in the production of clothing; the EU classifies 165 as hazardous to health or the environment (European Parliamentary Research Service [EPRS], 2019). Note that during the publication of this article, the SAICM framework was superseded by the Global Chemical Framework during the fifth session of the International Conference on Chemicals Management (ICCM5) in September 2023. However, the recommendations and commentary that we have offered on SAICM are still relevant for the Global Chemical Framework.

To understand how the externalities driving chemicals risks associated with textiles production, use, and disposal may change in the face of climate change, it is necessary to characterize them. The United Nations Environment Programme Chemicals Branch (UNEP, 2011) identified:

- pesticides used in the growing of natural fibers and any dyes used in their formulation;
- effluent from the manufacture of dyes and colorants (e.g., dye baths); and
- effluent from the tanning and treatment of leather products.

China leads the global textile industry and accounts for over 35% of global textile exports, seven times more than second place, Vietnam, and 35 times more than 10th place, Chinese Taipei (Leal Filho et al., 2022). While China's textile industry is that of one country, the size of the country and quantity of produced textiles have a global effect. Using global climate models like the IPCC's SRES B2 Scenario (Xu et al., 2006), the expected increase in air temperatures by the 2080s is projected to result in significant precipitation decreases in specific regions of China in winter and summer. Increased temperatures and drought are associated with increased pests in cotton crops in China (Huang & Hao, 2018), and therefore increased pesticide use. Organophosphate pesticides have been found in flood sediments across China (Qian et al., 2020; Yuan et al., 2013) and transportation of chemicals applied to soils or deposited in freshwater through this route is likely to increase. Further examples of how climate change can impact the risks from chemicals due to the textile industry in China are provided below in Table 3.

In terms of the risk management and implementation component of EMC^4, a chemical pressure such as that resulting from textile manufacture, use, and disposal is global in nature due to the nature of the supply chains involved. Without a global response, the impacts of chemical pollution may simply be transferred to a less wealthy nation with less stringent regulatory regimes (Shattuck, 2021). Since 2006, SAICM has been one of the primary actors in coordinating global action on chemicals management but they are not the stakeholders with decision-making powers (ICCM, 2006). An important question is whether the new framework emanating from the SAICM Beyond 2020 process can incentivize governments, who have the power to regulate, to ask the questions listed above. Second, UNEP is currently developing a Science Policy Panel that is intended to bridge the information gap between governments and current scientific research on chemical and waste risks (Ågerstrand et al., 2023). The Science Policy Panel is ideally placed to collate and communicate existing knowledge of the likely impact of climate change on chemicals risk assessment, in addition to taking steps to understand, prioritize, and close evidence gaps. It will also be necessary for someone to identify the different actors required to design effective management mechanisms to tackle the issue. While this is necessary at a national level, there may be a

TABLE 3 EMC^4 guiding assessment and management questions for integrating climate change into environmental risk assessment

Guiding assessment and management questions	Global: Integrating climate change into SAICM regarding textiles	Regional: Nutrients pollution in a European catchment	Local: Mercury contamination in South River, West Virginia, USA
1. What are the current chemical risks associated with your case study?	Pesticide usage, effluent of dyes, treatments, coatings and detergents, microplastic release.	Nutrients diffuse pollution from agriculture, point-source pollution, eutrophication.	Methyl mercury (MeHg), PAHs, organochlorine pesticides.
2. How is the climate changing within the area and/or region of concern?	Textiles is a global industry; however, increased flooding, weakening of the monsoon, increased air temp, and reduced precipitation are expected in textile growing and/or manufacturing areas.	Changes will be different across Europe: Temperature will increase, while precipitation might increase in the north but decrease in the south.	Increased river temperature; increased in land flooding.
3. How will the physical stressors induced by climate change affect the fate, transportation, or the susceptibility of the exposed system?	Lower dilution capacity for pollutants, increased run-off into fresh and marine water, increased deposition into new areas, change in transformation of metabolites.	Lower dilution capacity for nutrients, increased erosion and thus nutrient transport, higher risk of eutrophication (increased nutrient availability and temperature).	Habitat alteration for aquatic species; release and/or resuspension of contaminated soil into river; increased suspended solids.
4. How will climate change affect the use/release/ toxicity of the chemicals of interest in the exposed system?	Increased and changed pesticide and fertilizer usage, increased and changed use of textile treatments (e.g., antimold), likely change in the way society uses and washes textiles.	Uncertainty about fertilizer use: changing crop distribution, population growth, green policies, and so forth. Changes in the water demand for multiple uses.	More research needed to understand the influence of change in water flow and temperature on toxicity of legacy MeHg contamination.
5. Are there evidence and data available to understand the relationship between the chemical risks and climate change?	The impact of climate change on the types of chemical pollution caused by textiles is increasingly well evidenced. The impact of climate change on textiles as a source of chemical risk is not well understood.	European Union member states have a strong monitoring network to cope with the Water Framework Directive requirements, registering nutrient concentrations (among other parameters) in every continental and transitional waterbody. Availability of hydrological and ecological models incorporating climate change scenarios provided by downscaled regional climate models.	Historical record of assessed stressors and monitored assessment endpoints; multiyear feasibility study of each management option; Downscaled regional climate change projects specific to South River.
6. What stakeholders with decision-making powers and implementation and interface actors need to be involved in the assessment and management of these risks?	International Governments, UNEP, IOMC, industry bodies, new global science and/or policy panel.	European Union administration, Ministries of Environment, River Basin Authorities, farmers, and/or regional administrations.	South River Science team (consortium of academics, consultants, government personnel, nongovernment organizations).
7. How can human behavior be modified to mitigate greenhouse gas emissions, chemical emissions, and climate change impacts at the same time?	Consume less clothing and fabric-based products, preferentially buy sustainable fabrics, wash clothes less often, avoid fabrics with applied treatments.	Decreasing fertilizer use, working toward a sustainable and high-tech agriculture; implementing nature-based solutions to improve water quality through nutrient uptake, carbon sequestration, and biodiversity conservation.	Adaptive management to monitor and assess efficacy of riverbank stabilization; adding riparian vegetation and trees; and agricultural best management practices

