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Next generation application of DPSIR for sustainable policy implementation

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ABSTRACT

As our societies and natural systems are becoming ever more interconnected, it is critical that sustainable management can adapt to new knowledge from both the ecological and the social domains, and act on it in a timely and effective manner. This need is amplifying in the Anthropocene as we are approaching the limit for humanity's safe operating space, leading to irreversible change to ecosystem function. This urgently requires increased attention and concern regarding the information feedbacks between the silos of science, policy and society. A web of policies is in place to protect the health of people and the planet, but to ensure that they are effective we need frameworks to make sense of real-world complexities and interlinkages between multiple factors. The Drivers-Pressures-State-Impacts-Response (DPSIR) framework was created for this purpose, however, its' implicit focus on 1) analytical and 2) procedural aspects must be made explicit, to enable coordination across silos and studies. Continued creation of new DPSIR derivatives may limit its impact, while more explicit coordination between these two aspects can improve the effectiveness of DPSIR while retaining its flexibility. We thus propose five elements to support sustainable policy development and implementation using DPSIR: 1) iteration; 2) risk, uncertainty and analytical bias; 3) flexible integration; 4) use of quantitative methods, and; 5) clear and standard definitions for DPSIR. We illustrate these elements in four cases: Three highlight missing feedbacks when DPSIR elements are not made explicit and a fourth case – on *per*-and-polyfluorinated alkyl substances (PFAS) – showing a potential roadmap to successful policy implementation using DPSIR.

1. Introduction

It has become increasingly complex to assess the effectiveness of environmental legislation, to achieve the goal of preventing harm from anthropogenic activities on the health of humans and the environment (EEA, 2020; Fu et al., 2020; Kwiatkowski et al., 2020; Reid et al., 2018). To better understand how different policy interventions relate, and thereby facilitate such assessments, create transparency, and guide future interventions, frameworks such as Drivers-Pressures-State-Impacts-Response (DPSIR) have been developed. DPSIR represents a framework applied on coupled social-ecological systems (SES) which are composed of multiple, relatively separable, yet (nonlinearly) interacting subsystems (Ostrom, 2009). From previous SES studies, we recognize that understanding how the different elements relate is key to ensuring that intervention points are effective in achieving the set goals, and also efficient in creating change (Fritsch, 2017; Halbe et al., 2018) through transdisciplinary cooperation.

To achieve this across a variety of ecosystems and scales, frameworks should enable the flexible, interdisciplinary application of analytical methods (Binder et al., 2013). Further, frameworks must enable clear communication across stakeholder groups to prevent unavoidable inherent biases (Svarstad et al., 2008) and enhance policy relevance and uptake (Tscherning et al., 2011), which together will support effective governance and decision making (Halbe et al., 2018). Frameworks

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should enable not only downstream policy responses to recognized existing environmental challenges, but also support the design of a more sustainable upstream policy, thereby reducing the need and occurrence of stopgap measures (Buck et al., 2020) with potential for rebound effects.

Contemporary and emerging initiatives illustrate the need for frameworks to support both analysis and communication of innovative, post-normal scientific approaches. Without frameworks to support problem structuring, challenges plaguing e.g. implementation of the Water Framework Directive (WFD) (Voulvoulis et al., 2017) are likely to limit the success of nested strategies in new initiatives. For example, achieving carbon reduction may not always lead to improved surface water quality and may indeed hamper it (Lemaire et al., 2021; Marttila et al., 2020). Examples include the Chemicals strategy for sustainability (CSS) and Zero pollution ambition (ZPA) under the European Green Deal (EGD). The latter has many overlapping aims, for instance within the CSS, ZPA, Nature-based Solutions (NbS), Biodiversity strategy (BDS) and Farm to Fork (F2F) strategy. There is an opportunity for trans-disciplinary learning across initiatives supported by a framework such as DPSIR for enhanced knowledge co-creation (Norström et al., 2020). To achieve these multiple goals in increasingly complex settings requires that hurdles to prioritizing policy, science and society interactions be grappled with (Odume et al., 2021). This is needed to support policy efforts that aim to achieve sustainable management (European Commission, 2020a), within planetary boundaries (Randers et al., 2018; Rockström et al., 2009). Furthermore, challenges must be addressed beyond country or regional borders, and include extensive international cooperation (EEA, 2020). Achieving this will require a flexible and mutually intelligible framework for clear communication across research disciplines, political cultures and regions.

DPSIR has been extensively applied, functioning as a tool for assessing the sustainability of SES and covering a wide range of environmental issues (Gari et al., 2015). This includes topics such as urban ecosystems (Kohsaka, 2010; Zhao et al., 2021), ecotourism (Swangjang and Kornpiphat, 2021), marine and coastal management (Delgado et al., 2021), greenhouse agriculture policies (Liu et al., 2022) and desertification (Akbari et al., 2021). DPSIR has been applied (and recommended) by international organizations such as The Organisation for Economic Co-operation and Development, The European Environmental Agency and The United Nations Environment Programme, as well as within and across national and local organizations (Tscherning et al., 2011). Environmental reporting became a routine use for DPSIR, evolving to a conceptual framework for organizing information describing environmental problems via indicators and statistics, and their relationship to the socio-economic domain to support policy development and decision-making (Cooper, 2013; Svarstad et al., 2008). DPSIR is more often utilized European contexts, with Asian, African, American and Oceanic applications appearing less frequently in the literature (Troian et al., 2021).

Two related features that have contributed heavily to the use of DPSIR are: 1) It helps provide structure to environmental indicators with reference to political objectives, or policy responses; 2) it focuses on causal relationships, which is beneficial when analysing complex systems (Maxim et al., 2009), and managing informational flows (Kristensen, 2004). Broadly, these features are a part of the procedural and analytical aspects of DPSIR which have seen many suggestions for improvement in the literature.

Modifications to DPSIR have broadly sought to support the integration of additional methods and tools (Gari et al., 2015). Analytical methods have been qualitative, semi-quantitative and quantitative in nature (Lewison et al., 2016). Surprisingly, only a few studies have used DPSIR with both qualitative and quantitative tools simultaneously (see e.g. Benini et al., 2010; Zare et al., 2019). Procedural modifications have reshaped definitions (Gari et al., 2015; Oesterwind et al., 2016) and extended efforts to better incorporate additional interdisciplinary perspectives, such as policy-makers and other stakeholders (Bell, 2012).

Modified applications of DPSIR have reported positive outcomes, across multiple areas of environmental research (Anandhi et al., 2020; Gari et al., 2015). This shows the potential of DPSIR to harmonise and support important policy directives. For example, approaches that make the framework more accessible to stakeholders opens new opportunities for its use as a tool in fulfilling policy requirements, including those for increased public participation (Apostolaki et al., 2019; Voulvoulis et al., 2017).

The potential of the DPSIR framework cannot be realised if it becomes entangled with specific analytical approaches. We therefore argue that key challenge for DPSIR is therefore clarification and synthesis, with minimal standardisation, to allow for the inclusion of existing and novel approaches for evaluating environmental systems. To demonstrate this, we break down DPSIR into explicit elements of successful application. Our analysis draws upon systems thinking, reflecting previous modifications, to show why retaining the flexibility of the original DPSIR framework is crucial. We begin by introducing some previous modifications of DPSIR. Next, we frame the DPSIR approach based on the concept of information feedback and control (Fig. 1) to improve its potential for supporting meaningful, sustainable policy development and implementation. Finally, we illustrate this with examples from South Africa, China and Europe to demonstrate how DPSIR can continue to be useful across vastly different environmental topics, governance scales and geographies.

