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Published in:
Environmental Toxicology and Chemistry

DOI:
10.1002/etc.3513

Publication date:
2017

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Selck, H., Adamsen, P. B., Backhaus, T., Banta, G. T., Bruce, P. K. H. ., Burton Jr., G. A., ... Chapman, P. M. (2017). Assessing and Managing Multiple Risks in a Changing World–the Roskilde Recommendations. *Environmental Toxicology and Chemistry*, *36*(1), 7-16. https://doi.org/10.1002/etc.3513

Assessing and Managing Multiple Risks in a Changing World—The Roskilde Recommendations

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Abstract—*Roskilde University (Denmark) hosted a November 2015 workshop, Environmental Risk—Assessing and Managing Multiple Risks in a Changing World. This Focus article presents the consensus recommendations of 30 attendees from 9 countries regarding implementation of a common currency (ecosystem services) for holistic environmental risk assessment and management; improvements to risk assessment and management in a complex, human-modified, and changing world; appropriate development of protection goals in a 2-stage process; dealing with societal issues; risk-management information needs; conducting risk assessment of risk management; and development of adaptive and flexible regulatory systems. The authors encourage both cross-disciplinary and interdisciplinary approaches to address their 10 recommendations: 1) adopt ecosystem services as a common currency for risk assessment and management; 2) consider cumulative stressors (chemical and nonchemical) and determine which dominate to best manage and restore ecosystem services; 3) fully integrate risk managers and communities of interest into the risk-assessment process; 4) fully integrate risk assessors and communities of interest into the risk-management process; 5) consider socioeconomics and increased transparency in both risk assessment and risk management; 6) recognize the ethical rights of humans and ecosystems to an adequate level of protection; 7) determine relevant reference conditions and the proper ecological context for assessments in human-modified systems; 8) assess risks and benefits to humans and the ecosystem and consider unintended consequences of management actions; 9) avoid excessive conservatism or*

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Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/etc.3513

possible underprotection resulting from sole reliance on binary, numerical benchmarks; and 10) develop adaptive risk-management and regulatory goals based on ranges of uncertainty. Environ Toxicol Chem 2017;36:7–16. © 2016 SETAC

Keywords—Risk assessment; Risk management; Ecosystem services; Climate change; Wicked problems; Multiple environmental stressors

Roskilde University (Denmark) hosts annual Sunrise conferences and workshops that focus on important and groundbreaking science and its applications. Between 16 and 17 November 2015, the university hosted an international workshop, Environmental Risk—Assessing and Managing Multiple Risks in a Changing World. The present Focus article outlines consensus conclusions and recommendations regarding risk assessment and management arising from the workshop during an iterative process that involved initial keynote talks, discussions in breakout and plenary sessions, and subsequent communications between all coauthors.

The workshop was organized based on an identified need to improve our current approach to assessing environmental risks to humans and ecosystems. In a finite world with limited resources it is paramount that major, multiple risks be appropriately addressed using efficient and effective approaches. However, we currently assess risks for different stressors individually, with risk-assessment frameworks that are not easy to integrate and that typically disregard other stressors. The workshop provided recommendations for a more holistic perspective for assessing and managing risks from the multiple stressors and "natural" hazards that impact ecosystems and the humans who rely on those ecosystems.

Our consensus recommendations are provided in 7 categories (see the text box *The Roskilde workshop recommendations*). Some of them are new; others are well known but not generally adopted. Two additional articles resulting from the workshop, published in the journal *Integrated Environmental Assessment and Management* and cited herein, provide relevant case studies and additional supportive information [1–2].

Common Currency for Risk Assessment and Risk Management

We recommend implementation of a "common currency" of ecosystem services as a comparable unit of measure, which will greatly improve 3 aspects of risk assessment and risk management. First, it will improve communication of risk among different groups (e.g., across organizations with different risk-management mandates and with communities of interest including citizens, aboriginal groups, special interest groups, and nongovernment, government, and intergovernmental organizations) and enhance scientific transparency (Figure 1). Second, it will permit ranking risks posed by different stressors within a range of environmental and social contexts. Third, it will permit potential aggregation of multiple risks in both time and space, for improved cumulative and integrated risk assessment. Syberg et al. [2] provide practical examples of how ecosystem services can be translated into a common currency amenable for decision making.

Building on Munns et al. [3] and references therein, we recommend that the benefits people obtain from ecosystems, ecosystem services, serve as this common currency. *The Economics of Ecosystems and Biodiversity* [4] suggests that ecosystem services can be categorized into 4 main types. Although other categorizations exist, the following 4 categories are reasonably comprehensive: 1) provisioning services are the products obtained from ecosystems such as food, fresh water, wood, fiber, genetic resources, and medicines (also termed "ecosystem goods"); 2) regulating services are defined as the benefits obtained from the regulation of ecosystem processes such as climate regulation, natural hazard regulation, water purification, waste management, pollination, and pest control; 3) habitat services highlight the importance of ecosystems to provide habitat for species and to maintain the viability of gene pools; and 4) cultural services include nonmaterial benefits that people obtain from ecosystems such as spiritual enrichment, intellectual development, recreation, and aesthetic values.