(*Continued*)

TABLE 3 (*Continued*)

Guiding assessment and management questions	Global: Integrating climate change into SAICM regarding textiles	Regional: Nutrients pollution in a European catchment	Local: Mercury contamination in South River, West Virginia, USA
8. What actions or policy options are available to affect change while taking into consideration the pros and cons of each option?	Harsher regulation of emissions; incentivize integrated pest management; incentivize improvement in manufacturing and detergent technology; improved collection for reuse, repair, and recycling; improved transparency and/or labeling; consumer awareness campaigns.	Water Framework Directive, Nitrates Directive, European Green Deal, EU's Common Agricultural Policy. Definition and implementation of specific catchment adaptation plans, nested in the national and regional adaptation strategies.	Collaborative assessment and management process driven by diverse knowledge and experience needed to ensure successful long-term bank stabilization by working with the existing old-growth trees along the bank.

Note: Three case studies (e.g., global, regional, local) provide example applications of these questions. The answers to each question are not meant to be exhaustive but illustrative.
Abbreviations: EMC^4, environmental management cycles for chemicals and climate change; EU, European Union; IOMC, Inter-Organization Programme for the Sound Management of Chemicals; PAHs, polycyclic aromatic hydrocarbons; SAICM, Strategic Approach to International Chemicals Management; UNEP, United Nations Environment Programme.

role for SAICM to lead this process to ensure that learning is shared globally.

Regional case study: Nutrient pollution in European catchments

The EU water policy, highlighted by the European Water Framework Directive (European Parliament, 2000), aims at achieving a good ecological status in all surface waterbodies by 2027. This ecological status is determined with several indicators, including the nutrients concentrations. In fact, nutrients pollution, mainly in the form of diffuse pollution from agriculture, has been a concern in Europe for several decades now, particularly since the proclamation of the Nitrates Directive in 1991 (European Parliament, 1991). However, despite all the efforts done, nutrients pollution is still one of the main environmental problems in Europe and one of the most important threats for aquatic ecosystems (EEA, 2018; Grizzetti et al., 2017). The impact of global change on the fate and transport of nutrients in Europe is uncertain and an in-depth analysis of current findings is needed to plan adequate management strategies to cope with this problem and reduce the risk of eutrophication. Also, the ongoing 2014 Russo-Ukrainian War, and potential food security issues in its wake, influence the European handling of the issues.

Table 3 provides a brief overview of how global change (climate change and their associated changes in the society) might affect nutrients pollution in European catchments, which tools are available to investigate this problem, and who is playing a role in the matter (e.g., various actors, policy options; Wallin, 2014). Nutrients pollution management will not be an easy task in the next few decades in Europe since the impacts might be different depending on the region: climate will change differently (e.g., increasing precipitation in the north, decreasing in the south) and the social changes will take different directions, too (e.g., Mack et al., 2019; Molina-Navarro et al., 2020). However, actions are being taken to address this problem, including coping with the Water Framework Directive and the Nutrients Directive requirements, a sustainable food system pursued in the implementation of the Green Deal, or the imminent 2023 Integrated Nutrient Management Action Plan (EPRS, 2021; European Commission, 2023b).

Local case study: Legacy and active contamination of the South River, Virginia, USA

We describe the South River, Virginia site as an example of considering climate change in ecological risk and remedial decision-making at a local and/or site scale (Table 3). The explicit inclusion of climate change as a compounding stressor produced a suite of prospective risk assessments that facilitated a risk management and implementation process producing management actions tailored to both the exposure and impact of chemical and climate change-induced stressors. More than 20 years of investigation culminated in a plan for remediating legacy mercury at this site (Stahl, 2022; Stahl et al., 2014). The plan included specific evaluation of ecological risks coupled with climate change (e.g., methyl mercury contamination of fish and wildlife, habitat alteration, increasing air and water temperatures; Johns et al., 2017; Landis et al., 2017). Results of the ecological risk assessments were incorporated into an adaptive management framework (see Foran et al., 2015) designed to evaluate the effectiveness of remedial actions (e.g., riverbank stabilization). Restoration actions were also coupled with the remedial actions and were driven by considerations described elsewhere (Hooper et al., 2016; Kapustka et al., 2016). All work was conducted under the Resource Conservation and Recovery Act, Corrective Action program overseen by the Commonwealth of Virginia and the USEPA. Full details of this effort are documented by the South River Watershed Coalition (South River Watershed Coalition, 2023).

IMPLICATIONS AND PATH FORWARD

In contrast to the other articles in this special series (Landis et al., forthcoming; Mentzel et al., forthcoming; Moe et al., forthcoming; Oldenkamp et al., 2023;

Stahl et al., forthcoming), our task was to determine if and how any new approaches for incorporating climate change projections into ecological risk assessment could become a standard practice in chemicals management programs and policies. While the case studies provided by the other work groups in this workshop focused on spatial and temporal scales suitable for ecological risk assessment (Landis et al., forthcoming; Mentzel et al., forthcoming; Oldenkamp et al., 2023), our focus was on chemicals management at multiple geographic scales, which was particularly important as management occurs across scales. This was the backdrop for developing the EMC^4 conceptual framework.

