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Assessing chemical risk within an ecosystem services framework: Implementation and added value

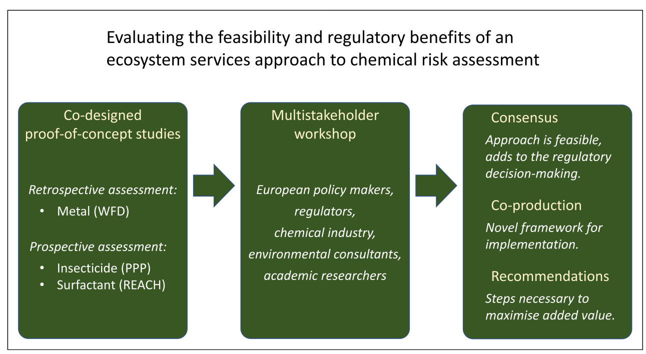
Lorraine Maltby [a,*], Ross Brown [b], Jack H. Faber [c], Nika Galic [d], Paul J. Van den Brink [c,e], Oliver Warwick [f], Stuart Marshall [g]

[a] Department of Animal and Plant Sciences, The University of Sheffield, Sheffield S10 2TN, UK
[b] Biosciences, University of Exeter, Geoffrey Pope Building, Stocker Road, Exeter, UK
[c] Wageningen Environmental Research, P.O. Box 47, 6700 AA Wageningen, the Netherlands
[d] Syngenta Crop Protection LLC., Greensboro, NC, USA
[e] Aquatic Ecology and Water Quality Management Group, Wageningen University, P.O. Box 47, 6700 AA, the Netherlands
[f] Peter Fisk Associates Ltd, Saxon House, John Roberts Business Park, Pean Hill, Whitstable, Kent CT5 3BJ, UK
[g] 6 Prestwick Road, Great Denham, Bedford, UK

HIGHLIGHTS

- Presents a novel framework for assessing chemical risk to ecosystem services (ES).
- Implementation of an ES approach is feasible, but limited by available data and tools.
- An ES approach adds value to regulatory decision making.
- Protection of ES requires a systems-level approach across regulatory frameworks.
- ES trade-off analysis requires a move from a threshold approach to assessing risk.

GRAPHICAL ABSTRACT



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ABSTRACT

An ecosystem services (ES) approach to chemical risk assessment has many potential advantages, but there are also substantial challenges regarding its implementation. We report the findings of a multi-stakeholder workshop that evaluated the feasibility of adopting an ES approach to chemical risk assessment using currently available tools and data. Also evaluated is the added value such an approach would bring to environmental decision making. The aim was to build consensus across disparate stakeholders and to co-produce a common understanding of the regulatory benefits and feasibility of implementing an ES approach in European chemicals regulation. Workshop discussions were informed by proof of concept studies and resulted in the development of a novel tiered framework for assessing chemical risk to ES delivery. There was consensus on the substantial added value of adopting an ES-based approach for regulatory decision making. Ecosystem services provide a common currency and a 'unifying approach' across environmental compartments, stressors and regulatory frameworks. The ES approach informs prioritisation of risk and remedial action and aids risk communication and risk management. It facilitates a more holistic assessment, enables ES trade-offs to be compared across alternative interventions, and supports comparative risk assessments and a socio-economic analysis of management options and decisions. Key to realising this added value is a shift away from using a single threshold value to categorise risk, towards a consideration of the exposure-effect distribution for individual ES of interest. Also required is the development of an integrated systems-level approach across regulatory frameworks and agreement on

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* Corresponding author.

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specific protection goals and scenarios for framing environmental risk assessments. The need to further develop tools for extrapolating toxicity data to service providers and ES delivery, including logic chains and ecological production functions, was highlighted. Also agreed was the need for methods and metrics for ES valuation to be used in assessing trade-offs.

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1. Introduction

The delivery of ecosystem services (i.e. direct and indirect contributions of ecosystems to human-wellbeing (TEEB 2010)) is at risk from multiple stressors, including chemical contaminants (IPBES, 2019). Understanding and predicting the risks that chemicals pose to ecosystem service delivery requires, either measuring the effects of chemicals on the ecosystem functions that underpin service delivery, or extrapolating from the effects of chemicals on service providing units to ecosystem service delivery. Whereas the former may be possible in, for example, field or semi-field ecosystem (e.g. mesocosm) studies, in many cases and especially in prospective risk assessment, extrapolation of data for single species will be required. An example of such an extrapolation would be linking the effects of a chemical on the abundance and feeding behaviour of an insectivorous bird to its predation rate on insects, and then linking the consequences of the effects on this predation to insect pest populations and hence to the control of pest damage on crops (Mols and Visser, 2007).

The use of an ecosystem services approach in guiding chemical environmental risk assessment has a number of advantages, but there are also a number of challenges related to its implementation, as we have highlighted in previous publications (Maltby et al., 2018; Faber et al., 2019). An ecosystem services approach could result in more relevant environmental risk assessment and better informed risk management decisions by focusing protection goals on what stakeholders value. It increases transparency in trade-offs and prioritisation of ecosystem services (i.e. what to protect where and why) and offers the potential of a more holistic approach to environmental management by integrating across stressors and environmental compartments. However, because ecosystems have the potential to provide many services, adopting an ecosystem services approach requires greater ecological understanding of the consequences of chemical impacts, which may be a challenge for implementation. There is also a need to develop tools that either directly measure the impacts of chemicals on ecosystem service delivery or produce information that can be robustly extrapolated to ecosystem service delivery. Advancing the regulatory implementation of an ecosystem services approach to chemical risk assessment requires a shared understanding between scientists in regulatory authorities and the industries they regulate, of what is possible with the tools currently available. In addition, there needs to be an evaluation of whether the investment of time and resources required to address the implementation challenges of adopting a different regulatory approach is worthwhile in terms of enhancing regulatory decision making (Faber et al., 2019).