2. Background to DPSIR

Several reviews of DPSIR and its predecessor frameworks have been conducted (Cooper, 2013; Gari et al., 2015; Patrício et al., 2016), which track its creation and adaptation since its inception as the Stress-Response Environmental Statistical System, or S-RESS, (Rapport and Friend, 1979) to today's well-known DPSIR format used by the European Environment Agency for reporting on the state of the European environment in their five-year reports (EEA, 1995a) and its subsequent

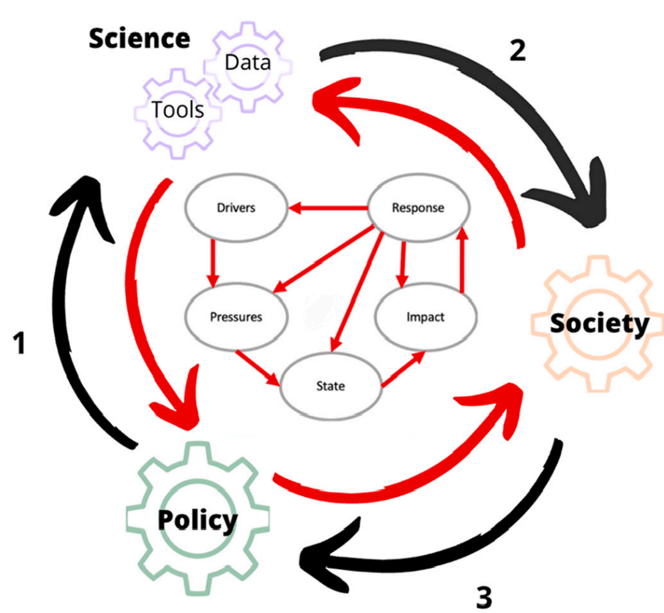

Fig. 1. DPSIR is a powerful tool to enable feedback between the three pillars of implementation by creating system wide (red and black) feedbacks. The black arrows indicate informational flow among the silos occurring within prevailing institutional arrangements. The red feedback emphasises the role of the DPSIR framework to create sectoral feedbacks (1, 2, & 3) to support the identification of weak or absent links among the silos. Once identified, efforts can then be (re) focused on procedural or analytical methods that can be used to strengthen these links. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

use and modifications. Summarizing and building upon these modifications, Gari et al. (2015) put forward six recommendations to support the evolution of DPSIR. We organize these into procedural and analytical aspects. Procedural aspects of DPSIR support transdisciplinary communication and interaction with stakeholders. Analytical aspects support analyses and collection of data to support understanding of the complex system:

Procedural:

- Terms should be clearly defined, and context explained to improve identification of ambiguous variables.
- Objectives should be evaluated together with stakeholders to prevent hierarchical bias.
- Multidisciplinary experts and stakeholders should be involved in the process.
- Local knowledge capacity should be evaluated and incorporated to achieve sustainable management.

Analytical:

- The system should be investigated comprehensively, applying DPSIR using established or novel field, laboratory, modelling and other approaches.
- Cause-effect relationships should be classified (e.g., positive, negative, synergistic, multiplicative) using additional research approaches to improve understanding of these relations.

Similar arguments regarding challenges to improve DPSIR are evidenced in the "Drivers-Activities-Pressures-State Change-Impacts (to Welfare)-Response (as Measures)" (DAPSI(*W*)R(M)) framework (Elliott et al., 2017; Patrício et al., 2016). DAPSI(*W*)R(M) couples explicitly to the ecosystem services concept to define state change, linking evaluation directly to human welfare impacts. This and other applications with explicit ecosystem services links (Apostolaki et al., 2019; Nassl and Löffler, 2015), can restrict integration with emerging approaches. Moreover, the application of an ecosystem services-based approach can overlook important trade-offs (Nesshöver et al., 2017), as well as functions of ecosystems which may not improve human wellbeing (e.g. allergies to pollen) (Kohsaka, 2010; Schaubroeck, 2017).

The DPSIR framework has also been criticised for not reporting objectively, introducing biases of the investigators and thus failing to deal with multiple stakeholder perspectives (Gupta et al., 2020; Svarstad et al., 2008). This may limit the equality of DPSIR analyses (Gupta et al., 2020). Perhaps as a means to overcome these deficiencies, studies have used DPSIR alongside semi-quantitative or quantitative analyses. Examples include expert-derived impact scores in a matrix-based approach; scaled vulnerability indices; impact and indicator indices; Bayesian Belief Networks (BBNs); steady-state biogeochemical models combined with empirical monitoring data; multivariate statistical approaches (Lewison et al., 2016) and system dynamics simulation (Zare et al., 2019).

Overall, the frequent literature recommendations to modify DPSIR actually stands as evidence of the flexibility of the original DPSIR framework (Lewison et al., 2016; Pacheco et al., 2007). In a recent review, Troian et al. (2021) analysed 63 articles on DPSIR applications in the realm of agriculture and aquatic ecosystems and found that DPSIR was combined with other approaches such as modelling (analytical) and stakeholder engagement (procedural) in 42% of those studies. However, the authors (ibid) noted that stakeholder engagement was, for the most part, vaguely described and therefore likely not well-leveraged.

It is a key point of departure for this paper that implicit strengths of DPSIR have not been made explicit, which has led to the creation of multiple incremental adaptations to fill this need. Therefore, a synthesis is needed that combines lessons from past recommendations while retaining the simplicity and flexibility that has made DPSIR so widely applied, leaving room for the incorporation of future environmental challenges and analysis of (policy) solution frameworks.

3. Method

3.1. Next generation application of DPSIR

Fig. 1 illustrates this updated conceptualisation centring on the three silos, Science, Society and Policy, which must be engaged to implement sustainable solutions for environmental challenges (Odume et al., 2021). The design and implementation of sustainable solutions must explicitly recognize and accelerate feedbacks across the system, and between each of the silos (Mastrángelo et al., 2019). The next generation application of DPSIR is represented conceptually by the red feedback loop that acts *across* the entire system. This creates feedbacks from (1) policy to science (and science to policy), (2) science to society (and society to science), and (3) society to policy (and policy to society) (Fig. 1). In each application, it is unlikely that all three of these individual feedbacks function simultaneously. However, they should all be activated during DPSIR application to ensure necessary information, originating within a silo, can be activated and drive the implementation of sustainable solutions.

We propose five elements focused on the concept of information feedback that can activate these three feedback mechanisms when applying DPSIR, namely: (1) procedural aspects that either (a) generate knowledge or (b) transfer knowledge and (2) analytical aspects that either (a) generate data or (b) make data useful. Importantly, these are intended to overlap one another – attention is most needed at the interfaces that create feedback between scientific research, policy formation and societal consequences.

Applying this framing, practitioners and researchers alike should be able to take stock of where their work or project is proceeding well and where it needs to be strengthened - encouraging evaluation of procedural elements of the work, such as communication with policymakers or stakeholders, as well as analytical aspects, such as an evaluation of the usefulness of a simulation model or missing data. In this manner, recognition of DPSIR procedural and analytical aspects has the potential to support the interaction between silos by identifying where informational feedback is present or lacking.

After presenting the five elements to support the next generation of DPSIR application, we ground our reasoning in four case studies to exemplify how the next-generation application of DPSIR can function, which can help to guide future work and ensure that all three feedbacks can become active by ensuring attention is given to both procedural and analytical aspects of the framework. To demonstrate this, we apply the five features to qualitatively evaluate four case studies. The first case features active application of DPSIR to show how an updated DPSIR concept can be directly applied. This is followed by two case studies that are chosen to investigate the missing feedbacks between different sectors. A final case, on *per*-and-polyfluorinated alkyl substances (PFAS), provides a solution roadmap.

3.2. Importance of iteration (procedural)

The iterative application of DPSIR is crucial to the development of an improved understanding of the system and identification of potential management actions and their intended or unintended results. The links forming feedbacks 1, 2 and 3 (Fig. 1) between the silos can be active independently and in parallel. DPSIR can collect and integrate information over time, improving determination of causality for a given environmental challenge. For example, strong feedback between science and society enabled through workshops, citizen-science efforts, etc. can elucidate the link between State and Impacts. DPSIR can capture this knowledge until additional iterations activate missing links in the feedback chain that are needed to reach implementation (i.e., link to policy).

In selecting the correct tools for addressing challenges in complex environmental systems, the analyst must make use of the available resources, working within the existing context and in relation to existing social factors whilst remaining adaptive (Clifford-Holmes et al., 2018; Voinov et al., 2018). Iteration with DPSIR allows for reflection on the choice of analytical technique, as emerging information gathered may indicate the need to, e.g., involve researchers/practitioners from other fields, engage with stakeholders previously not considered, or apply additional quantitative or qualitative methods. This allows DPSIR to align with recommendations to deliberately select a problem solving approach, and re-evaluate if it is found to be inappropriate for the task at hand (Voinov et al., 2018).