In the section "Introduction and implication of climate change for chemicals management," we touched on how climate change can influence the fate and effects of chemicals and potential barriers to address this in chemicals management programs. Nations first cooperated to address climate change in 1992 (Rio Convention; United Nations, 1992), and the first specific climate change convention was celebrated in 1995 (COP1, Berlin; United Nations, 1995). Yet, in 2022, when the most recent convention was held (COP27, Egypt; United Nations, 2023), measurable progress to achieve the goals nations set for themselves remains elusive. It appears also to be the case with SAICM that nations desire to participate and make progress, but that progress has been slow (Strategic Approach to International Chemicals Management, 2019). This presents the risk management and policy community with an opportunity since SAICM is under review and changes are likely. Thus, with the acknowledgment of a need, consideration of climate change could be incorporated into the SAICM Beyond 2020 framework and/or approach. Given that many frameworks rely on pre-existing knowledge and research for evidence-based chemical decision-making (e.g., Stockholm Convention), there is a need for a coordinated effort to understand and explain the relationship between chemicals and climate change on a global scale to stimulate an evaluation of the data that exist (e.g., sustainable product initiatives [SPI]; IOMC).

In this series of articles, case studies have been provided for chinook salmon in the US Pacific Northwest (Landis et al., forthcoming), the Great Barrier Reef in Australia (Mentzel et al., forthcoming), pesticides in Norway (Oldenkamp et al., 2023), and have shown the methodology for incorporating climate change projections into a wide variety of ecological risk assessments at various spatial scales and for differing environmental situations. These methods could be operationalized in the near future as there appear to be little, if any, technical barriers to preclude their use for ecological risk assessments. The next logical step would be to incorporate them into chemicals management programs worldwide and to require that they are used in future industry data submissions for new chemicals and for new uses of existing chemicals. The consequences of not incorporating climate change considerations into chemicals management programs range from increased pesticide susceptibility of nontarget species to approving widespread use of a new chemical prior to understanding the effects of that chemical in the environment, as was the case for per- and PFAS, dichlorodiphenyltrichloroethane, and chlorofluorocarbons (Willi et al., 2021).

Since many chemicals management programs and frameworks rely on pre-existing knowledge and additional research on chemicals management decision-making (e.g., Stockholm Convention), the use of the EMC^4 framework would enhance the incorporation of climate change into chemical risk assessments. Furthermore, it makes sense to develop a scientific expert process to evaluate chemical fate and effects data that exist and the implications that may result due to climate change (e.g., SPI, IOMC). With the development of the UNEP's new Chemical and Waste Science Policy Panel (Ågerstrand et al., 2023), the opportunity is there to develop a collaborative relationship between the IPCC and Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services for a partnership focused on the effect of chemicals in the environment under climate change. Partnership success requires involved parties to find common or related priorities such that decision-makers and representatives from each party have programmatic reason to work together. Key actions of this potential partnership include, but are not limited to, identifying and remedying critical data gaps for more robust chemical-climate change risk assessments. Even though the UNEP Chemical and Waste Science Policy Panel's focus is "policy relevant, not policy prescriptive," the panel could suggest approaches and tools that might be useful to interface actors, implementation actions, and decision-making stakeholders (e.g., nongovernmental organizations, academia, government, industry) involved with chemical manufacture and management.

AUTHOR CONTRIBUTION

Mariana G. Cains: Conceptualization; supervision; visualization; writing—original draft; writing—review & editing. **Alizée O. S. Desrousseaux:** Conceptualization; data curation; writing—original draft; writing—review & editing. **Alistair B. A. Boxall:** Conceptualization; data curation; writing—original draft; writing—review & editing. **Sverker Molander:** Conceptualization; visualization; writing—original draft; writing—review & editing. **Eugenio Molina-Navarro:** Conceptualization; data curation; writing—original draft; writing—review & editing. **Julia Sussams:** Conceptualization; writing—original draft; writing—review & editing. **Andrea Critto:** Conceptualization; writing—original draft; writing—review & editing. **Ralph G. Stahl:** Funding acquisition; project administration; writing—original draft; writing—review & editing. **Hanna-Andrea Rother:** Conceptualization; funding acquisition; writing—original draft; writing—review & 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, (6) NiPERA, (7) NIVA's Computational Toxicology Program, (8) Research Council of Norway, (9) Rio Tinto, (10) SETAC, (11) Shell, (12) Teck, and (13) US Environmental Protection Agency. The authors also acknowledge the organizations who sponsored the travel costs and working time of participants.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

DISCLAIMER

The views expressed in this manuscript are those of the authors alone. The peer review for this article was managed by the Editorial Board without the involvement of M. Cains.

DATA AVAILABILITY STATEMENT

All data provided/discussed herein are publicly available.

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REFERENCES

Ågerstrand, M., Arinaitwe, K., Backhaus, T., Barra, R. O., Diamond, M. L., Grimalt, J. O., & Scheringer, M. (2023). Key principles for the intergovernmental science—Policy panel on chemicals and waste. *Environmental Science & Technology*, *57*(6), 2205–2208. https://doi.org/10.1021/acs.est.2c08283

American Chemistry Council. (2023). Guide to the business of chemistry (p. 132). https://www.americanchemistry.com/content/download/14468/file/2023-Guide-to-the-Business-of-Chemistry.pdf

AMR Industry Alliance. (2022). *Minimizing risk of developing antibiotic resistance and aquatic ecotoxicity in the environment resulting from the manufacturing of human antibiotics*. https://www.amrindustryalliance.org/wp-content/uploads/2022/06/AMRIA_Antibiotic-Manufacturing-Standard_June2022.pdf

Bailey, S. W. (2004). Climate change and decreasing herbicide persistence. *Pest Management Science: Formerly Pesticide Science*, *60*(2), 158–162. https://doi.org/10.1002/ps.785

Balbus, J. M., Boxall, A. B. A., Fenske, R. A., McKone, T. E., & Zeise, L. (2013). Implications of global climate change for the assessment and management of human health risks of chemicals in the natural environment. *Environmental Toxicology and Chemistry*, *32*(1), 62–78. https://doi.org/10.1002/etc.2046