The feasibility of applying an ecosystem services-based approach to environmental risk assessment using currently available data and methodologies was explored by conducting proof of concept studies. A detailed description of these proof of concept studies is provided elsewhere (Brown et al., 2021; Van den Brink et al., 2021, Supplementary information). The purpose of this paper is to report on a multi-stakeholder workshop that used these studies to evaluate the feasibility of adopting an ecosystem services approach to chemical risk assessment using currently available tools and data, and the added value such an approach would bring to environmental decision making. The approach adopted was one of co-design and co-production with the emphasis on building consensus across diverse stakeholder groups (i.e. European policy makers and regulators, chemical industry, environmental consultants and academic researchers). The aim of the study was to reach a common understanding of: (i) what is currently possible regarding the implementation of an ecosystem services approach to chemical risk assessment; (ii) how adopting an ecosystem services approach may improve environmental decision making; (iii) what additional steps are required to fully implement an ecosystem services approach to chemical risk assessment. To aid implementation, a novel tiered framework was developed for assessing chemical risk to ecosystem service delivery.

2. Methods

2.1. Proof-of-concept (PoC) studies

Three PoC studies were co-designed by expert groups comprised of multiple stakeholders involved in European chemical risk assessment (i.e. chemical producers, chemical regulators and researchers). Each proof of concept study focused on a different EU regulatory framework and addressed the impacts of individual chemical exposures on the delivery of multiple ecosystem services. One PoC study was a retrospective assessment of metal contamination of a freshwater ecosystem and was relevant to the Water Framework Directive (2000/60/EC). It focused on a UK lowland river, in which measured concentrations of bioavailable metal exceed the Environmental Quality Standard (EQS) (Brown et al., 2021). The other two PoC studies were prospective assessments relevant to the Plant Protection Products (PPP) Regulation (EC No. 1107/2009) and REACH (EC No. 1907/2006). The PPP PoC study focused on a generic European apple orchard and the study chemical was an insecticide applied twice per year as pre- and post-blossom treatments (Van den Brink et al. (2021)). The final PoC study focused on a surfactant used in consumer products. This scenario is relevant to a wide range of chemicals released into domestic wastewater leading to environmental exposure via continuous wastewater treatment plant effluent discharges to surface waters (Supplementary information).

The PoC studies followed the conceptual framework developed through previous stakeholder engagement (Faber et al., 2019). Identification of the ecosystem services assessed in each study was informed by the application or use scenario of the chemical of interest, the landscape types that may be exposed, and the ecosystem services they potentially provide (Maltby et al., 2018). The Common International Classification of Ecosystem Services (CICES v5.1) (Haines-Young and Potschin, 2018) was used as the master list from which ecosystem services were selected. The final selection of exemplar ecosystem services (Table 1) was pragmatic and based on available models and data. The objective was to assess feasibility using currently available data and methodologies rather than to undertake detailed risk assessments.

For prospective risk assessments (i.e. insecticide, surfactant), standardised toxicity test data (of the type required for regulatory compliance) were coupled with population and food-web modelling to predict the risk of chemicals to selected service providing units. For the retrospective risk assessment (i.e. metal), site water chemistry-adjusted toxicity data (i.e. adjusted for bioavailability) and field monitoring data were used to assess risk to selected service providing units. Evidence-based logic chains (Hayes et al., 2018) were developed to link effects on service providing units to potential impact on ecosystem service delivery. Where possible, effects on ecosystem services were modelled (prospective risk assessment) or assessed using field monitoring data and trait-based approaches (retrospective risk assessment). An illustrative trade-off analysis for the exemplar ecosystem services and crop production was developed for the insecticide PoC study.

Table 1
The exemplar ecosystem services and associated service providing units used in the proof of concept (PoC) studies. Service providing units are the species, populations, communities or habitats that provide an ecosystem service (Luck et al., 2009).

Ecosystem service		Service providing units in each PoC study		
		Insecticide	Surfactant	Metal
Regulatory services	Soil quality regulation	Soil fauna (earthworms & springtails)		
	Natural pest control	Pest predators (ladybirds)		
	Pollination	Pollinating insects (bees)		
	Freshwater quality regulation		Macrophytes microbes, algae filter-feeding invertebrates fish	Macrophytes, algae deposit and filter-feeding invertebrates
	Maintaining nursery populations and habitats		Habitat providers (macrophytes)	Habitat providers (macrophytes)
Cultural services	Recreation (observing nature)	Charismatic invertebrates (butterflies)	Birds, charismatic invertebrates (mayflies), plants	Charismatic invertebrates (odonates), flowering plants
	Recreation (engaging with nature)		Game fish	Game fish

2.2. Stakeholder workshop

A multi-stakeholder workshop was held in January 2020 to review and discuss the findings of the proof of concept studies; evaluate the added value to regulatory decision making of adopting an ecosystem service approach to chemical risk assessment; and identify priorities for future development/ implementation. There were 32 workshop participants from European environmental policy and regulatory agencies (European Commission and Members States), academia (universities and research institutes) and business (chemical industry, environmental consultancies). Half of the workshop participants had been involved in the co-design of the PoC studies.

Using information from the PoC studies and drawing on their own expertise and experience, workshop participants were asked to discuss the following topics:

- Extrapolating data from toxicity test species to service providing units
- Linking effects on service providers to effects on ecosystem service delivery
- Developing scenarios for modelling and ecosystem service assessment

The outputs from these discussions were used to develop a novel framework for a tiered assessment of the potential risk of chemicals to service providing units and ecosystem services. Workshop participants were then asked to discuss the question: What is the added value from evaluating chemical effects on ecosystem services for regulatory decision making? Finally, they were tasked with developing recommendations for the implementation of an ecosystem services approach to chemical risk assessment. It is the consensus from this multi-stakeholder co-production process that is reported here.

3. Results and discussion

3.1. Extrapolating data from toxicity test species to service providing units

The first challenge when implementing an ecosystem services approach to chemical risk assessment is how to extrapolate from what is routinely measured – effects on a small number of species in standardised laboratory toxicity tests – to effects on the large number of species underpinning ecosystem service delivery. In addition, ecosystem services are provided by populations or assemblages of species within functional groups, rather than individual organisms. However, ecotoxicity data are generally focussed on effects on individuals, although population-level responses may be possible for species with short generation times (e.g. microbes, algae, zooplankton), if the study duration is long enough. Multispecies studies (e.g. mesocosms) can provide information on the effects of chemicals on species assemblages but these are performed for relatively few chemicals.