Ecosystem services, which integrate ecosystem functions and ecosystem goods, can provide an integrated package of information that includes considerations of ecological and social issues (people and communities), the resilience of ecosystems and human communities, and dynamic changes to human economies [5]. Because changes in ecosystem services can be valued quantitatively in either monetary or, preferably,

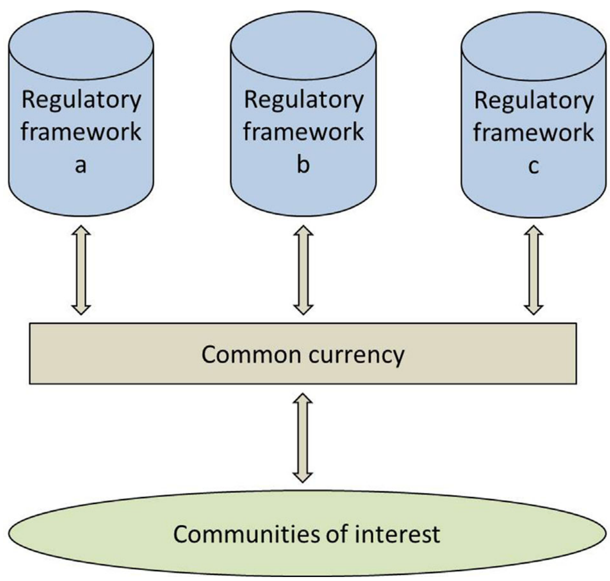

FIGURE 1: A common currency (ecosystem services) will improve communication (illustrated with arrows) and transparency among different regulatory frameworks (the silos shown as regulatory frameworks a, b, c) and communities of interest.

nonmonetary (i.e., socioecological) terms (see Silverton [6] regarding problems with the monetization and "financialization" of nature), this common currency can effectively communicate potential influences on the environment and human interests including, but not restricted to, socioeconomic interests. Changes to ecosystem services can also form the basis for risk assessment and subsequent risk management, providing a metric of impacts at different geographic and temporal scales. Ecosystem services thus provide an integrative approach to environmental and social impact assessment [7] and can help resolve 3 key problems with risk assessment: transparency, objectivity, and communication [8,9].

One of the critical aspects of integrating ecosystem services into risk assessment and risk management is to develop a definition of ecosystem services (i.e., a common currency). We believe that this currency should ideally be driven by a nonmonetary unit and preferentially by ecological standards (i.e., by impacts on ecosystem services). An impact on an ecosystem service can clearly have economic consequences, but we believe that impacts need to be estimated based on ecology rather than solely on economy; geographic differences should not be ignored or overlooked in favor of simple monetary comparisons.

The common currency approach using ecosystem services is appropriate for, but has not been considered in, environmental risk assessments related to risks of disasters (extreme events such as earthquakes, hurricanes, tsunamis, forest fires) that result in loss of natural resources, economic impacts, human injuries, and fatalities. Extreme events will likely also affect existing risks of, for example, chemicals (e.g., dispersion of contaminated sediments downstream, impacts to habitat and resident biota), such that existing risk assessments and related risk-management activities will no longer be valid. Another challenge which requires further discussion and development is translating data from regulatory frameworks focused on human health risks (e.g., chemical regulations that assess the risks of personal care products and pharmaceuticals) into this common currency.

Improving Risk Assessment and Management in a Complex and Changing World

Global ecosystems are under increasing pressure from human activities. Rockström [10] identified 10 interlinked planetary boundaries (i.e., affected earth-system processes) that, if transgressed, might lead to irreversible changes to the living conditions on the planet: climate change, loss of biodiversity, nitrogen cycling, phosphorus cycling, ozone depletion, ocean acidification, freshwater use, changes in land use, atmospheric aerosol loading, and chemical pollution. The resulting risks and accompanying benefits within these boundaries are not static; they change over time, and they interact with and impact each other [11]. For example, global climate change increases both uncertainties in risk assessments of chemicals [12] and difficulties in long-term decision making [13–15]. Long-term changes to Earth's climate are occurring, resulting in direct effects on ecosystems and human living conditions. Examples include increased temperatures, sea-level rise, ocean acidification, changing rainfall patterns (e.g., floods, droughts), increased extreme weather events (e.g., hurricanes, cyclones, storm surges), and more bush and forest fires.