Basel Convention. (1989). *Basel convention on the control of transboundary movements of hazardous wastes and their disposal*. 28 I.L.M. 657; 1673 U.N.T.S. 125. https://www.basel.int/

Bogdal, C., & Scheringer, M. (2011). Release of POPs to the environment. In *UNEP/AMAP expert group report—Climate change and POPs: Predicting the Impacts*. United Nations Environment Programme/Arctic Monitoring and Assessment Programme. https://www.informea.org/sites/default/files/imported-documents/UNEP-POPS-GMP-REP-ClimateChangePredictImpacts-2.En.pdf

Boxall, A. B., Hardy, A., Beulke, S., Boucard, T., Burgin, L., Falloon, P. D., & Williams, R. J. (2009). Impacts of climate change on indirect human exposure to pathogens and chemicals from agriculture. *Environmental Health Perspectives*, *117*(4), 508–514. https://doi.org/10.1289/ehp.0800084.

Brand, J. H., Spencer, K. L., & O'shea, F. T., & Lindsay, J. E. (2018). Potential pollution risks of historic landfills on low-lying coasts and estuaries. *Wiley Interdisciplinary Reviews: Water*, *5*(1), e1264. https://doi.org/10.1002/wat2.1264

Brunner, P. H., & Rechberger, H. (2016). *Handbook of material flow analysis: For environmental, resource, and waste engineers* (2nd ed.). CRC Press. https://doi.org/10.1201/9781315313450

Cains, M. G., & Henshel, D. (2021). Parameterization framework and quantification approach for integrated risk and resilience assessments. *Integrated Environmental Assessment and Management*, *17*(1), 131–146. https://doi.org/10.1002/ieam.4331

Christensen, F. M., Eisenreich, S. J., Rasmussen, K., Sintes, J. R., Sokull-Kluettgen, B., & Plassche, E. J. V. D. (2011). European experience in chemicals management: Integrating science into policy. *Environmental Science & Technology*, *45*(1), 80–89. https://doi.org/10.1021/es101541b

Corvalán, C. F., Kjellström, T., & Smith, K. R. (1999). Health, environment and sustainable development: Identifying links and indicators to promote action. *Epidemiology*, *10*(5), 656–660. https://www.jstor.org/stable/3703362

Costello, E., Rock, S., Stratakis, N., Eckel, S. P., Walker, D. I., Valvi, D., & Chatzi, L. (2022). Exposure to per- and polyfluoroalkyl substances and markers of liver injury: A systematic review and meta-analysis. *Environmental Health Perspectives*, *130*(4), 046001. https://doi.org/10.1289/EHP10092

Cunningham, M. M., Tran, L., McKee, C. G., Polo, R. O., Newman, T., Lansing, L., & Guarna, M. M. (2022). Honey bees as biomonitors of environmental contaminants, pathogens, and climate change. *Ecological Indicators*, *134*, 108457. https://doi.org/10.1016/j.ecolind.2021.108457

Diamond, M. L., de Wit, C. A., Molander, S., Scheringer, M., Backhaus, T., Lohmann, R., & Zetzsch, C. (2015). Exploring the planetary boundary for chemical pollution. *Environment International*, *78*, 8–15. https://doi.org/10.1016/j.envint.2015.02.001

Diffey, B. (2003). Climate change, ozone depletion and the impact on ultraviolet exposure of human skin. *Physics in Medicine & Biology*, *49*(1), R1. https://doi.org/10.1088/0031-9155/49/1/R01

Edokpolo, B., Allaz-Barnett, N., Irwin, C., Issa, J., Curtis, P., Green, B., & Dennekamp, M. (2019). Developing a conceptual framework for environmental health tracking in Victoria, Australia. *International Journal of Environmental Research and Public Health*, *16*(10), 1748. https://doi.org/10.3390/ijerph16101748.

Esteve-Selma, M. A., Martínez-Martínez, J., Fitz, C., Robledano, F., Martínez Paz, J. M., Francisca Carreño, M., García, N. G., Martínez-López, J., & Miñano, J. (2016). Conflictos ambientales derivados de la intensificación de los usos en la cuenca del Mar Menor: Una aproximación interdisciplinar. In V. M. León & J. M. Bellido (Eds.), *Mar Menor: una laguna singular y sensible. Evaluación científica de su estado* (pp. 79–112). Instituto Español de Oceanografía, Ministerio de Economía y Competitividad.

European Chemicals Agency. (2023). *Legislation*. https://echa.europa.eu/legislation

European Commission. (2021). '*Fit for 55*': *Delivering the EU's 2030 climate target on the way to climate neutrality*. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0550

European Commission. (2023a). *Air quality: Law*. https://environment.ec.europa.eu/topics/air/air-quality_en#law

European Commission. (2023b). *Knowledge for Integrated Nutrient Management Action Plan (INMAP)*. Publications Office of the European Union. https://data.europa.eu/doi/10.2760/692320

European Environment Agency (EEA). (1999). *Environmental indicators: Typology and overview*. EEA Report. https://www.eea.europa.eu/publications/TEC25

European Environment Agency (EEA). (2018). E*uropean waters. Assessment of status and pressures 2018*. EEA Report. https://www.eea.europa.eu/publications/state-of-water

European Parliament. (1991). Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources. *Official Journal of the European Communities*, *375*, 1–8.

European Parliament. (2000). Directive 2000/60/CE of the European Parliament and of the Council, of 23 October 2000, establishing a framework for Community action in the field of water policy. *Official Journal of the European Communities*, *327*, 1–73.

European Parliament. (2012). Directive 2011/92/UE of the European Parliament and of the Council, of 13 December 2011, on the assessment of the effects of certain public and private projects on the environment. *Official Journal of the European Union*, *26*, 1–21.