Possible approaches for extrapolating from test species to service providing units include using vulnerable surrogate species or interspecific extrapolation via methods based on correlation, traits, taxonomic relatedness or phylogeny (van den Berg et al., 2021). Species sensitivity distributions can be used to assess whether service providers are more sensitive than other taxa in the same broad taxonomic group (e.g. game fish versus non-game fish, Brown et al., 2021) or whether species used as exemplar service providers are more sensitive than other species that provide the same service (e.g. ladybird *Coccinella septempunctata* versus other insect predators, Van den Brink et al., 2021).

Mechanistic approaches such as dynamic energy budget and toxicokinetic/toxicodynamic modelling can be used to extrapolate sub-organism responses to effects on vital rates, and population modelling can use vital rates to predict population level effects. In the insecticide PoC study, population models were used to extrapolate the effects of an insecticide on bees (pollinators), butterflies (charismatic insects), ladybirds (pest predators), springtails and earthworms (soil quality regulators) in standard toxicity tests, to effects of long-term insecticide exposure on populations of these organisms in orchards. There was considerable variation in population response across and within service providing units, which was driven by a difference in inherent sensitivity coupled with variation in exposure related to dispersal, habitat heterogeneity and recovery potential. For example, interspecific differences in the sensitivity of springtails and earthworms to the study insecticide were much more pronounced for the modelled populations than the laboratory toxicity data would suggest. Whereas springtail populations went extinct at the modelled application rates, earthworm populations did not deviate from their normal operating range (Fig. 1: Van den Brink et al., 2021). This difference in magnification of effect between species highlights the importance of spatial heterogeneity in models and its influence on chemical exposure and recovery potential.

Most ecosystem services are provided by multiple species and single species can contribute to multiple services. Understanding how species interact within food webs and the consequences for ecosystem service delivery is therefore an important element to assessing chemical risk within an ecosystem services framework. The US EPA's model AQUATOX (Park et al., 2008) has been developed and used to investigate the impact of chemicals on food web structure and could therefore be useful for exploring potential impacts on ecosystem service delivery (Galic et al., 2019). The response variable in AQUATOX is biomass of individual food web elements. Chemical partitioning into biomass is also predicted. The model therefore has potential to provide information on ecosystem services that are strongly related to the biomass and chemical contamination levels of service providers or to the transfer of

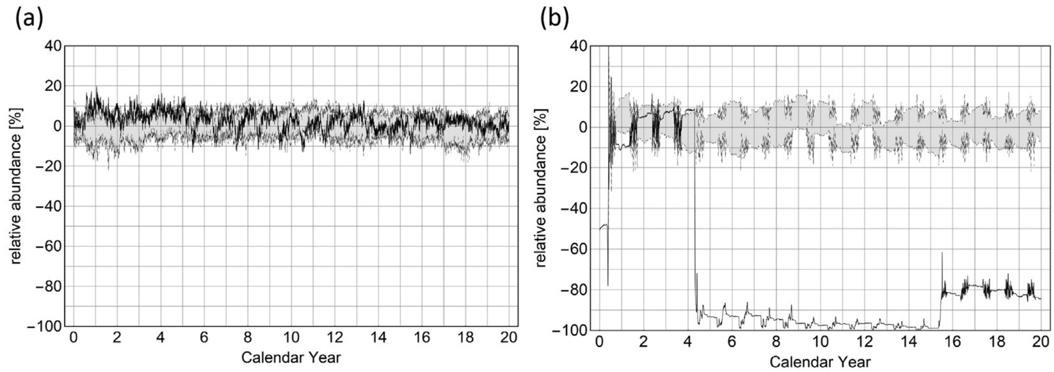

Fig. 1. Outputs for (a) earthworm and (b) springtail model. Models are run for 5 years pre-treatment, 10 years pesticide treatment (2 applications per year at approved application rates) and 5 years post treatment. Grey shaded area represents the normal operating range and black lines are the population response relative to no-application controls (For full description of methods and results, see Van den Brink et al., 2021).

biomass across food web compartments. Most function or process-based ecosystem services are not directly predicted by AQUATOX, although it can provide predictions of water clarity.

AQUATOX has been used to explore the risk of surfactants to specific riverine communities (Lombardo et al., 2015; Grechi et al., 2016; Gredelj et al., 2018) and the surfactant PoC study explored how it could be used in a prospective risk assessment to assess risk to ecosystem services delivered by a generic riverine community. The model used laboratory toxicity data to predict direct and indirect effects of varying surfactant exposure on the population biomass of species in a simulated food web (Fig. 2). Whilst the food web approach provided useful estimates of biomass that were related to several ecosystem services, identifying causes of the predicted responses in biomass over the range of surfactant exposure required interpretation of the interplay between direct inhibition caused by surfactant toxicity and their consequential indirect effects.

3.2. Linking effects on service providers to effects on ecosystem service delivery

Linking effects on service providing units to the ecosystem services they deliver may involve qualitative evidence-based logic chains or quantitative ecological production functions. Fig. 3 illustrates a logic-chain network developed as part of the surfactant PoC study. On the left hand side are service providing units defined as major taxonomic groups (white ovals) and on the right hand side are the ecosystem services of interest (black boxes) in this study. The grey boxes are the ecological processes and structural elements that link surfactant-induced changes in the abundance of specific service providing units to the ecosystem services they deliver. The linkages in this network (indicated by arrows) are based on evidence in the literature and the approach follows that of Hayes et al. (2018).

The study surfactant has a non-specific mode of action and so is toxic to a wide range of taxa within a narrow range of exposure concentrations. This means that there is the possibility for a wide range of direct impacts. If impacts could occur at any trophic level, it follows that the direction of secondary effects on some ecosystem entities could be both positive and negative. For reasons of simplicity, the study focused on developing logic chains that generally excluded trophic feedback loops.