These changes and their effects are not readily predictable or easily quantified [16], particularly when combined with other stressors such as pathogens, invasive species, and habitat loss [17]. Interactive effects between chemical contaminants and nonchemical (physical, biological) stressors will occur and will complicate assessments including the statistical power to detect effects in the face of increasing variability [18–20]. However, regulation-driven risk assessment and management programs have not adequately considered the indirect effects of climate change, for instance, increased harmful algal blooms [13], unexpected toxicosis [21], ecological advantages to invasive species [22], and habitat effects to biodiversity [15].

The fact that risks and benefits are dynamic, and thus will change, means that past experiences will increasingly no longer be a reliable guide to the future, particularly given climate change. Ecosystems, humans, and engineered structures increasingly face multiple, rather than single, stressors in our human-dominated ecosystems, either in combination or in a more or less connected series of events. Simply modeling, measuring, or comparing risks of different anthropogenic or natural stressors individually is no longer sufficient. An integrated approach that also includes future, changing scenarios needs to be considered for effective, strategic, long-term management decisions [23], including monitoring to assess those decisions. Therefore, single-substance risk assessments must give way to assessments of chemical mixtures combined with other stressors (i.e., cumulative risk assessment [24]) in dynamic environments, along with associated risk-management activities. Conceptual frameworks and tools for assessing multiple stressors across ecosystems are being developed [25–28].

The starting point for all risk assessments (and subsequent risk-management actions) should be based on an agreed protection goal(s). There must be agreement between risk assessors, risk managers, and communities of interest regarding which protection goals to focus on and acceptable levels of uncertainty. Agreement implies a consensus, which will be difficult [29], but not impossible, to achieve [30]. Policy decisions should be made by those with the democratic mandate to make such decisions; decision makers must be held responsible for their decisions should they differ from consensus opinions. It is critical that policy decisions, including uncertainties and risk–risk trade-offs, be fully transparent. Doorn [1] discusses allocation of responsibility

A hypothetical example of risk assessment and risk management of multiple stressors under changing environmental conditions relative to a defined protection goal. The process must be transparent (Figure 2) with cross-sectoral information flow (i.e., horizontal integration) based on the common currency of ecosystem services (Figure 1).

- It is initially agreed to protect Atlantic salmon in Denmark to allow fishing *X* tons annually without affecting long-term population stability (protection goal).
- It is agreed that, to meet this protection goal, a sustainable population of Atlantic salmon is required in at least 50% of all Danish freshwater systems.
- Hazards to this protection goal are identified during the risk-assessment problem formulation:
  - Loss or degradation of physical habitat
  - Competing invasive species
  - Loss or degradation of food sources
  - Legacy sediment contamination
  - Indirect and direct effects of continued contamination (e.g., from pesticides and nutrients)
  - Increasing water temperatures and water level fluctuations (floods and droughts)
- Risk assessments are conducted for these stressors both individually and in combination (cumulatively, e.g., a multihazard risk assessment with correlation among hazards).
- Based on the outcome of the risk assessment, critical stressors affecting the protection goal are identified (often from multiple sectors).
- Effective risk-management measures are determined for all of the critical stressors (see section *Risk Assessment of Risk Management*) and implemented relative to 2 possibilities:
  - Risk-management measures can provide for the original protection goal to be met.
  - Risk-management measures are insufficient to effectively meet the original protection goal but can meet a modified protection goal. For example, pesticides could be adversely affecting sensitive juvenile fish and their food supply; however, adequate reduction in usage to meet the original protection goal would adversely affect human food supplies. In this case a decision could be made to modify the protection goal by a certain percentage while also focusing on enhancing Atlantic salmon in areas relatively unaffected by agriculture.
- Risk-management measures relative to the unmodified or modified protection goal (see bullet above) result in an acceptable reduction of total risks.
- Monitoring of Atlantic salmon populations, while they are in Danish freshwater systems, is conducted to assess success in meeting the original or modified protection goal and to provide early warning of any additional and necessary risk-management measures in the context of dynamic risk (risk-mitigation methods and choices may change with time).

for policy decisions in terms of both effectiveness and fairness, providing 4 case studies and 12 principles.

A new partnership between scientists and communities of interest is necessary to agree on protection goals but also because increasing uncertainties require increased integration (i.e., communication, information exchange) among risk assessors, risk managers, and particularly communities of interest. Risk assessments should be demystified; their complexity must be translatable for all engaged or interested in the process.

Both risk managers and communities of interest must be involved in the risk assessment, not just at the start (the problem formulation) and after completion but rather throughout the entire iterative process, via the common currency of ecosystem services (Figure 1 and Figure 2). They should both understand and provide input to the process (e.g., issues, values, uncertainties) so that resulting management decisions are credible and more likely to be implemented. Similarly, risk assessors must be involved in the risk-management process (see section *Risk Assessment of Risk Management*).