European Parliament. (2014). Directive 2014/52/EU of the European Parliament and of the Council of 16 April 2014 amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment. *Official Journal of the European Union*, *124*, 1–18.

European Parliament. (2018). *Assessment of the certain effects of plans and programmes on the environment (SEA)*. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=LEGISSUM:l28036

European Parliament. (2021). *The European Economic and Social Committee and the Committee of the Regions EU Soil Strategy for 2030 reaping the benefits of healthy soils for people, food, nature and climate*. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52021DC0699

European Parliament. (2023). Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC. *Official Journal of the European Union*, *396*, 1–574.

European Parliamentary Research Service (EPRS). (2019). *Environmental impact of the textile & clothing industry*. Report to the European Parliament. https://www.europarl.europa.eu/RegData/etudes/BRIE/2019/633143/EPRS_BRI(2019)633143_EN.pdf

European Parliamentary Research Service (EPRS). (2021). *The European Green Deal and cohesion policy*. Briefing to European Parliament. https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/698058/EPRS_BRI(2021)698058_EN.pdf

Foran, C. M., Baker, K. M., Grosso, N. R., & Linkov, I. (2015). An enhanced adaptive management approach for remediation of legacy mercury in the South River. *PLoS One*, *10*(2), e0117140. https://doi.org/10.1371/journal.pone.0117140

Forister, M. L., Pelton, E. M., & Black, S. H. (2019). Declines in insect abundance and diversity: We know enough to act now. *Conservation Science and Practice*, *1*(8), e80. https://doi.org/10.1111/csp2.80

Fuller, R., Landrigan, P. J., Balakrishnan, K., Bathan, G., Bose-O'Reilly, S., Brauer, M., & Yan, C. (2022). Pollution and health: A progress update. *The Lancet Planetary Health*, *6*(6), e535–e547. https://doi.org/10.1016/S2542-5196(22)00090-0

Geels, F. W. (2011). The multi-level perspective on sustainability transitions: Responses to seven criticisms. *Environmental Innovation and Societal Transitions*, *1*(1), 24–40. https://doi.org/10.1016/j.eist.2011.02.002

Goodman, S., & Baudu, S. (2023). C*limate change as a "Threat Multiplier": History, uses and future of the concept* (Briefer No. 38). Center for Climate & Security, Council on Strategic Risks. https://councilonstrategicrisks.org/wp-content/uploads/2023/01/38-CCThreatMultiplier.pdf

Granero Castro, J., Fernando Sánchez, M., Sánchez Arango, M., & Pérez Burgos, C. (2015). *Evaluación de Impacto Ambiental. Guía Metodológica para la Redacción de Estudios de Impacto Ambiental* (2ª Edición Revisada y Ampliada). FC Editorial.

Grizzetti, B., Pistocchi, A., Liquete, C., Udias, A., Bouraoui, F., & Van De Bund, W. (2017). Human pressures and ecological status of European rivers. *Scientific Reports*, *7*(1), 1–11. https://doi.org/10.1038/s41598-017-00324-3

Hader, J. D., Lane, T., Boxall, A. B., MacLeod, M., & Di Guardo, A. (2022). Enabling forecasts of environmental exposure to chemicals in European agriculture under global change. *Science of the Total Environment*, *840*, 156478. https://doi.org/10.1016/j.scitotenv.2022.156478

Harris, C. A., Hamilton, P. B., Runnalls, T. J., Vinciotti, V., Henshaw, A., Hodgson, D., & Sumpter, J. P. (2011). The consequences of feminization in breeding groups of wild fish. *Environmental Health Perspectives*, *119*(3), 306–311. https://doi.org/10.1289/ehp.1002555

Hering, D., Carvalho, L., Argillier, C., Beklioglu, M., Borja, A., Cardoso, A. C., & Birk, S. (2015). Managing aquatic ecosystems and water resources under multiple stress—An introduction to the MARS project. *Science of the Total Environment*, *503*, 10–21. https://doi.org/10.1016/j.scitotenv.2014.06.106.

Hooper, M. J., Glomb, S. J., Harper, D. D., Hoelzle, T. B., McIntosh, L. M., & Mulligan, D. R. (2016). Integrated risk and recovery monitoring of ecosystem restorations on contaminated sites. *Integrated Environmental Assessment and Management*, *12*(2), 284–295. https://doi.org/10.1002/ieam.1731

Huang, J., & Hao, H. (2018). Detecting mismatches in the phenology of cotton bollworm larvae and cotton flowering in response to climate change. *International Journal of Biometeorology*, *62*(8), 1507–1520. https://doi.org/10.1007/s00484-018-1552-0

International Conference on Chemicals Management (ICCM). (2006). *Strategic Approach to International Chemicals Management*. First International Conference on Chemicals Management. https://www.saicm.org/About/Documents/tabid/5460/language/en-US/Default.aspx

Intergovernmental Panel on Climate Change (IPCC). (2021). Contribution of Working Group I to the Sixth Assessment Report of the intergovernmental panel on climate change. In V. P. Masson-Delmotte, A. Zhai, S. L. Pirani, C. Connors, S. Péan, N. Berger, Y. Caud, L. Chen, M. I. Goldfarb, M. Gomis, K. Huang, E. Leitzell, J. B. R. Lonnoy, T. K. Matthews, T. Maycock, O. Waterfield, R. Yelekçi, Y. Zhou, & B. Zhou (Eds.), *Climate change 2021: The physical science basis*. Cambridge University Press. https://doi.org/10.1017/9781009157896

Intergovernmental Panel on Climate Change (IPCC). (2023). Summary for policymakers. In H. Lee & J. Romero (Eds.), *Climate change 2023: Synthesis report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the intergovernmental panel on climate change* (pp. 1–34). https://doi.org/10.59327/IPCC/AR6-9789291691647.001

Inter-Organization Programme for the Sound Management of Chemicals. (2021). *IOMC Toolbox for Decision Making in Chemicals Management*. https://iomctoolbox.org/