The logic chains developed for the surfactant study have few links between primary effect and potential impact on ecosystem service delivery and most of the evidence supporting causal relationships in the logic chains provided qualitative directional information rather than quantitative information (Supplementary information). The scope and

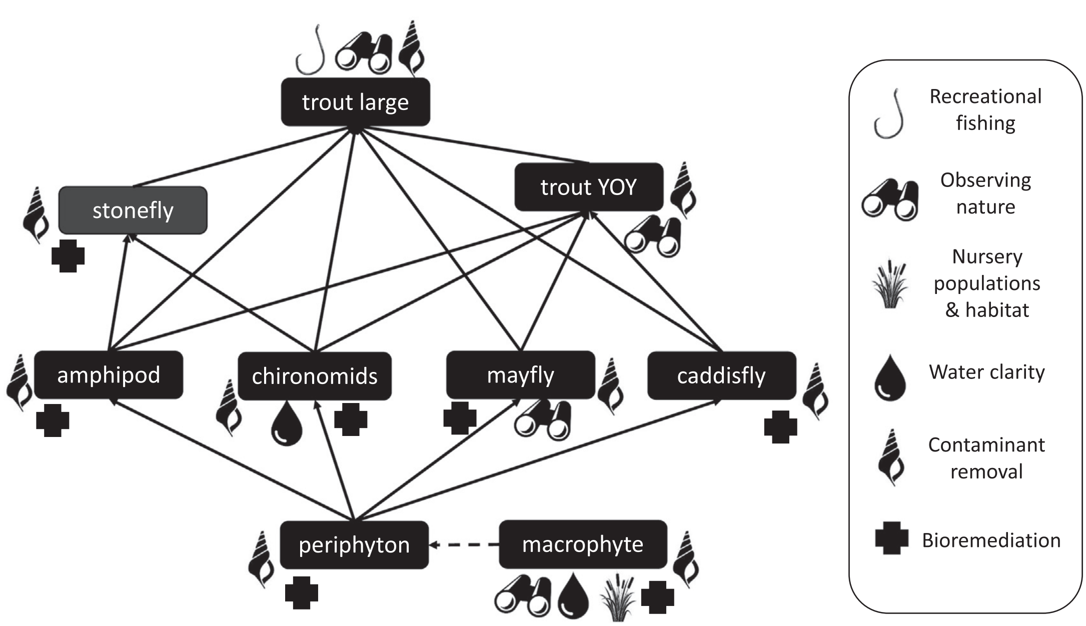

Fig. 2. AQUATOX model food web showing trophic links (solid arrows) and other biotic interactions (broken arrow). Icons indicate the potential ecosystems services provided by food web taxa. Contaminant removal may be a result of sequestration, filtration, accumulation or storage. Note that trout are split into large fish and young of year (YOY) fish.

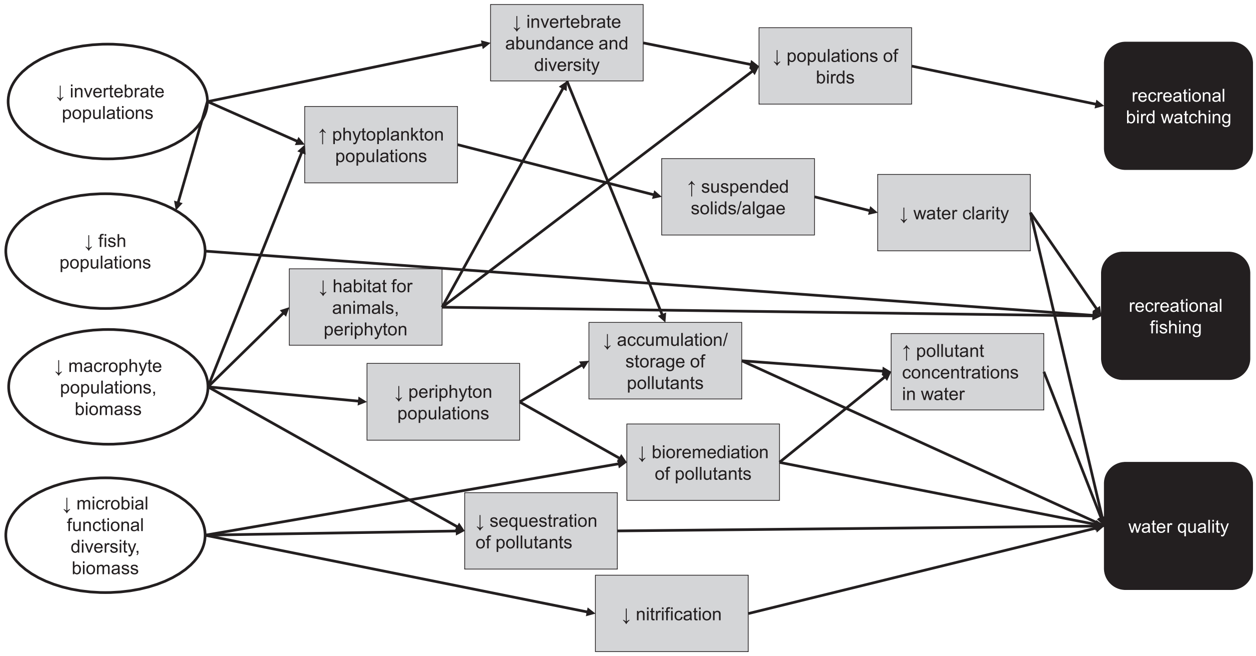

Fig. 3. Logic-chain network linking chemical-induced effects on biological elements through to ecosystem service delivery.

applicability of the relationships, even as qualitative indicators, can be difficult to evaluate because of multiple influencing factors including feedback loops and hysteresis.

Quantitative ecological production functions (EPFs) have been reviewed for all CICES classified biotic provisioning and regulating ecosystem service classes (Faber et al., 2021). A major challenge is that standardised toxicity tests do not exist for most service providing taxa in EPFs although relevant tests are available for taxonomically related taxa. Of the literature reviewed by Faber et al. (2021), just a single study involving honey bees (*Apis mellifera*) extended over the whole range of extrapolation steps from standard test species to final ecosystem service delivery and economic valuation (Kleczkowski et al., 2017). This gap notwithstanding, we consider that EPFs can be used if uncertainty from taxonomic extrapolation is taken into consideration. Encouragingly for an ecosystem services-based approach to ERA, is the observation that for all ecosystem service classes, EPFs are available for at least some part of the extrapolation trajectory, with varying degrees of quantification and causality.