To provide a fair and inclusive process, transparency in risk assessment and management is paramount. All information considered by risk managers, both supportive and contradictory, must be presented and available for broad evaluation. The consequences of alternative decisions also need to be clearly explained. Economists and other social scientists should be involved to provide estimates of societal costs; ecologists should be involved to provide estimates of ecosystem costs. Clearly, conflicts of interest will occur; for example, an alternative solution may result in adverse effects to 1 ecosystem service, whereas another may benefit when the alternative is chosen. Syberg et al. [2] provide a case study of conflicting ecosystem services, specifically banana plantations benefiting from applying pesticides to their crops

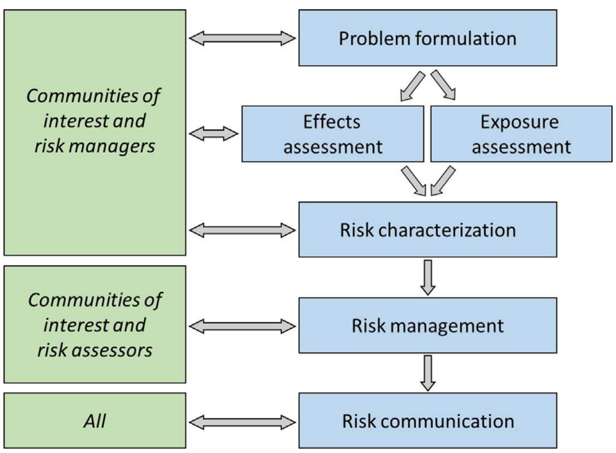

FIGURE 2: Necessary involvement of risk managers and communities of interest throughout the risk-assessment process, risk assessors and communities of interest in risk management, and all (communities of interest, risk assessors, and risk managers) in risk communication.

Examples of unintended consequences of risk mitigation actions

Risk Mitigation	Unintended Consequence(s)
Dredging to remove contaminated sediments	Habitat degradation and contaminant dispersal
Antifouling paint to decrease fuel usage	Paint flakes contaminating surface waters and sediments
Replacing a chemical of potential concern with another	The replacement chemical has a greater but different risk
Wetland enhancement	Increased flooding and insect-borne disease
Wind power to reduce reliance on fossil fuels	Birds and bats killed; aesthetic considerations
Solar power to reduce reliance on fossil fuels	Birds killed
Hydroelectric power generation to reduce reliance on fossil fuels	Altered habitat, water flow, fisheries, traditional uses

(e.g., increased terrestrial food production), while pesticide runoff from those plantations affects downstream ecosystems (e.g., reduced aquatic food production).

The approach shown in Figure 2 is essential for dealing with "wicked problems" [30,31], which are nonlinear and complex, indeterminate in scope and scale, and not easily solvable. Wicked problems are subject to the following: incomplete, contradictory, and changing requirements; ambiguity with regard to the problem definition; uncertainty regarding causal relations between the problem and potential solutions; and a wide variety of regulatory, business, and societal interests and values. There are no clear, straightforward answers to wicked problems; their solutions require optimization and adaptation. Risk from a stressor to 1 component of an ecosystem can also provide benefits to another component of the ecosystem (see the text box *A hypothetical example of risk assessment and risk management of multiple stressors under changing environmental conditions relative to a defined protection goal*).

Interventions to manage or reduce risks can complicate risk predictions. For example, increasing flood protection increases floodplain development (e.g., New Orleans, LA, USA) or development below sea level (e.g., The Netherlands), with increasing risks to human health and socioeconomic well-being should flood protection fail. Trade-offs are required relative to the common currency of ecosystem services. The risk of catastrophic events is increasing because of both climate change and human activities (e.g., modified land cover; increased impermeability of land surfaces; reduced riparian zones and floodplains; increased density of human populations in areas prone to floods, earthquakes, tsunamis, or other extreme events). Fully integrated risk assessments across all relevant ecosystem stressors must be conducted, with equally integrated management decisions involving communities of interest (Figure 2). In this regard, lessons could be learned from regional strategic environmental assessments, which include cumulative risks from multiple stressors (e.g., Gunn and Noble [32]).

Protection Goals

Environmental risk management typically poses a risk-distribution problem. For example, many risks are inherently unfair in the sense that some humans and ecosystems are exposed to higher risks than others and some are more vulnerable than others. And there is often no connection between those who produce the risk and those who are exposed.

It is impossible to guarantee all humans or ecosystems the same level of protection, but all have the ethical right to an adequate level of protection. Although different standards apply to human-modified systems (e.g., a bay used as an urban harbor can never be a pristine ecosystem), relevant reference conditions (i.e., adequate levels of protection) should be identified for those human-modified systems relative to protection goals.