Jaffe, D. A., O'Neill, S. M., Larkin, N. K., Holder, A. L., Peterson, D. L., Halofsky, J. E., & Rappold, A. G. (2020). Wildfire and prescribed burning impacts on air quality in the United States. *Journal of the Air & Waste Management Association*, *70*(6), 583–615. https://doi.org/10.1080/10962247.2020.1749731

Jarque, S., Quirós, L., Grimalt, J. O., Gallego, E., Catalan, J., Lackner, R., & Piña, B. (2015). Background fish feminization effects in European remote sites. *Scientific Reports*, *5*(1), 11292. https://doi.org/10.1038/srep11292

Johns, A. F., Graham, S. E., Harris, M. J., Markiewicz, A. J., Stinson, J. M., & Landis, W. G. (2017). Using the Bayesian network relative risk model risk assessment process to evaluate management alternatives for the South River and upper Shenandoah River, Virginia. *Integrated Environmental Assessment and Management*, *13*(1), 100–114. https://doi.org/10.1002/ieam.1765

Kapustka, L. A., Bowers, K., Isanhart, J., Martinez-Garza, C., Finger, S., Stahl, Jr., R. G., & Stauber, J. (2016). Coordinating ecological restoration options analysis and risk assessment to improve environmental outcomes. *Integrated Environmental Assessment and Management*, *12*(2), 253–263. https://doi.org/10.1002/ieam.1673

Landis, W. G., Ayre, K. K., Johns, A. F., Summers, H. M., Stinson, J., Harris, M. J., & Markiewicz, A. J. (2017). The multiple stressor ecological risk assessment for the mercury-contaminated South River and upper Shenandoah River using the Bayesian network-relative risk model. *Integrated Environmental Assessment and Management*, *13*(1), 85–99. https://doi.org/10.1002/ieam.1758

Landis, W. G., Mitchell, C. J., Hader, J. D., Nathan, R., & Sharpe, E. E. (forthcoming). Incorporation of climate change into a multiple stressor risk assessment for the Chinooksalmon (*Oncorhynchus tshawytscha*) population in the Yakima River, Washington USA. *Integrated Environmental Assessment and Management*.

Leal Filho, W., Perry, P., Heim, H., Dinis, M. A. P., Moda, H., Ebhuoma, E., & Paço, A. (2022). An overview of the contribution of the textiles sector to climate change. *Frontiers in Environmental Science*, *10*, 1419. https://doi.org/10.3389/fenvs.2022.973102

Le Conte, Y., & Navajas, M. (2008). Climate change: Impact on honey bee populations and diseases. *Revue Scientifique et Technique-Office International des Epizooties*, *27*(2), 499–510.

Lönngren, R. (1992). *International approaches to chemicals control: A historical overview*. KemI.

Mack, L., Andersen, H. E., Beklioğlu, M., Bucak, T., Couture, R. M., Cremona, F., & Birk, S. (2019). The future depends on what we do today–Projecting Europe's surface water quality into three different future scenarios. *Science of the Total Environment*, *668*, 470–484. https://doi.org/10.1016/j.scitotenv.2019.02.251

MacLeod, M., Breitholtz, M., Cousins, I. T., Wit, C. A. D., Persson, L. M., Rudén, C., & McLachlan, M. S. (2014). Identifying chemicals that are planetary boundary threats. *Environmental Science & Technology*, *48*(19), 11057–11063. https://doi.org/10.1021/es501893m

McKenzie, R. L., Aucamp, P. J., Bais, A. F., Björn, L. O., Ilyas, M., & Madronich, S. (2011). Ozone depletion and climate change: Impacts on UV radiation. *Photochemical & Photobiological Sciences*, *10*(2), 182–198. https://doi.org/10.1039/c0pp90034f

Mejia-Avendaño, S., Munoz, G., Vo Duy, S., Desrosiers, M., Benoît, P., Sauvé, S., & Liu, J. (2017). Novel fluoroalkylated surfactants in soils following firefighting foam deployment during the Lac-Megantic railway accident. *Environmental Science & Technology*, *51*(15), 8313–8323. https://doi.org/10.1021/acs.est.7b02028

Mentzel, S., Nathan, R., Noyes, P., Brix, K., Moe, S. J., Rohr, J. R., Verheyen, J., & Van den Brink, P. J. (forthcoming). Evaluating the effects of climate change and chemical, physical and biological stressors on nearshore coral reefs: a case study in the Great Barrier Reef, Australia. *Integrated Environmental Assessment and Management*.

Moe, S. J., Brix, K., Landis, W. G., Stauber, J., Carriger, J. F., van den Brink, P., & Benestad, R. E. (forthcoming). Integrating climate model projections into environmental risk assessment: A probabilistic modelling approach. *Integrated Environmental Assessment and Management*.

Molina-Navarro, E., Andersen, H. E., Nielsen, A., Thodsen, H., & Trolle, D. (2018). Quantifying the combined effects of land use and climate changes on stream flow and nutrient loads: A modelling approach in the Odense Fjord catchment (Denmark). *Science of the Total Environment*, *621*, 253–264. https://doi.org/10.1016/j.scitotenv.2017.11.251

Molina-Navarro, E., Segurado, P., Branco, P., Almeida, C., & Andersen, H. E. (2020). Predicting the ecological status of rivers and streams under different climatic and socioeconomic scenarios using Bayesian Belief Networks. *Limnologica*, *80*, 125742. https://doi.org/10.1016/j.limno.2019.125742

Molina-Navarro, E., Trolle, D., Martínez-Pérez, S., Sastre-Merlín, A., & Jeppesen, E. (2014). Hydrological and water quality impact assessment of a Mediterranean limno-reservoir under climate change and land use management scenarios. *Journal of Hydrology*, *509*, 354–366. https://doi.org/10.1016/j.jhydrol.2013.11.053