Primary direct toxic effects can have multiple indirect outcomes linked to many ecological processes, ecosystem functions and ecosystem services. Therefore, assessments must be capable of dealing with multiple logic chains either in parallel (e.g. by combining population models for relevant service providing units) or in an integrated manner (e.g. via the use of food web models). In principle, both approaches could be feasible, but further development of population models is needed to cover a wider range of species and to be capable of predicting effects of toxicants under a range of environmental typologies and conditions.

The food web model AQUATOX has been used previously to explore the impact of a hypothetical insecticide on a recreational fishery in a lake (Galic et al., 2019) and was used in the surfactant PoC study to investigate effects on a riverine trout game fishery. The use and value of a recreational fishery is not simply a function of the abundance and size of the focal fish species, but it is also influenced by other factors including the aesthetics of the fishing location and its accessibility (Paetzold et al., 2010). For chemicals, such as surfactants, that may have direct effects on focal fish species, their prey and the habitat (i.e. macrophytes) defining the best fishing spots, the overall effect on the fishery may be complex and will depend on the relative magnitude of direct and indirect effects (Galic et al., 2019) and how these are perceived by anglers (Fulford et al., 2016).

Workshop participants recognised the potential added value of using food web models to assess chemical risk to ecosystem service delivery. They highlighted the benefit of evaluating risk due to both direct and indirect effects, but noted the limitations of AQUATOX, which include the lack of single species toxicity and life history data needed for parameterising the food web. The use of surrogate data introduces considerable uncertainties in food web relationships and model outputs (Grechi et al., 2016). In addition to the scarcity of data, other limitations to the application of AQUATOX to prospective risk assessment include the lack of standard ecological scenarios and impact indicators (Lombardo et al., 2015). As discussed by Gredelj et al. (2018) AQUATOX is a deterministic model that does not incorporate the stochasticity of taxa diversity and abundance into an assessment. In complex food webs, stochasticity could lead to differences in outcomes. Varying starting conditions in AQUATOX simulations could, in part, account for stochasticity, but there would be resource and time constraints associated with such an approach. Whilst the deterministic approach can be criticised, workshop participants noted that the majority of assessment methodologies in prospective chemical risk assessment are deterministic.

In some cases it may be possible to model the implications of changes in populations of service providers for ecosystem service delivery. For example, in the insecticide proof-of-concept study, the models BEEHAVE and BEESCOUT were used to model the impact of long-term insecticide exposure on colony survival and pollination flights, which were used as a proxy for pollination (Van den Brink et al., 2021). In this case it was therefore possible to extrapolate from data generated in standard toxicity tests to effects on potential ecosystem service delivery. However, this is a rare example and in the majority of cases the protection of the service providing unit will act as a proxy for the protection of ecosystem service delivery.

An approach to linking impacts on service providing units to changes in ecosystem service delivery in a retrospective risk assessment is to consider how the trait profile of service providing units is changed by exposure to chemical stressors. The metal proof of concept study used information on the abundance and relative contribution of key traits to the delivery of specific ecosystem services to calculate an ecosystem service delivery score (Brown et al., 2021). This score was calculated both for the species assemblage observed at a site and the species assemblage expected to occur at the site if it was minimally impacted. The difference between the observed and expected score being a measure of impact on potential ecosystem service delivery.

Workshop participants noted that a key factor when assessing the effect of chemicals on ecosystem services in a retrospective assessment is the resilience of the system, which is linked to functional diversity and functional redundancy. The resilience of ecosystem service delivery to chemical exposure effects depends on the number of contributing species. If numerous species make up a service providing unit, redundancy is high and if one or two species are removed, theoretically others may compensate and there may be minimal loss of function overall. Species within a service providing unit are likely to have a range of sensitivities to a given chemical and their abilities to deliver an ecosystem service (functional importance) may also vary in space and time. However, the relationship between the number of species in a service providing unit and functional redundancy is not necessarily linear (Heemsbergen et al., 2004). The more effective service providers may be 'key' species and the loss of just one of these could significantly affect ecosystem service delivery. In the context of the Water Framework Directive, key functional species may not be the most important in terms of classification of biological quality. Indeed, rare and sensitive species often score more highly than key functional species in the current classification of ecological status under the Water Framework Directive.

3.3. Scenarios for modelling and ecosystem service assessment

Models will be critical to the implementation of an ecosystem services approach, but models need to be developed within appropriate environmental scenarios (Centofanti et al., 2006; Franco et al., 2016). Environmental scenarios should include both a scenario defining exposure and a scenario defining the ecological components that influence effects, both direct and indirect, and recovery, including life-history traits and trophic dependencies. There should be consistency in the definition of environmental parameters and management practices that influence both exposure and effects (Rico et al., 2016). If environmental scenarios are broadly similar to the test systems (e.g. in exposure profiles, life histories and species interactions) then models will offer little refinement over empirical studies (e.g. mesocosm studies). Models are useful for capturing the complexities in natural systems and thereby reducing some of the uncertainties in extrapolating from test systems to the real world.

In addition to environmental scenarios, ecosystem service scenarios are needed to frame the risk assessment. Ecosystem service scenarios need to specify the ecosystem services of concern, where in the landscape these services are provided (i.e. service providing area) and which ecological components provide them (i.e. service providing units). The environmental and ecosystem service scenarios should be as consistent as possible across regulatory frameworks to aid integration and holistic assessments. One approach is to develop a suite of generic scenarios, each with a defined set of ecosystem services. Scenarios should be flexible to cover changes to regulation and special cases, e.g. EU wide vs country-specific risk assessments.

Particularly important for model construction are landscape configuration, spatial and temporal scale and spatial and temporal resolution. For example, in the insecticide PoC study, the modelled risk of insecticide exposure to butterfly populations was much greater than the modelled risk to bees, even though they are both flying insects (Van den Brink et al., 2021). Part of the reason for these differences will be interspecific differences in sensitivity to insecticide exposure, differences in routes of exposure, differences in dispersal and differences in life-history strategies. However, the modelling scenario for each species was also different. The scenario used for the bee model was a heterogeneous landscape comprised of multiple orchard and non-orchard areas and within the orchard there were different floral resources. In contrast, the scenario for the butterfly model was a homogeneous grassland landscape that comprised the orchard plus a small off-crop area. The off-crop area provided some refuge for caterpillars, but there was no spatial variation in insecticide exposure within the orchard. Therefore, all caterpillars in the orchard are affected equally. This is in contrast to the bee scenario where spatial and temporal variation in habitat and hence exposure means that not all individuals are affected equally and therefore colonies have the potential to recover and persist. These examples illustrate the importance of selecting the appropriate landscape scale and structure (i.e. scenario) when assessing effects on associated ecosystem services.