Although it is possible to identify protection goals based on ecosystem services, human health, and societal interests [33], the assessment of those protection goals is still largely considered and managed by separate regulatory frameworks (i.e., silos; Figure 1) and, as such, does not include factors from all relevant disciplines that might impact the protection goals. Protection goals should not be ambiguous and difficult to manage (e.g., a healthy ecosystem); they must be translated into more tangible, understandable site-specific or problem-specific protection goals (e.g., the waters of a lake must be safe to drink, the fish plentiful and safe to eat).

We recommend an explicit division of protection goals into 2 levels (Figure 3): 1) universal protection goals (e.g., global assessment endpoints such as maintaining ecosystem services); and 2) workable, site-specific, region-specific, or problem-specific protection goals (i.e., site-specific, region-specific, or problem-specific assessment endpoints such as the specific ecosystem service of adequate water flow), where translation between the 2 levels is integrated [34] and facilitated by input from risk assessors, risk managers, and communities of interest (Figure 3). The translation framework should consider all relevant factors and stressors potentially affecting the protection goals in a site-specific setting. The result of the translation process (Figure 3) leads to the identification of relevant, tangible protection goals that then can be assessed by well-developed and established procedures (measurement endpoints and an assessment loop, integrated with the management system). Ecosystem services are therefore intended both to focus protection goals and as the bases for both risk-assessment and risk-management processes.

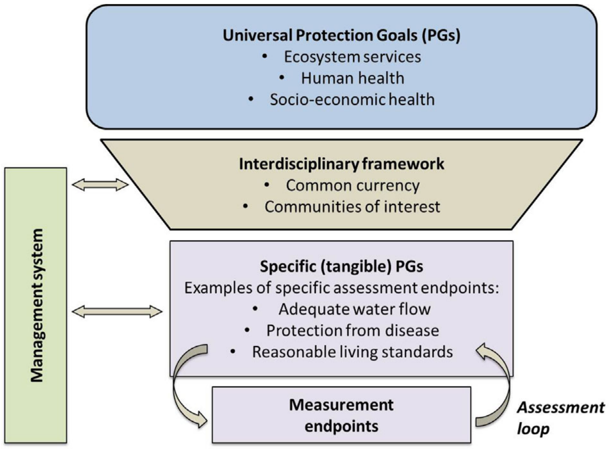

FIGURE 3: Two-step process for developing specific protection goals from universal protection goals via an interdisciplinary framework involving common currency, communities of interest, and other elements described in the present Focus article. The protection goals are then used to form the measureable (site-specific) endpoints that are used within a management system and the assessment loop to manage and monitor these protection goals. See text for additional explanation.

The process of defining protection goals may differ depending on whether the risk assessment is prospective or retrospective. The former tends to have larger temporal and spatial ranges than the latter. It may be useful, with input from communities of interest, to score and prioritize protection goals using a weight-of-evidence approach (see hypothetical example of a wicked problem in the text box *A hypothetical example of risk assessment and risk management of multiple stressors under changing environmental conditions relative to a defined protection goal*).

Societal Issues

Humans are inseparable from the ecosystem; risk assessors must consider direct and indirect impacts on humans. For example, there may be adverse health consequences from consuming contaminated fish and shellfish, loss of income from decreased harvest, loss of recreational opportunities because of habitat degradation, and declines in water supply or flood control with soil and landscape degradation. Risk assessors must also consider less tangible but still important ecosystem services such as cultural heritage.

Ecosystem services should be considered within the context that optimizing some services may come at the expense of other services [35] (see the text box *A hypothetical example of risk assessment and risk management of multiple stressors under changing environmental conditions relative to a defined protection goal* and the text box *Examples of unintended consequences of risk mitigation actions*). Such an assessment of trade-offs is further complicated by the uncertainties attached to both the risks and benefits, which may be quantified and, to a certain extent, reduced but can never be eliminated. Communities of interest should be involved in developing likely scenarios for both risk assessment and risk management to provide information on possible future outcomes, including recognition of unknown factors (i.e., uncertainties) that could affect those outcomes. These scenarios should be based on ecosystem services, including potential impacts to vulnerable humans and ecosystems. They should also explicitly consider socioeconomic risks. Developing likely scenarios, and when possible including sensitivity analysis of included parameters to better calibrate protection models, will allow for a more explicit characterization of related uncertainties.

Risk assessors and risk managers should tailor communications and knowledge dissemination to the target audience. Training and briefing classes could inform and educate risk assessors and risk managers regarding appropriate and effective communications with each other and with communities of interest. Communities of interest could be similarly informed and educated. Illustrative models to improve the translational process could be developed with input from communities of interest.