National Research Council (NRC). (1983). *Risk assessment in the Federal Government: Managing the Process*. The National Academies Press. http://www.nap.edu/catalog/366.html

National Research Council (NRC). (2009). *Science and decisions: Advancing risk assessment*. The National Academies Press. https://doi.org/10.17226/12209

Naidu, R., Biswas, B., Willett, I. R., Cribb, J., Singh, B. K., Nathanail, C. P., & Aitken, R. J. (2021). Chemical pollution: A growing peril and potential catastrophic risk to humanity. *Environment International*, *156*, 106616. https://doi.org/10.1016/j.envint.2021.106616

Neale, P. J., Williamson, C. E., Banaszak, A. T., Häder, D. P., Hylander, S., Ossola, R., & Zepp, R. (2023). The response of aquatic ecosystems to the interactive effects of stratospheric ozone depletion, UV radiation, and climate change. *Photochemical & Photobiological Sciences*, *22*, 1–35. https://doi.org/10.1007/s43630-023-00370-z

Oaks, J. L., Gilbert, M., Virani, M. Z., Watson, R. T., Meteyer, C. U., Rideout, B. A., & Ahmed Khan, A. (2004). Diclofenac residues as the cause of vulture population decline in Pakistan. *Nature*, *427*(6975), 630–633. https://doi.org/10.1038/nature02317

Oldenkamp, R., Benestad, R. E., Hader, J. D., Mentzel, S., Nathan, R., Madsen, A. L., & Jannicke Moe, S. (2023). Incorporating climate projections in the environmental risk assessment of pesticides in aquatic ecosystems. *Integrated Environmental Assessment and Management*. https://doi.org/10.1002/ieam.4849

1992 OSPAR Convention. (2007). *Convention for the protection of the marine environment of the North-East Atlantic*. https://www.ospar.org/site/assets/files/1169/ospar_convention.pdf

Patrício, J., Elliott, M., Mazik, K., Papadopoulou, K. N., & Smith, C. J. (2016). DPSIR—Two decades of trying to develop a unifying framework for marine environmental management. *Frontiers in Marine Science*, *3*, 177. https://doi.org/10.3389/fmars.2016.00177

Persson, Å. (2019). Global adaptation governance: An emerging but contested domain. *Wiley Interdisciplinary Reviews: Climate Change*, *10*(6), e618. https://doi.org/10.1002/wcc.618

Persson, L., Carney Almroth, B. M., Collins, C. D., Cornell, S., De Wit, C. A., Diamond, M. L., & Hauschild, M. Z. (2022). Outside the safe operating space of the planetary boundary for novel entities. *Environmental Science & Technology*, *56*(3), 1510–1521. https://doi.org/10.1021/acs.est.1c04158

Pineda, A. C., Chang, A., & Faria, P. (2020). *Foundations for science-based net zero target setting in the corporate sector*. Version 1. Science Based Targets Initiative (p. 53). https://sciencebasedtargets.org/resources/files/foundations-for-net-zero-full-paper.pdf

Qian, Z., Mao, Y., Xiong, S., Peng, B., Liu, W., Liu, H., & Qi, S. (2020). Historical residues of organochlorine pesticides (OCPs) and polycyclic aromatic hydrocarbons (PAHs) in a flood sediment profile from the Longwang Cave in Yichang, China. *Ecotoxicology and Environmental Safety*, *196*, 110542. https://doi.org/10.1016/j.ecoenv.2020.110542

Redshaw, C. H., Stahl-Timmins, W. M., Fleming, L. E., Davidson, I., & Depledge, M. H. (2013). Potential changes in disease patterns and pharmaceutical use in response to climate change. *Journal of Toxicology and Environmental Health, Part B*, *16*(5), 285–320. https://doi.org/10.1080/10937404.2013.802265

Rotterdam Convention. (1998). *Rotterdam Convention on the prior Informed consent procedure for certain hazardous chemicals and pesticides in international trade*. https://www.pic.int/

Strategic Approach to International Chemicals Management. (2019). *Independent evaluation of the strategic approach 2006–2015*. Prepared by R. Nurick. SAICM_IP3_INF3_Final-IndependentEvaluation.pdf

Sánchez-Bayo, F., & Wyckhuys, K. A. (2019). Worldwide decline of the entomofauna: A review of its drivers. *Biological Conservation*, *232*, 8–27. https://doi.org/10.1016/j.biocon.2019.01.020

Shattuck, A. (2021). Generic, growing, green? The changing political economy of the global pesticide complex. *The Journal of Peasant Studies*, *48*(2), 231–253. https://doi.org/10.1080/03066150.2020.1839053

South River Watershed Coalition. (2023) *Resources*. https://southriverwatershed.org/resources

Stahl Jr., R. G. (2022). Science lessons from a mercury site. *Environmental Toxicology and Chemistry*, *41*(3), 497–498. https://doi.org/10.1002/etc.5288

Stahl, Jr., R. G., Boxall, A., Brix, K., Landis, W., Moe, S. J., & Stauber, J. (forthcoming). Incorporating climate change models into ecological risk assessments to help inform risk management and adaptation strategies. *Integrated Environmental Assessment and Management*.