The AQUATOX library (www.epa.gov/ceam/aquatox) contains a number of existing site templates that have been parameterised from field-collected data including hydromorphology, physico-chemistry and climate. For example, the surfactant PoC study used a scenario based on a Danish stream (McKnight et al., 2010; Bigi et al., 2018), whereas Galic et al. (Galic et al., 2019) based their hypothetical study on the impact of an insecticide on lake ecosystem services, on the Coralville Reservoir. The AQUATOX library could be expanded to include standard scenarios for prospective risk assessment that, for instance, align with the waterbody types (ditch, stream, pond) defined in the FOCUS models (FOCUS, 2001). This would also allow for a more seamless integration of exposure profiles generated by FOCUS models which account for waterbody sizes, hydromorphology, and climate. Workshop participants highlighted that, for all model scenarios, there is a need to balance realism of complex ecological systems with the paucity of data needed to parameterise, calibrate and validate models. There is also a trade-off between realism and complexity and ease of interpretation of models and model outputs.

3.4. Tiered approach to assessing risk to ecosystem services

Fig. 4 presents a novel framework for a tiered approach to assessing the risk to ecosystems services that integrates logic chains, ecological production functions and environmental scenarios. Assessments start with a complete list of ecosystems services (e.g. CICES v5.1) that is refined based on information on chemical application/use patterns and broad landscape components at risk of exposure (Fig. 4, (i)). In addition, stakeholder participation may be used to refine ecosystem service lists for retrospective risk assessments. The risk assessment would then focus on this refined list and qualitative logic chains would be used to identify generic service providing units (e.g. functional or taxonomic groups) for each of the ecosystem services listed (Fig. 4 (ii)).

Prospective risk assessments are most commonly based on data from standardised single species toxicity tests and exposure estimation By mapping the taxonomic groups used in standard toxicity tests onto ecosystem services (Maltby et al., 2018), it is possible to use the data from these tests within an ecosystem services framework. For example, invertebrates are important in the delivery of many aquatic ecosystem services and standard toxicity tests are available for several aquatic invertebrates including crustaceans, insects, annelids and molluscs (Maltby et al., 2018). The output from standard single-species toxicity tests could be used as an initial screening level in which the assessment of risk is based on a threshold value (e.g. predicted no observed effect concentration ($PNEC_{SPU}$) or regulatory acceptable concentration (RAC_{SPU})) for a generic service providing unit (Fig. 4 (iii)). If only limited standard toxicity data are available (e.g. *Daphnia*, algae, fish), the outcome of the assessment scheme in Fig. 4 may be similar to the current Tier 1 assessment. However, the added value would be that it would identify which ecosystem services were potentially at risk and whether the risk was due to direct toxicity to the service providing unit or via trophic or other ecological interactions.

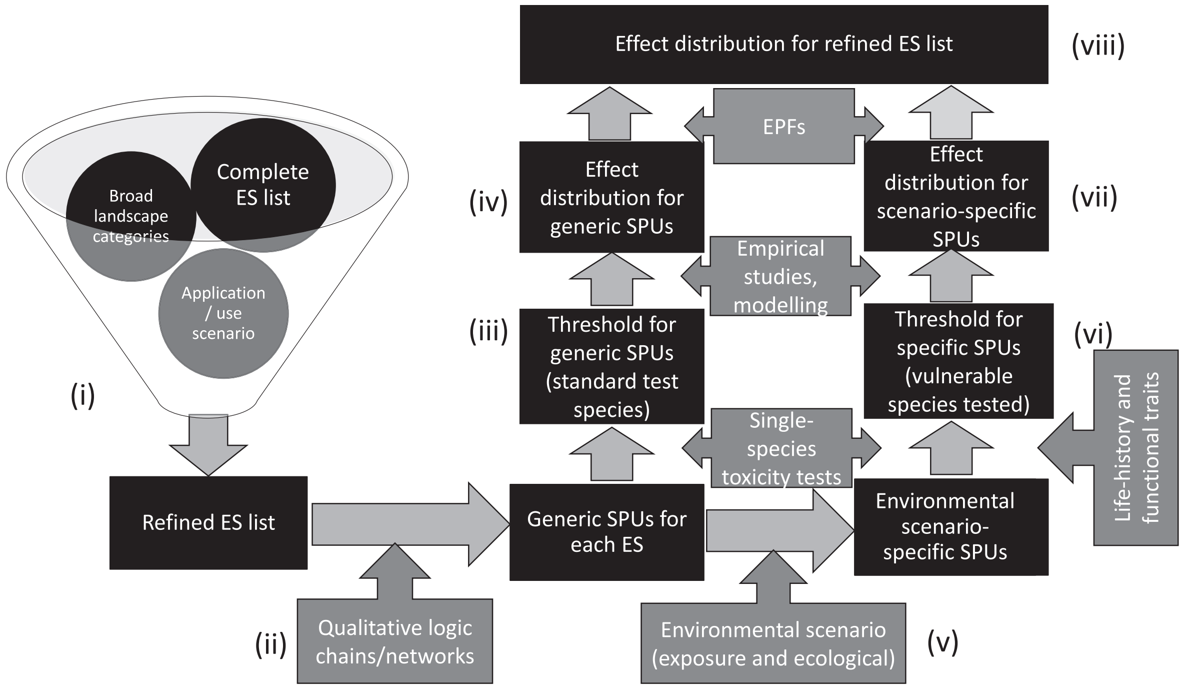

Fig. 4. Framework for a tiered assessment of the potential risk of chemicals to service providing units (SPUs) and ecosystem services (ES). EPFs are ecological production functions. Roman numerals refer to points discussed in the text.