Both risk assessment and risk management would greatly benefit from including all relevant societal considerations, which will require input from a range of experts including, but not limited to, economists and other social scientists. Risk management should also address issues such as justice, fairness, and protection of culture. To ensure these latter issues, it is important to obtain a high degree of transparency in the risk-management process so that the foundations for policy decisions are clear to all involved.

Risk-Management Information Needs

Risk assessment is conducted within many different disciplines but rarely with the combined effects of all relevant chemical and nonchemical stressors in mind. For example, current practices in chemical risk assessment place undue emphasis on single substances, leading to an underestimation of the cumulative risk of chemical mixtures, let alone the risk of those mixtures combined with other stressors. The chemical mixture assessment problem is exacerbated by a lack of integration in chemical regulation (e.g., among regulatory agencies with different mandates); there are differences in legislated procedures for different chemical classes (e.g., pesticides, pharmaceuticals, industrial chemicals). Stressors that occur at larger temporal and spatial scales (e.g., changes in hydrological conditions [36]) undoubtedly affect the fate and effect of such chemical mixtures but are rarely considered. Risk management must be informed by the totality of all stressors, chemical and nonchemical (e.g., human modification of water and nutrient cycles).

The information required to manage risks will differ depending on the individual and combined stressors, the complexity of the ecosystems and of human societies, the available risk-management options, and human choices regarding acceptable risk. For example, in the case of

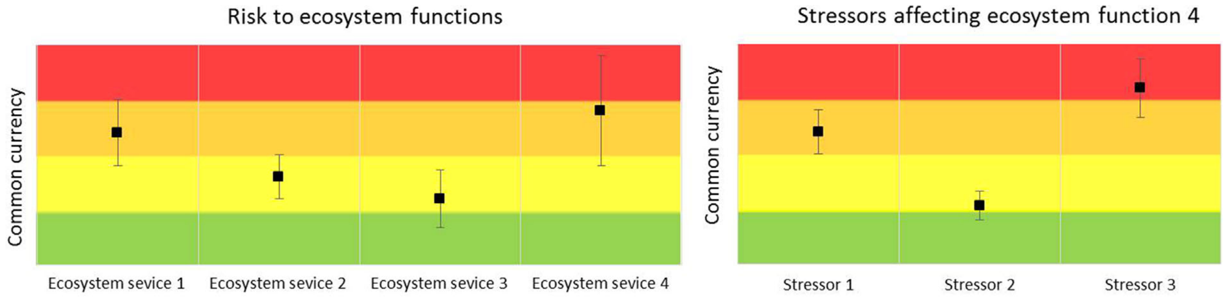

FIGURE 4: A visual approach to risk assessment and communication for both risks to ecosystem services (left) and severity of risk to ecosystem services from different stressors (right). This visual approach can incorporate both quantitative and qualitative data, as well as uncertainty, while allowing for risk-management prioritization. Red indicates relatively high risk and green, relatively low risk. Stressors and risks can also be color-coded as shown (e.g., to distinguish local from region stressors, biological from chemical stressors).

chemicals, information needs will center on their environmental and societal costs versus their benefits and possible alternatives. Similar trade-offs will apply to loss of human housing and other human structures and activities. Key information needs in this case would include the ecosystem services that would be lost versus the benefits and the potential for extreme events (e.g., floods, tidal surges, landslides, earthquakes) to cause damage to property and injury or loss of human life. Clearly, building on a floodplain, near a volcano, or below sea level is fraught with risks. However, people often accept these risks, sometimes despite established policies or laws. Ecosystems do not accept risks; they simply attempt to persist. Thus, a key risk-management information need would be the level of acceptable risk for humans and for ecosystem services as determined in collaboration with the communities of interest, in the face of uncertainty as to when an extreme event might occur and how resilient the impacted ecosystem might be. The Workshop discussed challenges related to communicating uncertainty, including reluctance to address evidence of uncertainty (i.e., uncertainty avoidance).

Risk management in cases such as climate change or invasive species (more prevalent with climate change) will realistically involve adaptation, based on the best possible predictions for an uncertain future. Efforts to eradicate invasive or introduced species have generally been inadequate, and new species are not always undesirable. For example, rainbow trout is an introduced species to eastern North America, Central and South America, and all other continents but is a highly desirable species globally for sport and commercial fishing. As another example, the Baltic Sea has been colonized by a new polychaete genus, *Marenzelleria* spp., which now dominates most of its sediment coastal areas. It burrows deeper than all other native benthic fauna and may thus lead to the release of previously buried legacy chemical contaminants [37], but it may also counteract eutrophication and resulting hypoxia by decreasing the release of phosphate from sediments [38].