3.3. Addressing risk, uncertainty, and analytical bias (procedural/analytical)

Applications of the DPSIR framework should be transparent, with sensitivity towards the important roles of salience, credibility and legitimacy in shaping communication about uncertainty and bias offered by the lens of a given analytical technique (Saltelli et al., 2020a). Information must not only relate to scientific and political stakeholders but also to civil society, where many different definitions of risk and uncertainty have developed within silos (Wassénius and Crona, 2022). In fact, integrating diverse perspectives has been shown to be as effective for designing solutions for natural resource management as scientifically derived approaches (Aminpour et al., 2020). Such post-normal approaches are highly relevant to the potential for implementation of proposed solutions, supporting inclusion of the full spectrum of uncertainty, originating from individual subjective space possibilities (bias) due to variation in backgrounds (deficiencies as well as proficiencies) (Faulkner et al., 2017). Further, transparency is a fundamental cornerstone of EU policy processes (The European Parliament and of the Council, 2020).

As an example, consider stopgap measures put in place to "buy time" while more lasting solutions are pursued (Buck et al., 2020), which can also be characterised as "shifting the burden" to a temporary solution (Ford, 2010). Within a next-generation DPSIR application such measures might be considered as an interim solution, but should also utilize the feedback concept to ensure that sources of uncertainty are addressed from the respective "new" knowledge to reduce blind spots that can shift risk or resource exploitation elsewhere (Gupta et al., 2020). The EU Green Deal, together with the Paris Agreement, provide such an example, where carbon emissions targets are fulfilled at the cost of resource degradation elsewhere (Fuchs et al., 2020).

3.4. Importance of flexible integration (analytical)

DPSIR application must remain decoupled from specific analytical frames to remain relevant. An example of this necessity is Nature-based Solutions (NbS), a concept that embodies new ways to approach and optimize socio-ecological adaptation and resilience (Escobedo et al., 2019; European Commission, 2021)(European Commission, 2021; Escobedo et al., 2019). NbS aims to enhance the benefits for *both* nature and people in addressing various global societal challenges that are often intertwined, including climate adaptation (e.g. hydrometeorological risk reduction; (Ruangpan et al., 2020), food and energy security, and social and economic development (Faivre et al., 2017; Nesshöver et al., 2017). The increasing global application of NbS shows its potential for furthering the evaluation and restoration of natural systems and supporting biodiversity policy objectives (European Commission, 2020b). Furthermore, growing interest in NbS including current testing in several EU-funded projects may lead to its further incorporation into formal policy (Cohen-Shacham et al., 2019; Nesshöver et al., 2017; Seddon et al., 2020). Should this become reality, DPSIR derivatives that are coupled to specific analytical approaches, such as the aforementioned DAPSI(*W*)R(M) or the DPSIR-ESA would require an entire redesign.

A decoupled, flexible DPSIR would allow, for example, an NbS expert to be brought into the dialogue to ensure biodiversity policy objectives are achieved alongside ecosystem services for human well-being. This is a plausible example, especially as it has been pointed out that we lack knowledge of how to design and plan NbS in a non-anthropocentric manner (Pineda-Pinto et al., 2022; Viti et al., 2022), and the ramifications of this are evident (Lemaire et al., 2022; Marttila et al., 2020).

Further, If DPSIR continues to be coupled to specific methods, frameworks and analytical approaches, then the >25 DPSIR derivative frameworks currently found in the literature (Anandhi et al., 2020) are likely to fragment further. This would be a missed opportunity for shared insights across ecosystems, scales and geopolitical boundaries. For example, DPSIR can be useful in helping especially municipalities ensure they holistically design strategies, or at least can be open and honest about which trade-offs are necessary, especially within a peri-urban context (Lemaire et al., 2022).

3.5. Quantitative analysis in DPSIR (analytical)

A widely applied approach to operationalizing scientific knowledge is simulation modelling for decision support. This may be due to evidence that simulation models outperform expert judgement in prioritizing management actions for ecological systems (Czaika and Selin, 2017). Additionally, the application of modelling within the environmental domain point to its multiple uses, including to clarify values, explore trade-offs, and mediate conflicting perspectives (Bots and Van Daalen, 2008). However, such simulation models are also dependent upon system understanding and available data. Data can enrich simulation models and knowledge regarding environmental processes, which in-turn, enriches system understanding. Quantitative tools – even in data-scarce settings – can support the development of consensus in unique ways (Carnohan et al., 2021; Zulkafli et al., 2017). Advances in data visualisation in environmental settings is making this even more accessible to broader audiences than ever before (Grainger et al., 2016). DPSIR, as a framework that has evolved from reporting to analysis, has a strong communicative legacy. This gives it a unique position to drive the implementation of novel practices that can increase the uptake of science in society through democratization of knowledge.

3.6. Defining DPSIR (procedural)

The definitions of the DPSIR components are another important element, as they support qualitative analyses, and communication (within and between silos) as a procedural aspect. Definitions provide the boundary conditions and frame for the analysis and ultimately determine what to in- and exclude. Thus, updated, standardized definitions are an important tool to improve communication of results across disciplines. The sound meta-analysis provided by Oesterwind et al. (2016) led to a set of definitions which should be applicable in any ecosystem context, and which could be adopted as a standard. Indeed, Gupta et al. (2022) utilize these same definitions to structure their review of community-based actions to address SES challenges in mountain ecosystems at global scale. In another review, Quevedo et al. (2023) adapted the definitions from Oesterwind et al. (2016) to the context of mangrove degradation and management in Indonesia. It is reasonable to expect that these examples are reflective of the future best practices for DPSIR application with regards to consistency in definitions. While some differences in interpretation are likely unavoidable in all future applications, and updates are expected, departing from the Oesterwind et al. (2016) can provide consistency in communication across scales and resources.

4. Results: Illustrating feedback with DPSIR

4.1. Qualitative DPSIR analysis of nanosilver regulation in the EU

Hansen and Baun (2015) applied DPSIR in combination with stakeholder analysis to explore possibilities for reaching consensus among stakeholders regarding the regulation of nanosilver in Europe. The aim of the study was to explore the use of such a coupled approach as an alternative to quantitative risk assessment, which tends to lack focus on how to manage the environmental risks once identified. DPSIR analysis was first used to structure the available scientific and technical information describing the nature and level of potential risks and identify regulatory options that could be adopted with regards to the societal use of nanosilver. Stakeholder analysis was subsequently used to evaluate stakeholder preferences for implementing one or more of the identified regulatory options. Specifically, a top-down desktop approach was utilized (Reed et al., 2009), focussing on identifying and categorizing stakeholders, mapping their interests and interrelations, and assessing their importance and influence. A strength of this case study is that the analysis should serve to inform decision-makers about the best way to address nanosilver, which should increase the likelihood of stakeholder understanding, acceptance and buy-in with regards to regulatory options.

In their DPSIR analysis, the authors identified six regulatory response options that could address the drivers and pressures of nanosilver. These ranged from a “baseline option” of no action to a combined implementation of multiple up- and downstream policy options that emphasized nano-specific properties and risks. However, conflicting interests and values among industry and the NGOs ultimately revealed that a consensus policy option could not be found. This has led to a top-down regulation approach, via Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), which has created a web of detailed and sometimes ambiguously defined compliance demands for other stakeholders (Clausen and Hansen, 2018).

This application of DPSIR, in combination with stakeholder analysis, addressed some of the shortcomings discussed previously. However, Fig. 2 illustrates the missing connections to achieve a next generation result. As the authors performed the analysis from their desktop, biases were likely introduced into the policy options that were later presented to stakeholders. Here, the importance of iteration and transparent/inclusive risk and uncertainty assessment is clear. A potential next step would be to initiate a process in which stakeholders are given a stronger voice in the analytical process to explore if consensus solution could be found (activating feedback 1 in Fig. 2). While the authors were deliberate with their choice to remain qualitative, additional analytical techniques may have been useful to increase credibility and salience of policy options (activating feedback 3).

