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Advantages and challenges associated with implementing an ecosystem services approach to ecological risk assessment for chemicals

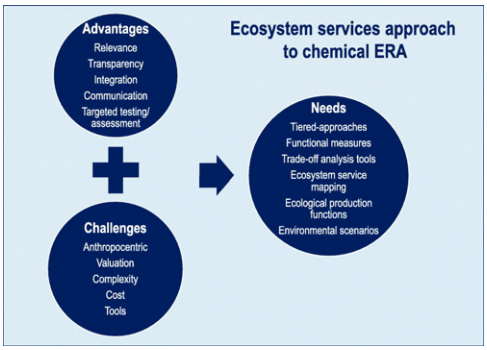
Maltby Lorraine [a,*], van den Brink Paul J. [b,c], Faber Jack H. [b], Marshall Stuart [d,1]

[a] Department of Animal and Plant Sciences, The University of Sheffield, Western Bank, Sheffield S10 2TN, UK
[b] Wageningen Environmental Research (Alterra), P.O. Box 47, 6700 AA, Wageningen, The Netherlands
[c] Aquatic Ecology and Water Quality Management Group, Wageningen University, P.O. Box 47, 6700 AA, The Netherlands
[d] Unilever, Safety & Environmental Assurance Centre, Colworth Science Park, Sharnbrook MK44 1LQ, UK

HIGHLIGHTS

- The ES approach has the potential to bring greater ecological relevance to ERA.
- EU regulators, industry and academia all supported an ES approach in ERA.
- ES approach is applicable to all chemical regulations but challenging for widely dispersive chemicals.
- ES approach integrates across environmental policies, stressors, habitats and scales.
- Tailor-made tools and models ES needed to link ecotoxicity measures to ES endpoints.

GRAPHICAL ABSTRACT



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ABSTRACT

The ecosystem services (ES) approach is gaining broad interest in regulatory and policy arenas for use in landscape management and ecological risk assessment. It has the potential to bring greater ecological relevance to the setting of environmental protection goals and to the assessment of the ecological risk posed by chemicals. A workshop, organised under the auspices of the Society of Environmental Toxicology and Chemistry Europe, brought together scientific experts from European regulatory authorities, the chemical industry and academia to discuss and evaluate the challenges associated with implementing an ES approach to chemical ecological risk assessment (ERA).

Clear advantages of using an ES approach in prospective and retrospective ERA were identified, including: making ERA spatially explicit and of relevance to management decisions (i.e. indicating what ES to protect and where); improving transparency in communicating risks and trade-offs; integrating across multiple stressors, scales, habitats and policies. A number of challenges were also identified including: the potential for increased complexity in assessments; greater data requirements; limitations in linking endpoints derived from current ecotoxicity tests to impacts on ES.

In principle, the approach was applicable to all chemical sectors, but the scale of the challenge of applying an ES approach to general chemicals with widespread and dispersive uses leading to broad environmental exposure, was highlighted. There was agreement that ES-based risk assessment should be based on the magnitude of impact rather than on toxicity thresholds. The need for more bioassays/tests with functional endpoints was recognized, as was the role of modelling and the need for ecological production functions to link measurement

* Corresponding author.
E-mail address: l.maltby@sheffield.ac.uk (L. Maltby).
[1] Present address: 6 Prestwick Road, Great Denham, Bedford, UK.

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endpoints to assessment endpoints. Finally, the value of developing environmental scenarios that can be combined with spatial information on exposure, ES delivery and service provider vulnerability was recognized.

1. Introduction

Human wellbeing depends on nature and the benefits it provides (Daily et al., 1997). The relationships between habitats, their biodiversity and human wellbeing are varied and complex (Sandifer et al., 2015) and the ecosystem services concept has been proposed as a vehicle for characterising and understanding these relationships (Millennium Ecosystem Assessment, 2005). There is clear consensus that ecosystem services (ES) are derived from biophysical structures and processes (Haines-Young and Potschin, 2010), however, there is no single definition of ES (Nahlik et al., 2012). Here we adopt The Economics of Ecosystem and their Biodiversity (TEEB) definition of ES: 'direct and indirect contributions of ecosystems to human well-being' (TEEB, 2010). Because ecosystems differ in their species composition the services that ecosystems can provide vary in time and space (Hassan et al., 2005; Science for Environmental Policy, 2015). Moreover, many ecosystems are actively managed for specific purposes (e.g. nature conservation, timber production, food, flood prevention) and because of interactions between species and ecological processes, the management or optimization of ecosystems for one service may have consequences for the delivery of other services (Raudsepp-Hearne et al., 2010).