Engagement of communities of interest that provide input to risk management can be increased by clear communication including developing with them simple models of different scenarios with appropriate boundaries to assess both reasonable and worst-case outcomes of risk-management decisions [1]. These different outcomes should be visual and should not rely solely on single numbers or cutoffs that fail to communicate uncertainty. We propose the simple traffic light approach (e.g., green = go, yellow = caution, red = stop), modified diagrammatically to show a range of risk predictions (from relatively low to relatively high risk, spanning 4 color-coded categories), in recognition of uncertainty. This approach is shown in Figure 4, a conceptual illustration of how risk can be estimated based on importance to the ecosystem(s) and not simply on an economic scale.

These diagrams could be based on an integration of probabilistic risk assessments using tools such as species sensitivity distributions, probabilistic population or community models, disturbance patterns, retrospective studies, and relevant reference conditions. They would be developed considering timescales, resilience, social and ethical issues, economic drivers, and ecosystem services valued by communities of interest, all of which will be context-dependent and case-dependent and require some level of best professional judgment.

One approach to address this complexity is through technological solutions that can support the risk-management and decision-making processes by pooling and communicating information, presenting uncertainties, and supporting multicriteria analyses. When designed together with communities of interest, these can provide powerful management and information tools [39].

Risk Assessment of Risk Management

All risk-management actions have both risks and benefits [40,41]. The challenge is to weigh risks and adverse consequences against benefits (see the text boxes *A hypothetical example of risk assessment and risk management of multiple stressors under changing environmental conditions relative to a defined protection goal*; *Examples of unintended consequences of risk mitigation actions*; and *Examples of the monetary and nonmonetary costs of overly*

Examples of the monetary and nonmonetary costs of overly conservative risk estimates and remediation goals. As previously noted (see section *Risk Assessment of Risk Management*), balance is required between acting too soon and acting too late.

- *Contaminated sediments* are driving ecological and beneficial use impairments in many human-dominated sediments. Dredging is generally the preferred option for remediating these systems. Dredging quantities are dictated by single-chemical cleanup goals that can be overly conservative; there are very few cases in which dredging has improved the dredged ecosystem [44]. However, there are clear economic impacts from dredging; residual contamination remains and is dispersed into the water column and downstream, and the dredged material must be disposed of with consequent environmental costs and risks from transport and disposal.
- *Selenium* is of increasing concern globally, related to potential reproductive effects to egg-laying animals (e.g., fish, birds, amphibians). Treatment to remove selenium from effluent discharges is dictated by toxicity benchmarks that can be overly conservative. As Chapman et al. [45] noted, "Se contamination of Belews Lake, Hyco and Kesterson Reservoirs (USA) resulted in whole-ecosystem exposures that had significant adverse population-level impacts. Few such widespread impacts on populations have been definitively documented in other ecosystems." These 3 historic cases of population-level impacts, which occurred over 2 decades ago, have not been repeated; but single-species toxicity benchmarks alone (i.e., without any other considerations) dictate treatment that involves habitat loss, greenhouse gas production, energy use, and other environmental costs in addition to economic costs. For example, in West Virginia (USA), local residents who initially wanted selenium treatment for coal mine runoff wished they had not when a scenic, forested hillside became the home for a large, unsightly selenium-treatment plant.

conservative risk estimates and remediation goals). For example, when is it preferable to substitute 1 product for another or the ingredients in a product? When are alternatives that will minimize potential risk necessary? How can unintended consequences be prevented? There is always the possibility of cascading events that may not be readily apparent.

Overly conservative risk estimates and remediation goals can result in excessive monetary (e.g., socioeconomic impacts) and nonmonetary (e.g., habitat loss, contaminant remobilization, loss of spiritual and recreational benefits) costs. The text box *Examples of the monetary and nonmonetary costs of overly conservative risk estimates and remediation goals* provides 2 examples in which remediation results in potentially greater risk to ecosystem services than originally existed as well as reduced benefits. Untimely management action can have both monetary and nonmonetary consequences. However, timely actions are also necessary when appropriate. For example, failure to act in a timely manner to prevent polychlorinated biphenyl contamination in the European Union was estimated to cost at least €15 billion [42]. Thus, as noted previously, balance is required between acting too soon and acting too late.

Because risk is dynamic, not static, it may change with time and even increase if risk-mitigation strategies are implemented without considering its evolution over time. Risk decisions must consider the possibility that increasingly extreme natural events may have dramatic impacts on ecosystems and risk predictions and that they will also affect other stressors. Natural stressors exacerbated by human activities (e.g., floods, droughts) now occur with increasing frequency and magnitude. They cause regime changes to ecosystem structure and function and to anthropogenic stressors such as contaminant exposures. Contaminants may be transported from land to water and vice versa, moving downstream, into estuaries or other transitional water bodies, or along coastlines. These altered contaminant distributions likely render previous predictions of ecological risk for those ecosystems irrelevant. The text box *Recommendations to improve risk management and risk assessment* includes specific recommendations to improve both risk assessment and risk management in this context.