4.2. Quantitative DPSIR analysis of greening in China

In the period 2000–2017, a global increase in leaf vegetation area (commonly referred to as “greening”) was reported, where China alone was found to have contributed with ca. 25% of the total increase. Of China’s contributions, ca. 42% came from conserving and expanding forests, and 32% from cropping (Chen et al., 2019). These changes have been encouraged by China’s Sloping Land Conversion Policy, or “Grain for Green” Policy initiated in 1999, which aimed to reduce soil erosion and air pollution impacts by replacing marginal agricultural land with forest alongside broader reforestation efforts (Qu et al., 2017). Analysis of the increased greening across China was conducted using a process-based ecohydrological model, examining gross primary production (GPP) and water loss directly from plants to atmosphere as evapotranspiration (ET) (Mo et al., 2018).

The annual GPP was found to be significantly increasing in all four of China’s climatic zones. Overall, the reforestation process is expected to greatly improve environmental protection and land degradation recovery (Chen et al., 2019). However, increasing ET will also reduce water availability for agricultural irrigation and industry under climate change, which will affect the social and economic sustainability.

With greening observable across China (i.e., via remote sensing), the iterations of quantitative analysis provided a more complete understanding of the coupling between the current state and any impacts, thus providing a basis for policy refinement. However, feedback is lacking from society and incorporating local knowledge could help target policy responses and support meaningful use of the existing data (Fig. 3) (Norström et al., 2020). In this case, mitigating water scarcity impacts is urgently needed in areas that are coming under the greatest pressure due to changing climatic conditions (Feng et al., 2016).

4.3. Semi-quantitative DPSIR analysis of Integrated Water Resources Management (IWRM) in South Africa

The Olifants River Catchment (ORC) underpins the economy of South Africa – providing water resources for a wide variety of industries, agriculture and tourism, as well as potable water for communities. Within a tributary of the ORC, the Selati River, mining, agriculture, tourism/conservation and municipal wastewater treatment works (WWTW) are each guided by different drivers. Water quality impacts to biodiversity downstream, including in Kruger National Park, led to the application of system dynamics modelling. Participatory modelling techniques involved stakeholders within a group decision-making space.

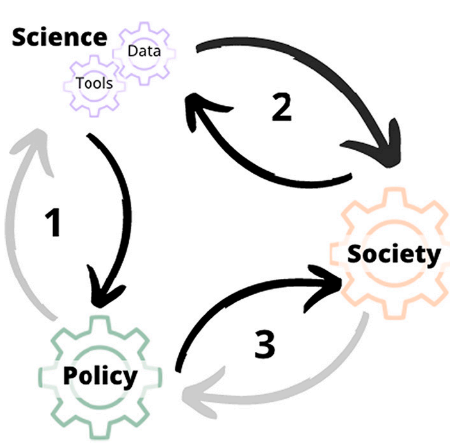

Fig. 2. DPSIR feedback analysis of nanosilver regulation in the EU showing the need for additional tools/procedures to fill the gap between science and policy (feedback 1), and society and policy (feedback 2).

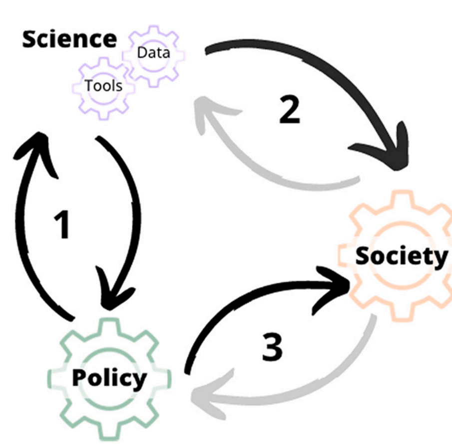

Fig. 3. DPSIR feedback analysis for Greening in China case study, where strong feedback between science and policy are present, but a lacking feedback to societal needs creates unintended consequences.

Because participants were involved in building the model, they gained ownership of the theory of the system that emerged and developed a shared language for discussing systemic problems. The resulting model was then used to test the impact of various policies/interventions, to support higher order learning among the participants.

In this data-scarce environment, the model development integrated: iterative stakeholder interviews and workshops, downscaled global climate modelling outputs, in-stream pollutant load data from other hydrological models, species-sensitivity distribution curves and reports gathered by local and national level public institutions (Carnohan et al., 2021). The final model was used to facilitate discussions with stakeholders that led to an enriched understanding of the interdependency of the drivers, pressures and state of the system, which lead to the undesirable impacts.

The mechanisms through which the drivers lead to pressures were simulated as scenarios: flooding caused by heavy rainfall, leading to overflowing mining tailings dams, causing spikes in sulphate concentrations, and under-capacity WWTW delivering high concentrations of phosphates. Participatory workshops with stakeholders from local and national organizations identified several potential responses and simulated the impacts until 2050. These results were communicated as narratives, videos and simulation results supported with conceptual diagrams. Participants' reflections, measured through a monitoring and evaluation process (Carnohan et al., 2021), indicated knowledge co-creation and learning had occurred.

A strength of this case study is its effective use of novel analytical methods to synthesize qualitative and quantitative data. The visualisation techniques and participatory approach reflect contemporary currents in environmental science (Grainger et al., 2016; Luna-Reyes et al., 2018). In particular the research team occupied different roles to facilitate knowledge exchange (Pohl et al., 2010). In addition, the approach taken was highly iterative and allowed for integration with other tools and scientific findings to respond to findings in process.

The multiple iterations between the simulation team and efforts to communicate scientific impacts via integrated modelling and visualisation activated feedback 2 (Fig. 4) (Pollard et al., 2020). The tool was subsequently used with members of the nascent Olifants Catchment Management Agency, which offered a route to national and regional policymaking (feedback 1). An unsteady governance environment prevented the continuation of this mixed-methods approach at a broader scale, although the systemic approach continued to be used within the project's institutional home (Pollard et al., 2020). The development of a visual user interface (VUI) to support use of, and broader local engagement with the tool was also undertaken (feedback 3). Further iterations should focus on the advancement of these findings to the policy level.

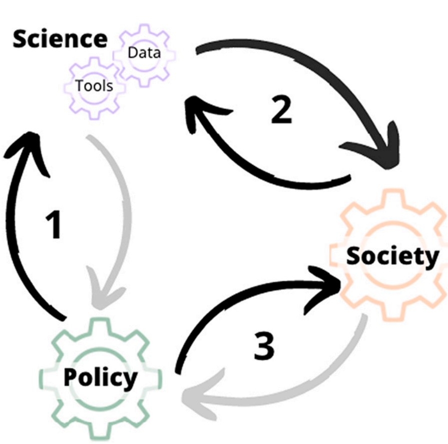

Fig. 4. DPSIR feedback analysis for the IWRM case in SA. The iterative process succeeded in generating good dialogue via the use of scientific tools, feedback to policy is needed, however, to drive implementation of identified solutions.

4.4. Next generation DPSIR roadmap: per-and-polyfluorinated alkyl substances (PFAS) and human health

The group of per-and-polyfluorinated alkyl substances (PFAS) comprise >9000 synthetic organofluoride chemicals, and with a few exceptions they are all of anthropogenic origin, first emerging alongside the discovery of Teflon in 1938. The types of PFAS and their uses have since diversified into all parts of modern life, ranging from industrial production, advanced materials (e.g. renewable energy technologies, medicines, agrochemicals) and in consumer products (e.g. textiles, food contact materials, cell phones) (Glüge et al., 2020). The extensive applications are linked to the properties of PFAS; resisting physical and chemical degradation, and repellence of water, oil and soil. However, PFAS are also highly persistent compounds, which has led to a global contamination and accumulation of PFAS in people and the environment. Studies have shown that the vast majority of single PFAS are harmful to humans and other living organisms (Kwiatkowski et al., 2020). Especially in Europe and North America, actions to prevent and control PFAS pollution has, since the late 1990s, occurred faster and across more legislations and countries than for any other broad group of chemicals. Close interaction between all three levels of policy, science and society can be observed through the DPSIR informational feedbacks (Fig. 1).