Threshold approaches apply the principle that protecting sensitive standard/vulnerable taxa within a service providing unit protects the ecosystem services they deliver. They also assume that the threshold value is sufficient to protect against indirect effects. Where there is evidence that indirect effects on service providers may be more sensitive than direct effects, the key supporting taxa (e.g. food sources, habitat elements) should be included in the assessment of the threshold value. Standard toxicity tests generally focus on effects on individual organisms however, most ecosystem services are provided by populations or functional groups. Effects on these higher levels of biological organisation can either be assessed empirically or by using ecological models (e.g. population models) to translate effects on individuals to effects on populations and functional groups. The risk assessment can therefore be refined by determining population-level thresholds and effect distributions by using empirical studies or modelling approaches that take direct and indirect effects into account (Fig. 4 (iv)).

An alternative refinement is to assess risk to vulnerable species rather than generic standard species. Ecosystem services can be provided by many different taxa and the dominant service providing units for an ecosystem service can vary in space and time (Culhane et al., 2018). To capture this spatio-temporal variation, an agreed set of environmental scenarios could be developed that include both exposure and ecological scenarios (Rico et al., 2016) and which could be used to specify scenario-specific service providing units and associated vulnerable species (Fig. 4 (v)). The identification of vulnerable species would take life history and functional traits into account that influence a species' likelihood of exposure, toxicological sensitivity and recovery potential. Again single species toxicity tests can be used to derive thresholds (Fig. 4 (vi)) and empirical or modelling approaches can be used to derive effect distributions (Fig. 4 (vii)).

Workshop participants agreed that the advantage of the proposed threshold approach (Fig. 4 (iii) and (vi)) is that it is straightforward, pragmatic and consistent with existing risk assessment procedures. However, the disadvantage is that, because it is a threshold approach and the translation of chemical effects on sensitive standard/vulnerable taxa to effects on ecosystem delivery are not quantified, trade-offs between ecosystem services can also not be quantified. Effect distributions for service providing units (Fig. 4 (iv) and (vii)) may be used to indicate potential trade-offs between the services they provide. However, in order to assess trade-offs between ecosystem services, it would be necessary to generate effect distributions for service providing units that can be extrapolated to effect distributions for ecosystem services using quantitative ecological production functions or extrapolation factors (Fig. 4 (viii)). Workshop participants agreed that the main advantage of this refinement is that it enables ecosystem service trade-offs to be quantified, but the main disadvantage is that it is resource and data intensive. There is also a major knowledge gap in terms of ecological productions functions. A recent literature review that compiled 121 ecological production functions for 25 ecosystem services, concluded that few ecological production functions were appropriate for extrapolating chemical effects measured in standard toxicity tests (Faber et al., 2021).

3.5. What is the added value from evaluating chemical effects on ecosystem service for regulatory decision making?

Assessing risk within an ecosystem services framework is additional work compared to a traditional risk assessment and there are still a number of methodological challenges in implementing this approach, so is the additional effort worthwhile from a regulatory risk assessment perspective? In particular, what added value does this approach provide to the regulatory decision making process?

Workshop participants identified four main areas of 'added value'. The first major benefit identified was that an ecosystem services approach provides a common currency that can be applied to different environmental compartments, stressors and regulatory frameworks, and as such provide the basis for a unifying approach to environmental policy and decision making. By integrating assessments required by different regulations, an ecosystem services approach provides a holistic and coherent mechanism for the implementation of measures necessary to meet the goals of the biodiversity strategy and other overarching environmental strategies. For example, an ecosystem services framework can be employed as a unifying approach to environmental assessment under the European Green Deal (EC, 2019). Meeting the goals of the European Green Deal within European agricultural landscapes, requires consideration of regulations for different types of chemicals (e.g. plant protection products, biocides, general chemicals), directives for protecting habitats and species (e.g. Habitats Directive, Birds Directive, Water Framework Directive), and policies for managing farming systems (Common Agricultural Policy; Sustainable Use Directive). The common currency of ecosystem services also enables the development of a knowledge-based systems approach to environmental management that facilitates the sharing of methods and data across regulatory frameworks.

Second, by focusing on the link between ecosystems and human wellbeing, the ecosystem approach helps to identify what is really important in the risk assessment and informs risk prioritisation and remedial action. This aids risk communication and risk management, particularly, if the costs and benefits in ecosystem service provisioning and trade-offs between ecosystem service delivery can be valued economically (monetarised).

Third, because an ecosystem services approach provides a more holistic assessment, it enables trade-offs between ecosystem services to be compared across different management scenarios and thereby enables a comparative and transparent assessment of the consequences of different possible interventions on a suite of potential environmental benefits to people (Fig. 5). Current regulatory risk assessments for the premarket approval of chemicals consider single chemicals or formulations in isolation. However, environments are exposed to chemical mixtures and multiple stressors (chemical and non-chemical). An ecosystem services approach can be used to inform a comparative risk assessment and substitution decisions by assessing simultaneous (i.e. mixtures) or sequential (e.g. pesticide applications during a crop cycle) exposures to multiple chemicals, alternative interventions (e.g. chemical versus non-chemical crop management) and the impact of multiple stressors (e.g. chemical and climate change impacts).

Fourth, because ecosystem services can be monetarised, they can be used as part of a socio-economic analysis that compares the overall benefits to society of the use of a chemical to the environmental risks to determine if specific uses should be authorised or not. The flow of ecosystem services can be quantified to evaluate how costs and benefits are allocated amongst end-users and other stakeholders, as a basis for implementation of incentives such as payments for ecosystem services (Jack et al., 2008, Simoncini et al., 2019). However, there are challenges with the valuation of ecosystem services and combining monetarisation with other valuation methods can strengthen the assessment (Flood et al., 2020).

3.6. Recommendations

In order to maximise the added value of an ecosystems services-based chemical risk assessment, workshop participants identified a set of recommendations:

- Move away from a threshold approach to assessing risk to an approach that considers the full chemical exposure-effect distribution for all ecosystems services of interest.
- Engage relevant regulatory stakeholders to facilitate the development of an integrated systems-level approach.
- Develop and agree scenarios and specific protection goals for framing the risk assessment and agree acceptability criteria for impacts on ecosystem services.
- Further develop interspecies extrapolation tools, logic chains, ecological production functions and ecological models so that we can link what we can measure in standardised toxicity tests to what we want to assess, i.e. change in ecosystem service delivery.
- Consider methods and metrics for ecosystem service valuation that may be used in assessing trade-offs between ecosystem services.
- Develop regulatory guidance and exemplar studies that explain how to use scenarios, ecological models, EPFs and trade-off analysis in chemical risk assessment

4. Conclusions

The unique co-design and subsequent evaluation of PoC studies by a multi-stakeholder group of European policy makers and regulators, chemical industry, environmental consultants and academic researchers, provides a strong platform for advancing the implementation of an ecosystem services-based approach to chemical risk assessment. The PoC studies demonstrate the feasibility of implementing an ecosystem services-based approach to chemical risk assessment using currently available data and methodologies, and identify the key limitations that need to be addressed before the approach can be implemented fully (Brown et al., 2021; Van den Brink et al., 2021).