Chemical products entering the environment have the potential to enhance or reduce human wellbeing. If the goal of environmental management is to optimise human wellbeing, then ES may provide a common currency for comparing the wellbeing benefits of chemical use with the potential wellbeing costs via environmental degradation (Maltby, 2013). Ecological risk assessment (ERA) is concerned with quantifying the adverse effects of chemicals on ES delivery, but risk management needs to consider both the risks and benefits of chemical products for human well-being. Effective assessment of chemical risks requires clear protection goals specifying what to protect, where to protect it and over what time period. A wide range of general protection goals are either explicit or implicit in legislation, most of which are vaguely defined, from a scientific perspective, and hence not easily measurable (Hommen et al., 2010; Brown et al., 2017). An important problem formulation step in the ERA of chemicals is therefore the operationalization of generic protection goals into specific protection goals (SPGs) that can be used to guide prospective or retrospective ERAs (Munns et al., 2009; Nienstedt et al., 2012; Thomsen et al., 2012).

Conventional ERA has focused predominantly on structural endpoints (e.g. population abundance, species richness etc.), but many ES flow from ecological processes (de Groot et al., 2002). Species or taxonomic groups currently used in ERA may not be important for the ES of concern or, if important, the measurement endpoints may not be relevant to ES provision. ES are delivered by natural capital, including habitats and the biodiversity they support, and understanding which natural capital attributes are important for delivering specific ES is an area of active research (Smith et al., 2017). Many chemicals are widely distributed and may potentially impact a number of habitats, varying from homogeneous monocultures (e.g. some arable or forested landscapes) to highly heterogeneous habitat mosaics. Retrospective ERAs focus on those sites and habitats known or suspected to be exposed to chemicals. However, prospective ERAs are generally not site-specific and are less habitat specific (e.g. they may not differentiate between lotic or lentic freshwater systems of different scales). This raises the challenge of deciding which ES to prioritise in order to contextualize the ERA. This prioritization is required to move risk management away from the impossible task of 'protecting everything, everywhere, all of the time' and towards a more nuanced and resource targeted assessment that effectively ensures the correct level of protection, in the right locations (Nienstedt et al., 2012; Devos et al., 2015).

The European chemical industry is highly regulated, although legislation varies across chemical sectors and involves different European agencies (Brown et al. 2017). For instance, whereas general chemicals under REACH (Regulation (EC) No 1907/2006) and biocides (Regulation (EU) No 528/2012) are the remit of the European Chemicals Agency (ECHA), the European Food Safety Authority (EFSA) has responsibility for plant protection products (Regulation (EC) No 1107/2009) and feed additives (Regulation (EC) No 1831/2003). EFSA has produced guidance for developing specific protection goals for the ERA of plant protection products and feed additives using the ES approach (EFSA PPR Panel, 2010; EFSA Scientific Committee, 2016a). Key taxa or functional groups delivering ES of concern have also been identified (EFSA PPR Panel, 2013, 2014, 2015, 2017). A recent joint workshop between ECHA and EFSA on soil risk assessment highlighted that "The [ES] approach is already incorporated in EFSA's guidance, but presents a somewhat new concept for ECHA" (ECHA, 2016).

Given the considerations above, implementing an ES approach raises a number of questions: what are the advantages and limitations of using the ES framework for ERA? How to incorporate spatio-temporal heterogeneity in landscapes and hence ES delivery? What is the general applicability of the approach across chemical sectors? How can we assess the impacts of chemicals on ES and to what extent do standardised test methods and approaches provide the information required? What are the current knowledge gaps and how may they be addressed?

Here we describe the outcome of an expert elicitation and consensus building process in which scientific experts from European regulatory authorities, chemical industry and academia discussed and evaluated the challenges associated with implementing an ES approach to chemical ERA. This was the first of a series of three workshops organised as part of the CARES project (Chemicals: Assessment of Risks to Ecosystem Services), which was funded by the European Chemical Industry Council (Cefic) Long Range Initiative.

2. Methods

A 2-day workshop was organised under the auspices of the Society of Environmental Toxicology and Chemistry (SETAC) Europe to bring together scientific experts from European regulatory authorities, chemical industry and academia to discuss and evaluate the advantages and challenges associated with implementing an ES approach to chemical ERA. The workshop was held in Brussels (15–16 July 2015) and was attended by twenty-four invited participants (9 business, 8 regulatory, 6 academic, 1 NGO[2]). The aim of the workshop was to reach consensus across stakeholders on: (1) the current state of knowledge and key information gaps; (2) possible ways forward and development needs.

Workshop participants addressed the following questions:

1. What are the advantages and challenges of using an ES framework in prospective and retrospective ERA?
2. What approaches could we use to account for heterogeneity in landscapes and ES delivery when undertaking prospective ERA?

[2] European Commission (Directorate-General Health and Food Safety), European Commission (Directorate-General Environment), European Commission (Directorate-General Internal Market, Industry, Entrepreneurship and SMEs), European Food Safety Authority, TCB (NL), ANSES (F), Environment Agency (UK), Cefas, University of Sheffield, University of Exeter, Wageningen UR, Arche Consulting, Bayer, BASF Shell, Syngenta, ECT Oekotoxikologie GmbH, L'Óreal, Estel Consult Ltd., Unilever, Cefic LRI.