Science has played a key role in the discovery of widespread environmental PFAS pollution. Crucially, efforts were made to communicate, not only within scientific communities, but also to policymakers and the public. In 2012, evidence revealed that one of the manufacturing companies had known, and kept quiet for >50 years, about the immunotoxicity of some PFAS. This led to the Helsingør Statement, where academic and authority scientists summarised the evidence, their concerns, and knowledge gaps in PFAS science, and called for action across stakeholders to prevent further PFAS pollution (Scheringer et al., 2014). This created momentum to initiate studies and further engagement and served as a signal to industry to phase-out PFAS. These combined actions led to increased societal awareness as a sense of community developed between scientists, authorities, NGOs, frontrunning businesses and media. In 2015, the Madrid Statement further emphasized stakeholder engagement giving NGOs increasing ownership, further strengthening feedback between science and society (Blum, 2015).

The link to policy was strengthened during the creation of the 2017 Stockholm Statement, where the Swedish chemicals agency played a key role (Cousins et al., 2020). Discussions led to the realisation that managing the thousands of PFAS traditionally, substance-by-substance, would not be sufficient in the case of PFAS. As linkages among and between the three silos were bolstered, the paradigm of PFAS regulation began to change. Additional analysis was required, surfacing insights about addressing PFAS as (sub)-groups (Cousins et al., 2020) and clarifying scientific arguments that multiple lines of evidence point to a need to address PFAS as a class (Kwiatkowski et al., 2020). In 2020, the EU PFAS strategy was published (European Commission, 2020c) with a long list of actions to be taken, and shortly after, the EU Drinking Water Directive (targeting a combination of 20 single and the whole group of PFAS) (European Commission, 2018) was adopted. An EU PFAS restriction of all non-essential uses of PFAS under the EU REACH regulation is foreseen for 2022.

Multiple iterations of feedback between the silos were supported and informed by analyses. Studies of relevance provided scientific evidence regarding toxicity, and economic studies showed the cost of inaction on PFAS providing economic and political argumentation for pollution prevention, rather than trying to remediate. This led to the development of sustainable policy responses tempered by the risks posed to human health, and recognition of the inadequacy of other response options (i.e., threshold values for single PFAS). Based on this well-functioning system of collaboration, restrictions for PFAS as a class across all uses at the EU level for industrial chemicals is expected as a next step.

5. Discussion

The multiple tools and approaches from each case were illustrative of the need for explicit recognition of analytical lenses used to support DPSIR application. It is likely that both qualitative and quantitative approaches are best used in combination to reach implementable and sustainable solutions by encouraging collaboration based upon scientific insight, ensuring transparency of biases found in methods, the analysts themselves and stakeholders (Saltelli et al., 2020b, 2020a). Frameworks like DPSIR serve an important role in encouraging the integration of emerging analytical approaches such as NbS and novel application of existing methodologies.

A critical aspect for many environmental issues lies within the scale of analysis, and the need for frameworks that can handle scalability and transferability when designing policy responses. By organizing information using the DPSIR framework, a suite of scientific research – spanning from qualitative (ethnographic analyses) to quantitative (simulation modelling) – could be synthesized and communicated holistically. This may help advance the use of DPSIR more frequently outside of European contexts, creating exciting learning opportunities for communities of practitioners and researchers alike. Furthermore, it can help situate the role of data in policy making, balanced by the ability to synthesize it into meaningful information for end-users. By focusing on the five elements of DPSIR, its flexible, yet synthesising capabilities can be leveraged across geopolitical boundaries – espousing benefits and exposing drawbacks of the different approaches used over time. Indeed, a key advantage of the iterative element of DPSIR may be its improved temporal flexibility, as its application need not be limited to the start of a project, as presented in the case studies. We encourage researchers embarking on a project using DPSIR to iteratively apply the framework when they encounter resistance to help prioritise actions.

The next generation DPSIR affords an opportunity for co-generation of knowledge across case studies, disciplines and silos, leveraging the procedural aspect of DPSIR. Transparent cataloguing of the limitations and challenges encountered should accompany this process to avoid complacency (Saltelli et al., 2020a), and can take advantage of DPSIR strengths as a reporting tool. A next step should be to develop a generic reporting guideline that incorporates the five elements of next generation DPSIR application. This could be implemented as a web-based portal that can connect disparate groups facing similar challenges (e.g. Hovmand et al., 2011). Simultaneously, communication should be friendly to scientific and non-scientific communities to increase transparency across different stakeholder groups, regardless of which silo they occupy. As other research investigating how to strengthen the integration of trans-disciplinary research at the science-policy-society interface has shown, there are many challenges that hamper our ability to address complex social-ecological challenges (Odume et al., 2021).

6. Conclusions

This paper has sought to make explicit the implicit strengths of the enduring DPSIR framework, and proposed five key elements for its successful, next-generation application. Case study examples illustrated how this revisited conceptualisation of DPSIR can be used to identify missing feedbacks that may hamper co-production of knowledge, bridging silos and enabling sustainable implementation of policies that serve society and are based upon science. Cases were chosen to show how DPSIR can be used to analyse projects at different scales and in different cultural contexts. However, we have not demonstrated the application of these elements in an active research project, having applied the concept retroactively, and we expect that active use of DPSIR using the five elements will lead to further learnings and evaluation potentials. This can be accomplished through deployment of DPSIR as an iterative, risk and bias conscious, integrative, and well-defined framework. With the elements of DPSIR that have contributed to its extensive application now made more explicit, it is better positioned to support development and implementation of sustainable policy in a complex, interconnected world.

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Declaration of Competing Interest

The authors declare no conflict of interest regarding this publication. The views expressed in the article are the authors' and do not necessarily represent view of the European Environment Agency.

Data availability

Data will be made available on request.

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References

Akbari, M., Memarian, H., Neamatollahi, E., Jafari Shalamzari, M., Alizadeh Noughani, M., Zakeri, D., 2021. Prioritizing policies and strategies for desertification risk management using MCDM–DPSIR approach in northeastern Iran. Environ. Dev. Sustain. 23, 2503–2523. https://doi.org/10.1007/S10668-020-00684-3/TABLES/3.

Aminpour, P., Gray, S.A., Jetter, A.J., Introne, J.E., Singer, A., Arlinghaus, R., 2020. Wisdom of stakeholder crowds in complex social–ecological systems. Nat. Sustain. 3, 191–199. https://doi.org/10.1038/s41893-019-0467-z.

Anandhi, A., Douglas-Mankin, K.R., Srivastava, P., Aiken, R.M., Senay, G., Leung, L.R., Chaubey, I., 2020. DPSIR-ESA vulnerability assessment (DEVA) framework: synthesis, foundational overview, and expert case studies. Trans. ASABE 63, 741–752. https://doi.org/10.13031/trans.13516.

Apostolaki, S., Koundouri, P., Pittis, N., 2019. Using a systemic approach to address the requirement for integrated water resource management within the water framework directive. Sci. Total Environ. 679, 70–79. https://doi.org/10.1016/j.scitotenv.2019.05.077.

Bell, S., 2012. DPSIR = a Problem Structuring Method? An Exploration from the "'Imagine'" Approach. https://doi.org/10.1016/j.ejor.2012.04.029.

Benini, L., Bandini, V., Marazza, D., Contin, A., 2010. Assessment of land use changes through an indicator-based approach: a case study from the Lamone river basin in northern Italy. Ecol. Indic. 10, 4–14. https://doi.org/10.1016/j.ecolind.2009.03.016.

Binder, C.R., Hinkel, J., Bots, P.W.G., Pahl-Wostl, C., 2013. Comparison of frameworks for analyzing social-ecological systems. Ecol. Soc. 18, art26. https://doi.org/10.5751/ES-05551-180426.

Blum, A., 2015. Perspectives | brief communication the Madrid statement on poly- and. Environ. Health Perspect. 123, A107–A111. https://doi.org/10.1021/es201662b.Fei.

Bots, P.W.G., Van Daalen, C.E., 2008. Participatory model construction and model use in natural resource management: a framework for reflection. Syst. Pract. Action Res. 21, 389–407. https://doi.org/10.1007/s11213-008-9108-6.

Buck, H.J., Martin, L.J., Geden, O., Kareiva, P., Koslov, L., Krantz, W., Kravitz, B., Noël, J., Parson, E.A., Preston, C.J., Sanchez, D.L., Scarlett, L., Talati, S., 2020. Evaluating the efficacy and equity of environmental stopgap measures. Nat. Sustain. 3, 499–504. https://doi.org/10.1038/s41893-020-0497-6.