Stahl, Jr., R. G., Kain, D., Bugas, P., Grosso, N. R., Guiseppi-Elie, A., & Liberati, M. R. (2014). Applying a watershed-level, risk-based approach to addressing legacy mercury contamination in the South River, Virginia: Planning and problem formulation. *Human and Ecological Risk Assessment: An International Journal*, *20*(2), 316–345. https://doi.org/10.1080/10807039.2014.844053

Stockholm Convention. (2001). *Stockholm convention on persistent organic pollutants*. 2256 U.N.T.S. 119; 40 I.L.M. 532. https://chm.pops.int/

Suter II, G. W., Vermeire, T., Munns, W. R., & Sekizawa, J. (2003). Framework for the integration of health and ecological risk assessment. *Human and Ecological Risk Assessment*, *9*(1), 281–301. https://doi.org/10.1080/713609865

Tao, Y., Xue, B., Lei, G., Liu, F., & Wang, Z. (2017). Effects of climate change on bioaccumulation and biomagnification of polycyclic aromatic hydrocarbons in the planktonic food web of a subtropical shallow eutrophic lake in China. *Environmental Pollution*, *223*, 624–634. https://doi.org/10.1016/j.envpol.2017.01.068

Teran, T., Lamon, L., & Marcomini, A. (2012). Climate change effects on POPs' environmental behaviour: A scientific perspective for future regulatory actions. *Atmospheric Pollution Research*, *3*(4), 466–476. https://doi.org/10.5094/APR.2012.054

Thonemann, N. (2020). Environmental impacts of CO_2-based chemical production: A systematic literature review and meta-analysis. *Applied Energy*, *263*, 114599. https://doi.org/10.1016/j.apenergy.2020.114599

United Nations. (1992). *Report of the United Nations Conference on environment and development. A/CONF.151/26/Rev.1* (Vol. I). https://documents-dds-ny.un.org/doc/UNDOC/GEN/N92/836/55/PDF/N9283655.pdf?OpenElement

United Nations. (1995). *Framework convention on climate change: Provisional agenda and annotations, including suggestions for the organization of work. Conference of the parties*. FCCC/CP/1995/1. https://unfccc.int/cop4/resource/docs/cop1/01.pdf

United Nations. (2023). *Report of the conference of the parties on its twenty-seventh session, held in Sharm el-Sheikh from 6 to 20 November 2022. Part one: Proceedings*. FCCC/CP/2022/10. https://unfccc.int/documents/626560

United Nations Environment Programme (UNEP). (2011). *The chemicals in products project: Case study of the textiles sector*. https://wedocs.unep.org/20.500.11822/27813.

United Nations Environment Programme (UNEP). (2021). *Regulating air quality: The first global assessment of air pollution legislation*. Nairobi. https://wedocs.unep.org/bitstream/handle/20.500.11822/36666/RAQ_GAAPL.pdf

United Nations Environment Programme (UNEP). (2023). *Mediterranean Action Plan (MAP)*. https://www.unep.org/unepmap/

USEPA. (2017). *Comprehensive Environmental Response, Compensation, and Liability Act*. 40 CFR Part 305. https://www.ecfr.gov/current/title-40/part-305

USEPA. (2020). *Toxic Substances Control Act*. 40 CFR Part 710. https://www.ecfr.gov/current/title-40/part-710

USEPA. (2023a). *Resource Conservation and Recovery Act*. 40 CFR Part 261. https://www.ecfr.gov/current/title-40/part-261

USEPA. (2023b). *Federal Insecticide, Fungicide, and Rodenticide Act*. 40 CFR Part 152. https://www.ecfr.gov/current/title-40/part-152

Van den Brink, P. J., Choung, C. B., Landis, W., Mayer-Pinto, M., Pettigrove, V., Scanes, P., Smith, R., & Stauber, J. (2016). New approaches to the ecological risk assessment of multiple stressors. *Marine and Freshwater Research*, *67*(4), 429. https://doi.org/10.1071/mf15111

Wallin, A. (2014). *Actors at the interface between socio-technical and ecological systems: Analytical starting point for identifying mitigation possibilities in the case of on-site sewage systems*. Chalmers Tekniska Hogskola.

Willi, K., Ravishankara, A. R., Velders, G. J., Daniel, J. S., McFarland, M., & Andersen, S. O. (2021). The precautionary principle and the environment: A case study of an immediate global response to the molina and rowland warning. *ACS Earth and Space Chemistry*, *5*(11), 3036–3044. https://doi.org/10.1021/acsearthspacechem.1c00244

World Health Organization (WHO). (2014). *The International Code of Conduct on pesticide management*. WHO/HTM/NTD/WHOPES/2014. https://www.who.int/publications/i/item/9789251085493

World Health Organization (WHO). (2017). *Chemicals road map*. WHO/FWC/PHE/EPE/17.03. https://www.who.int/publications/i/item/WHO-FWC-PHE-EPE-17.03

World Health Organization (WHO). (2021). *Review of Minamata Convention initial assessment reports: Key findings for health*. World Health Organization. https://iris.who.int/bitstream/handle/10665/351133/9789240041011-eng.pdf?sequence=1

World Health Organization (WHO). (2023). *Inter-organization programme for the sound management of chemicals*. https://partnership.who.int/iomc

Xu, Y., Zhang, Y., Lin, E., Lin, W., Dong, W., Jones, R., & Wilson, S. (2006). Analyses on the climate change responses over China under SRES B2 scenario using PRECIS. *Chinese Science Bulletin*, *51*, 2260–2267. https://doi.org/10.1007/s11434-006-2099-8

Yuan, L., Qi, S., Wu, X., Wu, C., Xing, X., & Gong, X. (2013). Spatial and temporal variations of organochlorine pesticides (OCPs) in water and sediments from Honghu Lake, China. *Journal of Geochemical Exploration*, *132*, 181–187. https://doi.org/10.1016/j.gexplo.2013.07.002

Zouboulis, A., & Tolkou, A. (2014). Effect of climate change in wastewater treatment plants: Reviewing the problems and solutions. In S. Shrestha, A. Anal, P. Salam, & M. van der Valk (Eds.), *Managing water resources under climate uncertainty: Examples from Asia, Europe, Latin America, and Australia* (pp. 197–220). Springer International Publishing. https://doi.org/10.1007/978-3-319-10467-6_10

 DOI: 10.1002/ieam.4872