Recommendations to improve risk management and risk assessment

- Risk assessments must consider inevitable extreme event impacts relative to stressor spatial patterns and recovery/resilience considerations. Tools for these evaluations, which will lead to further integrated risk assessments, remain to be developed.
- Focus on the cumulative impacts of all stressors, not individual stressors.
- Prioritization of stressors must consider not just absolute risks (e.g., environmental quality standards relative to policy determinations) but also relative risks that later can be used to prioritize stressors on the basis of monetary and nonmonetary costs.
- The risk-management process should designate a step in the decision-making process to consider unanticipated consequences (unknown unknowns and known unknowns), which will require new methods and tools to consider:
    - Direct and indirect economic impacts
    - Habitat degradation and loss
    - Invasive species
    - Harmful algal blooms
    - Contaminant dispersal
    - Future interactions with climate change (e.g., extreme weather events, rising temperatures)
    - Political boundaries

Adaptive and Flexible Regulatory Systems

There is a clear need to include a flexible and adaptive regulatory approach as part of an overall adaptive management approach. The current regulatory system is rigid, slow to act, and slow to change despite the reality of our rapidly changing world. For example, new chemicals are being developed and used at a much greater rate than they are being assessed, let alone regulated. Extensive resources are being spent to regulate a few chemicals and environmental issues, sometimes to an extent that is unreasonable (see the text box *Examples of the monetary and nonmonetary costs of overly conservative risk estimates and remediation goals*), whereas other chemicals and environmental issues go unregulated. Politically this approach may make sense, with overregulation in a few cases espoused as caring for the environment and human health. In reality this is inadequate and demonstrates a lack of appreciation for and appropriate prioritization of the environment and human health. All stressors of potential concern (i.e., not just contaminants) should be considered; however, this does not necessarily mean assessing all chemicals (e.g., Geiger et al. [43]).

Presently, most environmental criteria such as chemical benchmarks are numeric with 2 binary regulatory options. However, these benchmarks and regulatory options ignore the complex reality of chemical mixtures and the interactive effects of other stressors. It would be more appropriate to include a broader range of less precise criteria, for example, to regulate based on narrative protection goals (e.g., fishable, swimmable, drinkable water in a lake) that are holistic and adaptive rather than unnecessarily reductionist and prescriptive. Such benchmarks, if developed together with communities of interest, would begin to address the pressing issue of complex stressor combinations and the reality that risks do not occur in binary forms of risk or no risk.

Risk assessment and management must be allowed, by new regulations, to determine the major stressors in different environments; these may be chemical, nonchemical, or a combination. The risks from these major stressors should then be compared using the common currency of ecosystem services and evaluated by determining ranges of uncertainty rather than binary benchmarks that ignore uncertainty (see section *Risk Management Information Needs*, and Figure 4).

Summary

We provide 10 major, overarching recommendations (see the text box *The Roskilde workshop recommendations*). The focus of these recommendations is on improving risk assessment and risk management within the context of multiple risks and stressors in our changing world, recognizing that sustainable solutions to current and future challenges will require greater holism, flexibility, and participatory engagement.

The Roskilde workshop recommendations

1. Adopt ecosystem services as a common currency for risk assessment and management.
2. Consider cumulative stressors (chemical and nonchemical), and determine which dominate to best manage and restore ecosystem services.

Create partnership among risk assessors, risk managers, and communities of interest to:

3. Fully integrate risk managers and communities of interest into the risk-assessment process.
4. Fully integrate risk assessors and communities of interest into the risk-management process.
5. Consider socioeconomics and increased transparency in both risk assessment and risk management.
6. Recognize the ethical rights of humans and ecosystems to an adequate level of protection.
7. Determine relevant reference conditions and the proper ecological context for assessments in human-modified systems.
8. Assess risks and benefits to humans and the ecosystem, and consider unintended consequences of management actions.
9. Avoid excessive conservatism or possible underprotection resulting from sole reliance on binary, numerical benchmarks.
10. Develop adaptive risk-management and regulatory goals based on ranges of uncertainty.

Acknowledgment
We thank Roskilde University and their Environmental Risk Research Initiative for organizing, hosting, and funding this Sunrise Workshop. We also thank P. Sibley for very useful review comments. S. Loureiro acknowledges the financial support of CESAM (UID/AMB/50017), to FCT/MEC through national funds, and the cofunding by FEDER (POCI-01-0145-FEDER-007638), within the PT2020 Partnership Agreement and Compete 2020.

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The views expressed in the present Focus article are those of the individual authors and do not necessarily reflect the views or policies of any company, organization, or government agency. No official endorsement should be inferred.

Data Availability
Further information will be provided by the corresponding author (peter@chapmanenviro.com).

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