Carnohan, S.A., Clifford-Holmes, J.K., Retief, H., McKnight, U.S., Pollard, S., 2021. Climate change adaptation in rural South Africa: using stakeholder narratives to build system dynamics models in data-scarce environments. J. Simul. 15, 5–22. https://doi.org/10.1080/17477778.2020.1762516.

Chen, C., Park, T., Wang, X., Piao, S., Xu, B., Chaturvedi, R.K., Fuchs, R., Brovkin, V., Ciais, P., Fensholt, R., Tømmervik, H., Bala, G., Zhu, Z., Nemani, R.R., Myneni, R.B., 2019. China and India lead in greening of the world through land-use management. Nat. Sustain. 2, 122–129. https://doi.org/10.1038/s41893-019-0220-7.

Clausen, L.P.W., Hansen, S.F., 2018. The ten decrees of nanomaterials regulations. Nat. Nanotechnol. https://doi.org/10.1038/s41565-018-0256-2.

Clifford-Holmes, J.K., Carnohan, S.A., Palmer, C., Pollard, S., Slinger, J.H., 2018. Modelling as bricolage. In: 36th International Conference of the System Dynamics Society. Ryekjavik, Iceland, p. Presentation.

Cohen-Shacham, E., Andrade, A., Dalton, J., Dudley, N., Jones, M., Kumar, C., Maginnis, S., Maynard, S., Nelson, C.R., Renaud, F.G., Welling, R., Walters, G., 2019. Core principles for successfully implementing and upscaling nature-based solutions. Environ. Sci. Pol. https://doi.org/10.1016/j.envsci.2019.04.014.
Cooper, P., 2013. Socio-ecological accounting: DPSWR, a modified DPSIR framework, and its application to marine ecosystems. Ecol. Econ. 94, 106–115. https://doi.org/10.1016/j.ecolecon.2013.07.010.
Cousins, I.T., Dewitt, J.C., Glüge, J., Goldenman, G., Herzke, D., Lohmann, R., Miller, M., Ng, C.A., Scheringer, M., Vierke, L., Wang, Z., 2020. Strategies for grouping per-and polyfluoroalkyl substances (PFAS) to protect human and environmental health. Environ Sci Process Impacts 22, 1444–1460. https://doi.org/10.1039/d0em00147c.
Czaika, E., Selin, N.E., 2017. Model use in sustainability policy making: an experimental study. Environ. Model. Softw. 98, 54–62. https://doi.org/10.1016/j.envsoft.2017.09.001.
Delgado, L.E., Zúñiga, C.C., Asún, R.A., Castro-Díaz, R., Natenzon, C.E., Paredes, L.D., Pérez-Orellana, D., Quiñones, D., Sepúlveda, H.H., Rojas, P.M., Olivares, G.R., Marín, V.H., 2021. Toward social-ecological coastal zone governance of Chiloé Island (Chile) based on the DPSIR framework. Sci. Total Environ. 758, 143999 https://doi.org/10.1016/J.SCITOTENV.2020.143999.
EEA, 2020. Drivers of Change of Relevance for Europe's Environment and Sustainability. European Environment Agency (EEA), Copenhagen, Denmark. https://doi.org/10.2800/129404.
Elliott, M., Burdon, D., Atkins, J.P., Borja, A., Cormier, R., de Jonge, V.N., Turner, R.K., 2017. "And DPSIR begat DAPSI(W)R(M)!" - a unifying framework for marine environmental management. Mar. Pollut. Bull. 118, 27–40. https://doi.org/10.1016/j.marpolbul.2017.03.049.
Escobedo, F.J., Giannico, V., Jim, C.Y., Sanesi, G., Lafortezza, R., 2019. Urban forests, ecosystem services, green infrastructure and nature-based solutions: Nexus or evolving metaphors? Urban For. Urban Green. 37, 3–12. https://doi.org/10.1016/J.UFUG.2018.02.011.
European Commission, 2018. Proposal for a Directive on the quality of water intended for human consumption. http://Ec.Europa.Eu/Environment/Water/Water-Drink/Review_En.Html0332.
European Commission, 2020a. EU Chemicals Strategy for Sustainability Towards a Toxic-Free Environment. Brussels.
European Commission, 2020b. Biodiversity and nature-based. Solutions. https://doi.org/10.2777/183298.
European Commission, 2020c. Poly- and perfluoroalkyl substances (PFAS): chemicals strategy for sustainability towards a toxic-free environment. Comm. Staff Work. Doc. 1–22. SWD(2020)249.
European Commission, 2021. Evaluating the Impact of Nature-Based Solutions: A Handbook for Practitioners.
Faivre, N., Fritz, M., Freitas, T., de Boissezon, B., Vandewoestijne, S., 2017. Nature-based solutions in the EU: innovating with nature to address social, economic and environmental challenges. Environ. Res. 159, 509–518. https://doi.org/10.1016/J.ENVRES.2017.08.032.
Faulkner, P., Feduzi, A., Runde, J., 2017. Unknowns, Black swans and the risk/uncertainty distinction. Cambridge J. Econ. 41, 1279–1302. https://doi.org/10.1093/cje/bex035.
Feng, X., Fu, B., Piao, S., Wang, S., Ciais, P., Zeng, Z., Lü, Y., Zeng, Y., Li, Y., Jiang, X., Wu, B., 2016. Revegetation in China's loess plateau is approaching sustainable water resource limits. Nat. Clim. Chang. 6, 1019–1022. https://doi.org/10.1038/nclimate3092.
Ford, A., 2010. Modeling the Environment, 2nd ed. Island Press, Island Press.
Fritsch, O., 2017. Integrated and adaptive water resources management: exploring public participation in the UK. Reg. Environ. Chang. https://doi.org/10.1007/s10113-016-0973-8.
Fu, B., Horsburgh, J.S., Jakeman, A.J., Gualtieri, C., Arnold, T., Marshall, L., Green, T.R., Quinn, N.W.T., Volk, M., Hunt, R.J., Vezzaro, L., Croke, B.F.W., Jakeman, J.D., Snow, V., Rashleigh, B., 2020. Modeling water quality in watersheds: from Here to the next generation. Water Resour. Res. 56 https://doi.org/10.1029/2020WR027721.
Fuchs, R., Brown, C., Rounsevell, M., 2020. Europe's Green Deal offshores environmental damage to other nations. Nature. https://doi.org/10.1038/d41586-020-02991-1.
Gari, S.R., Newton, A., Icely, J.D., 2015. A review of the application and evolution of the DPSIR framework with an emphasis on coastal social-ecological systems. Ocean Coast. Manag. 103, 63–77. https://doi.org/10.1016/j.ocecoaman.2014.11.013.
Glüge, J., Scheringer, M., Cousins, I.T., Dewitt, J.C., Goldenman, G., Herzke, D., Lohmann, R., Ng, C.A., Trier, X., Wang, Z., 2020. An overview of the uses of per- and polyfluoroalkyl substances (PFAS). Environ Sci Process Impacts 22, 2345–2373. https://doi.org/10.1039/d0em00291g.
Grainger, S., Mao, F., Buytaert, W., 2016. Environmental data visualisation for non-scientific contexts : literature review and design framework. Environ. Model. Softw. 85, 299–318. https://doi.org/10.1016/j.envsoft.2016.09.004.
Gupta, J., Scholtens, J., Perch, L., Dankelman, I., Seager, J., Sánder, F., Stanley-Jones, M., Kempf, I., 2020. Re-imagining the driver–pressure–state–impact–response framework from an equity and inclusive development perspective. Sustain. Sci. 15, 503–520. https://doi.org/10.1007/s11625-019-00708-6.
Gupta, H., Nishi, M., Gasparatos, A., 2022. Community-based responses for tackling environmental and socio-economic change and impacts in mountain social–ecological systems. Ambio 51, 1123–1142. https://doi.org/10.1007/s13280-021-01651-6.
Halbe, J., Pahl-Wostl, C., Adamowski, J., 2018. A methodological framework to support the initiation, design and institutionalization of participatory modeling processes in water resources management. J. Hydrol. 556, 701–716. https://doi.org/10.1016/j.jhydrol.2017.09.024.