Frameworks for incorporating an ecosystem services approach in chemical risk assessment have been published (Nienstedt et al., 2012; Forbes et al., 2017; Faber et al., 2019). The tiered framework presented here, which was co-produced by regulators and the industries they regulate, extends previous frameworks by incorporating evidence-based logic chains and providing multiple options for higher tier refinement. It moves beyond the use of thresholds to regulate chemical risk and incorporates the use of exposure-effect distributions in the assessment of chemical risk and subsequent trade-off analysis. The proposed framework facilitates implementation of an ecosystem services-based approach to chemical risk assessment and highlights where additional tools and approaches can be deployed to refine the assessment of risk. The framework starts with assessing the chemical risk threshold for generic service providing units. This initial assessment, which is based on single species toxicity tests, is consistent with the guidance developed by EFSA for plant protection products (EFSA Scientific Committee, 2016) and can be implemented using currently available data and tools. The framework then provides several higher tier options for determining exposure-effect distributions for service providing units and the ecosystem services they provide, which can be implemented when information from additional empirical and modelling approaches are available.

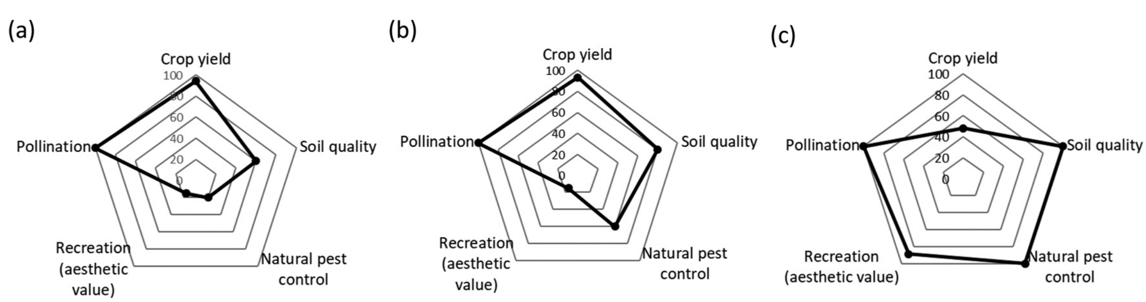

Fig. 5. Illustrative trade-offs between crop yield and four other ecosystem services (soil quality, natural pest control, recreation as aesthetic value, pollination) for different application scenarios of an insecticide (application rate reducing from a to c). The black dots represent the percentage delivery for each ecosystem service and the black line joins the dots. The trade-offs are based on the findings of the insecticide proof of concept study.

The multi-stakeholder group agreed that adopting an ecosystem services-based approach did provide additional benefits for regulatory decision making. In particular, by providing a 'common currency', an ecosystem services approach facilitates a more holistic and integrated assessment across environmental compartments, stressors and regulatory frameworks. The approach enables ecosystem service trade-offs to be compared within and between management interventions thereby informing prioritisation of risk and remedial action and supporting comparative risk assessments. In addition, the potential to monetarise or value ecosystem services facilitates a socio-economic analysis of management options and decisions.

However, key to realising the added value of an ecosystem services approach to chemical risk assessment is a shift away from using a single threshold value to categorise risk (e.g. predicted no effect concentration; one-out, all–out principle in the Water Framework Directive), towards a consideration of the exposure-effect distribution for individual ecosystems services of interest. Also required is the development of an integrated systems-level approach across regulatory frameworks, and agreement on specific protection goals and scenarios for framing environmental risk assessments and acceptability criteria for interpreting ecosystem service impact.

Ecological models play an important role in the implementation of an ecosystem services approach to environmental risk assessment (Forbes and Calow, 2013). It is therefore necessary to further develop tools for extrapolating toxicity data to service providers and ecosystem services delivery (Bruins et al., 2016; Faber et al., 2021). Incorporating spatio-temporal scale and heterogeneity in these models will increase the robustness of the evaluation of ecosystem system services (Agudelo et al., 2020; Fulford et al., 2020). Methods and metrics for ecosystem service valuation are also required for assessing trade-offs between services. Ideally, any future development of models, metrics and other tools, should be undertaken in collaboration with scientists in policy and regulatory authorities in order to enhance their regulatory applicability and acceptance.

In conclusion, an innovative co-design and co-production process, involving key stakeholders in European chemical regulation, has developed a common understanding of: (i) the feasibility of implementation of an ecosystem services approach to chemical risk assessment; (ii) the additional insights and regulatory benefits an ecosystem services approach provides to environmental decision making; (iii) the additional steps required to fully implement an ecosystem services approach to chemical risk assessment. A tiered framework is presented that demonstrates how chemical risk to ecosystems services delivery can be assessed using currently available tools and data and that guides future research and tool development required to reduce uncertainties in extrapolating from what we measure (i.e. chemical effects on individual species) to what we want to protect (i.e. ecosystem service delivery).

CRediT authorship contribution statement

Lorraine Maltby: Conceptualization, Investigation, Formal analysis, Writing – original draft, Supervision, Funding acquisition. **Ross Brown:** Investigation, Formal analysis, Writing – review & editing, Funding acquisition. **Jack H. Faber:** Conceptualization, Investigation, Formal analysis, Writing – review & editing, Funding acquisition. **Nika Galic:** Formal analysis, Writing – review & editing. **Paul J. Van den Brink:** Conceptualization, Investigation, Formal analysis, Writing – review & editing, Funding acquisition. **Oliver Warwick:** Investigation, Formal analysis, Writing – review & editing. **Stuart Marshall:** Conceptualization, Investigation, Formal analysis, Project administration, Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary infromation

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