Hansen, S.F., Baun, A., 2015. DPSIR and stakeholder analysis of the use of Nanosilver. Nanoethics 9, 297–319. https://doi.org/10.1007/s11569-015-0245-y.
Hovmand, P.S., Andersen, D.F., Calhoun, A., 2011. Scriptapedia: A Handbook of Scripts for Developing Structured Group Model Building Sessions, 1, pp. 1–16.
Kohsaka, R., 2010. Developing biodiversity indicators for cities: applying the DPSIR model to Nagoya and integrating social and ecological aspects. Ecol. Res. 25, 925–936. https://doi.org/10.1007/s11284-010-0746-7.
Kristensen, P., 2004. The DPSIR Framework.
Kwiatkowski, C.F., Andrews, D.Q., Birnbaum, L.S., Bruton, T.A., Dewitt, J.C., Knappe, D. R.U., Maffini, M.V., Miller, M.F., Pelch, K.E., Reade, A., Soehl, A., Trier, X., Venier, M., Wagner, C.C., Wang, Z., Blum, A., 2020. Scientific basis for managing PFAS as a chemical class. Environ. Sci. Technol. Lett. 7, 532–543. https://doi.org/10.1021/acs.estlett.0c00255.
Lemaire, G.G., Carnohan, S.A., Grand, S., Mazel, V., Bjerg, P.L., Mcknight, U.S., 2021. Data-driven system dynamics model for simulating water quantity and quality in peri-urban streams. Water 13 (21), 3002. https://doi.org/10.3390/w13213002.
Lemaire, G.G., Jessen Rasmussen, J., Höss, S., Figari Kramer, S., Schittich, A.R., Zhou, Y., Köppl, C.J., Traunspurger, W., Bjerg, P.L., McKnight, U.S., 2022. Land use contribution to spatiotemporal stream water and ecological quality: implications for water resources management in peri-urban catchments. Ecol. Indic. 143, 109360 https://doi.org/10.1016/J.ECOLIND.2022.109360.
Lewison, R.L., Rudd, M.A., Al-Hayek, W., Baldwin, C., Beger, M., Lieske, S.N., Jones, C., Satumanatpan, S., Junchompoo, C., Hines, E., 2016. How the DPSIR framework can be used for structuring problems and facilitating empirical research in coastal systems. Environ. Sci. Pol. 56, 110–119. https://doi.org/10.1016/j.envsci.2015.11.001.
Liu, S., Deichmann, M., Moro, M.A., Andersen, L.S., Li, F., Dalgaard, T., McKnight, U.S., 2022. Targeting sustainable greenhouse agriculture policies in China and Denmark: A comparative study. Land Use Policy 119, 106148. https://doi.org/10.1016/j.landusepol.2022.106148.
Luna-Reyes, L.F., Black, L.J., Ran, W., Andersen, D.L., Jarman, H., Richardson, G.P., Andersen, D.F., 2018. Modeling and simulation as boundary objects to facilitate interdisciplinary research. Syst. Res. Behav. Sci. https://doi.org/10.1002/sres.2564.
Marttila, H., Lepistö, A., Tolvanen, A., Bechmann, M., Kyllmar, K., Juutinen, A., Wenng, H., Skarbøvik, E., Futter, M., Kortelainen, P., Rankinen, K., Hellsten, S., Kløve, B., Kronvang, B., Kaste, Ø., Solheim, A.L., Bhattacharjee, J., Rakovic, J., de Wit, H., 2020. Potential impacts of a future Nordic bioeconomy on surface water quality. Ambio 49, 1722–1735. https://doi.org/10.1007/s13280-020-01355-3.
Mastrángelo, M.E., Pérez-Harguindeguy, N., Enrico, L., Bennett, E., Lavorel, S., Cumming, G.S., Abeygunawardane, D., Amarilla, L.D., Burkhard, B., Egoh, B.N., Frishkoff, L., Galetto, L., Huber, S., Karp, D.S., Ke, A., Kowaljow, E., Kronenburg-García, A., Locatelli, B., Martín-López, B., Meyfroidt, P., Mwampamba, T.H., Nel, J., Nicholas, K.A., Nicholson, C., Oteros-Rozas, E., Rahlao, S.J., Raudsepp-Hearne, C., Ricketts, T., Shrestha, U.B., Torres, C., Winkler, K.J., Zoeller, K., 2019. Key knowledge gaps to achieve global sustainability goals. Nat. Sustain. 2, 1115–1121. https://doi.org/10.1038/s41893-019-0412-1.
Maxim, L., Spangenberg, J.H., Connor, M.O., 2009. An analysis of risks for biodiversity under the DPSIR framework. Ecol. Econ. 69, 12–23. https://doi.org/10.1016/j.ecolecon.2009.03.017.
Mo, X., Liu, S., Chen, X., Hu, S., 2018. Variability, tendencies, and climate controls of terrestrial evapotranspiration and gross primary productivity in the recent decade over China. Ecohydrology 11, e1951. https://doi.org/10.1002/eco.1951.
Nassl, M., Löffler, J., 2015. Ecosystem services in coupled social–ecological systems: closing the cycle of service provision and societal feedback. Ambio 44, 737–749. https://doi.org/10.1007/s13280-015-0651-y.
Nesshöver, C., Assmuth, T., Irvine, K.N., Rusch, G.M., Waylen, K.A., Delbaere, B., Haase, D., Jones-Walters, L., Keune, H., Kovacs, E., Krauze, K., Külvik, M., Rey, F., Van Dijk, J., Vistad, O.I., Wilkinson, M.E., Wittmer, H., Vistad, I., Wilkinson, M.E., Wittmer, H., Vistad, O.I., Wilkinson, M.E., Wittmer, H., 2017. The science, policy and practice of nature-based solutions: an interdisciplinary perspective. Sci. Total Environ. 579, 1215–1227. https://doi.org/10.1016/j.scitotenv.2016.11.106.
Norström, A.V., Cvitanovic, C., Löf, M.F., West, S., Wyborn, C., Balvanera, P., Bednarek, A.T., Bennett, E.M., Biggs, R., de Bremond, A., Campbell, B.M., Canadell, J.G., Carpenter, S.R., Folke, C., Fulton, E.A., Gaffney, O., Gelcich, S., Jouffray, J., Leach, M., Le Tissier, M., Martín-López, B., Louder, E., Loutre, M., Meadow, A.M., Nagendra, H., Payne, D., Peterson, G.D., Reyers, B., Scholes, R., Speranza, C.I., Spierenburg, M., Stafford-Smith, M., Tengö, M., van der Hel, S., van Putten, I., Österblom, H., 2020. Principles for knowledge co-production in sustainability research. Nat. Sustain. 3, 182–190. https://doi.org/10.1038/s41893-019-0448-2.
Odume, O.N., Amaka-Otchere, A.B., Onyima, B.N., Aziz, F., Kushitor, S.B., Thiam, S., 2021. Pathways, contextual and cross-scale dynamics of science-policy-society interactions in transdisciplinary research in African cities. Environ. Sci. Pol. 125, 116–125. https://doi.org/10.1016/j.envsci.2021.08.014.
Oesterwind, D., Rau, A., Zaiko, A., 2016. Drivers and pressures - untangling the terms commonly used in marine science and policy. J. Environ. Manag. https://doi.org/10.1016/j.jenvman.2016.05.058.
Ostrom, E., 2009. A general framework for analyzing sustainability of social-ecological systems. Science (80-.) 325, 419–422. https://doi.org/10.1126/science.1172133.
Pacheco, A., Carrasco, A.R., Vila-Concejo, A., Ferreira Dias, J.A., 2007. A coastal management program for channels located in backbarrier systems ARTICLE IN PRESS. Ocean Coast. Manag. 50, 119–143. https://doi.org/10.1016/j.ocecoaman.2006.08.008.
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? Front. Mar. Sci. 3, 1–14. https://doi.org/10.3389/fmars.2016.00177.

Pineda-Pinto, M., Frantzeskaki, N., Nygaard, C.A., 2022. The potential of nature-based solutions to deliver ecologically just cities: lessons for research and urban planning from a systematic literature review. Ambio 51, 167–182. https://doi.org/10.1007/S13280-021-01553-7.

Pohl, C., Rist, S., Zimmermann, A., Fry, P., Gurung, G.S., Schneider, F., Speranza, C.I., Kiteme, B., Boillat, S., Serrano, E., Hadorn, G.H., Urs, W., 2010. Researchers' roles in knowledge co-production: experience from sustainability research in Kenya, Switzerland, Bolivia and Nepal. Sci. Public Policy 37, 267–281. https://doi.org/10.3152/030234210X496628.

Pollard, S.R., Retief, H., Clifford-Holmes, J.K., 2020. Systemic, Social Learning Approaches to Water Governance and Sustainability in the Olifants River Catchment. Limpopo.

Qu, M., Liu, G., Lin, Y., Driedger, E., Peter, Z., Xu, X., Cao, Y., 2017. Experts' perceptions of the sloping land conversion program in the Loess Plateau, China. Land Use Policy 69, 204–210. https://doi.org/10.1016/j.landusepol.2017.09.021.

Quevedo, J.M.D., Lukman, K.M., Ulumuddin, Y.I., Uchiyama, Y., Kohsaka, R., 2023. Applying the DPSIR framework to qualitatively assess the globally important mangrove ecosystems of Indonesia: a review towards evidence-based policymaking approaches. Mar. Policy 147, 105354. https://doi.org/10.1016/j.marpol.2022.105354.

Randers, J., Rockström, J., Stoknes, P.-E., 2018. Achieving the 17 sustainable development goals within 9 planetary boundaries. EarthArXiv 1–31. https://doi.org/10.31223/OSF.IO/XWEVB.

Rapport, D., Friend, A., 1979. Towards a comprehensive framework for environmental statistics : a stress- response approach. Stat. Canada Cat. 11–510.

Reed, M.S., Graves, A., Dandy, N., Posthumus, H., Hubacek, K., Morris, J., Prell, C., Quinn, C.H., Stringer, L.C., 2009. Who's in and why? A typology of stakeholder analysis methods for natural resource management. J. Environ. Manag. 90, 1933–1949. https://doi.org/10.1016/j.jenvman.2009.01.001.

Reid, A.J., Carlson, A.K., Creed, I.F., Eliason, E.J., Gell, P.A., Johnson, P.T.J., Kidd, K.A., MacCormack, T.J., Olden, J.D., Ormerod, S.J., Smol, J.P., Taylor, W.W., Tockner, K., Vermaire, J.C., Dudgeon, D., Cooke, S.J., 2018. Emerging threats and persistent conservation challenges for freshwater biodiversity. Biol. Rev. 94, 849–873. https://doi.org/10.1111/brv.12480.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A., 2009. Planetary boundaries: exploring the safe operating space for humanity. Ecol. Soc. 14.

Ruangpan, L., Vojinovic, Z., Di Sabatino, S., Leo, L.S., Capobianco, V., Oen, A.M.P., Mcclain, M.E., Lopez-Gunn, E., 2020. Nature-based solutions for hydro-meteorological risk reduction: a state-of-the-art review of the research area. Nat. Hazards Earth Syst. Sci. 20, 243–270. https://doi.org/10.5194/nhess-20-243-2020.

Saltelli, A., Bammer, G., Bruno, I., Charters, E., Di Fiore, M., Didier, E., Nelson Espeland, W., Kay, J., Lo Piano, S., Mayo, D., Pielke Jr., R., Portaluri, T., Porter, T. M., Puy, A., Rafols, I., Ravetz, J.R., Reinert, E., Sarewitz, D., Stark, P.B., Stirling, A., van der Sluijs, J., Vineis, P., 2020a. Five ways to ensure that models serve society: a manifesto. Nature 582, 482–484. https://doi.org/10.1038/d41586-020-01812-9.

Saltelli, A., Benini, L., Funtowicz, S., Giampietro, M., Kaiser, M., Reinert, E., van der Sluijs, J.P., 2020b. The technique is never neutral. How methodological choices condition the generation of narratives for sustainability. Environ. Sci. Pol. 106, 87–98. https://doi.org/10.1016/j.envsci.2020.01.008.

Schaubroeck, T., 2017. Nature-based solutions: sustainable? Nature. https://doi.org/10.1038/543315c.

Scheringer, M., Trier, X., Cousins, I.T., de Voogt, P., Fletcher, T., Wang, Z., Webster, T.F., 2014. Helsingør statement on poly- and perfluorinated alkyl substances (PFASs). Chemosphere 114, 337–339. https://doi.org/10.1016/j.chemosphere.2014.05.044.

Seddon, N., Chausson, A., Berry, P., Girardin, C.A.J., Smith, A., Turner, B., 2020. Understanding the value and limits of nature-based solutions to climate change and other global challenges. Philos. Trans. R. Soc. B Biol. Sci. 375 https://doi.org/10.1098/rstb.2019.0120.

Svarstad, H., Kjerulf, L., Rothman, D., Siepel, H., Wa, F., 2008. Discursive Biases of the Environmental Research Framework DPSIR, 25, pp. 116–125. https://doi.org/10.1016/j.landusepol.2007.03.005.

Swangjang, K., Kornpiphat, P., 2021. Does ecotourism in a Mangrove area at Klong Kone, Thailand, conform to sustainable tourism? A case study using SWOT and DPSIR. Environ. Dev. Sustain. 23, 15960–15985. https://doi.org/10.1007/S10668-021-01313-3/FIGURES/9.

Troian, A., Gomes, M.C., Tiecher, T., Berbel, J., Gutiérrez-Martín, C., 2021. The drivers-pressures-state-impact-response model to structure cause-effect relationships between agriculture and aquatic ecosystems. Sustain. 13 https://doi.org/10.3390/su13169365.

Tscherning, K., Helming, K., Krippner, B., Sieber, S., Gomez Paloma, S., 2011. Does research applying the DPSIR framework support decision making? Land Use Policy 29, 102–110. https://doi.org/10.1016/j.landusepol.2011.05.009.

Viti, M., Löwe, R., Sørup, H.J.D., Rasmussen, M., Arnbjerg-Nielsen, K., McKnight, U.S., 2022. Knowledge gaps and future research needs for assessing the non-market benefits of nature-based solutions and nature-based solution-like strategies. Sci. Total Environ. 841 https://doi.org/10.1016/j.scitotenv.2022.156636.

Voinov, A., Jenni, K., Gray, S., Kolagani, N., Glynn, P.D., Bommel, P., Prell, C., Zellner, M., Paolisso, M., Jordan, R., Sterling, E., Schmitt Olabisi, L., Giabbanelli, P. J., Sun, Z., Le Page, C., Elsawah, S., BenDor, T.K., Hubacek, K., Laursen, B.K., Jetter, A., Basco-Carrera, L., Singer, A., Young, L., Brunacini, J., Smajgl, A., 2018. Tools and methods in participatory modeling: selecting the right tool for the job. Environ. Model. Softw. 109, 232–255. https://doi.org/10.1016/j.envsoft.2018.08.028.

Voulvoulis, N., Arpon, K.D., Giakoumis, T., 2017. The EU water framework directive: from great expectations to problems with implementation. Sci. Total Environ. 575, 358–366. https://doi.org/10.1016/j.scitotenv.2016.09.228.

Wassénius, E., Crona, B.I., 2022. Adapting risk assessments for a complex future. One Earth 5, 35–43. https://doi.org/10.1016/j.oneear.2021.12.004.

Zare, F., Elsawah, S., Bagheri, A., Nabavi, E., Jakeman, A.J., 2019. Improved integrated water resource modelling by combining DPSIR and system dynamics conceptual modelling techniques. J. Environ. Manag. 246, 27–41. https://doi.org/10.1016/j.jenvman.2019.05.033.

Zhao, R., Fang, C., Liu, H., Liu, X., 2021. Evaluating urban ecosystem resilience using the DPSIR framework and the ENA model: a case study of 35 cities in China. Sustain. Cities Soc. 72, 102997 https://doi.org/10.1016/J.SCS.2021.102997.

Zulkafli, Z., Perez, K., Vitolo, C., Buytaert, W., Karpouzoglou, T., Dewulf, A., De Bièvre, B., Clark, J., Hannah, D.M., Shaheed, S., 2017. User-driven design of decision support systems for polycentric environmental resources management. Environ. Model. Softw. 88, 58–73. https://doi.org/10.1016/j.envsoft.2016.10.012.