3. To what extent is the ES approach universally applicable (i.e. across different habitats, chemicals, emission/exposure scenarios, legislations etc.)?
4. Assuming ES-based protection goals, how can we assess the impacts of chemicals on ES?
5. To what extent do standardised test methods and approaches provide the necessary information?
6. What developments are required to provide the tools and approaches needed to assess the impacts of chemicals on ES?

The questions were first addressed in small groups and then in plenary with all participants. These discussions formed the basis of the final plenary discussion aimed at identifying future needs and next steps. Questions 1–3 were considered separately by each sector (i.e. business, government, academia) and the outcome of those deliberations discussed by all participants in plenary. Questions 4–6 were considered by three mixed-sector groups, each focusing on different risk assessment scenarios (i.e. prospective ERA for chemicals with non-specific mode of action (baseline toxicity), prospective ERA for chemicals with a specific mode of action, retrospective ERA), before being discussed in plenary.

3. Results and discussion

3.1. What are the advantages and challenges of using an ES framework in prospective and retrospective ERA?

There was considerable consensus across different stakeholders of the main advantages and challenges of applying an ES framework to ERA (Table 1). Participants from all sectors identified relevance, transparency, integration and communication as the major advantages. Complexity, lack of available tools and anthropocentric focus of the approach were identified as major challenges.

Workshop participants from all sectors agreed that an ES framework can result in better informed risk management decisions and more relevant ERA by focusing protection goals on what stakeholders value and tailoring them to be spatially and/or temporally specific. A four-step process for identifying and prioritizing ecosystems and services potentially impacted by chemical emissions has been proposed to aid the derivation of specific protection goals (Maltby et al., 2017). Focusing ERAs in this way should also ensure greater acceptance of assessment outcomes and enhance stakeholder and societal support for potentially costly risk management (Faber, 2006; Cormier and Suter, 2008).

Table 1
Advantages and challenges of applying and ES framework to prospective and retrospective ERA identified by workshop participants from business (B), government (G) and academia (A).

Advantages	Challenges
Relevance: focus RA on what people want when defining protection goals (B, G, A)	Anthropocentric (B, G, A)
Transparency: prioritization and trade-offs made explicit (B, G, A)	Valuation – how to do it (B)
Integration: integration-across multiple stressors, habitats, scales and policies (B, G, A)	Complexity: data hungry, spatio-temporal variation (B, G, A)
Communication: more effective communication (B, G, A)	Unfamiliar language (G)
Informed RM decisions. Increases ecological realism, considers implications of different management in multifunctional landscapes, enables cost/benefit of remedial actions (B, G)	Cost – need time and money (B, A)
Combines ES with intelligent testing (B)	Tools: converting conventional ecotoxicity testing to ES/lack of ERA tools (B, G, A)

RA = risk assessment; RM = risk management.

Application of an ES approach increases transparency both in terms of the prioritization of ES (what to protect where?) and in describing trade-offs between ES (i.e. which services will be enhanced and which will be reduced by different management decisions).

Ecosystems may have the capacity to deliver many ES, but ecosystem functions can only be considered services when they are associated with human beneficiaries (Fisher et al., 2009). Workshop participants from all sectors noted that one of the challenges to implementing the ES approach is that it is anthropocentric and utilitarian. For instance, it has been argued that, in contrast to non-utilitarian approaches to biodiversity conservation, an ES approach ignores the intrinsic value of nature and consequently biodiversity only matters to the extent that it benefits humans (McCauley, 2006; Silvertown, 2015). However, as Loreau discusses, the distinction between utilitarian and non-utilitarian approaches to biodiversity conservation can be reconciled (Loreau, 2014). The intrinsic value of nature is included under the category of 'cultural services' and a recent report for the European Commission concluded that, although there are still uncertainties surrounding the question of whether the use of an ES approach protects biodiversity, the answer is "likely to be a qualified yes". The qualifiers being that "the approach is implemented via policies based on sound evidence, and in conjunction with strategies that recognise the intrinsic value of biodiversity" (Science for Environmental Policy, 2015).

The ES approach requires benefits to be valued but beneficiaries may differ in their value systems and/or their valuations of particular ES (Anderson et al., 2016; Pan et al., 2016). Workshop participants from business identified valuation as a challenge to the implementation of an ES approach. In particular, how are ES to be valued and whose values are to be taken into account? Will monetarization overvalue provisioning services that have a clear market (and are therefore easier to value) and undervalue other ES that do not (e.g. cultural services)? Similar concerns have been raised previously (de Groot et al., 2010; Hauck et al., 2013) and are areas of active research and debate (Calow, 2015; Kapustka and McCormick, 2015; Munns and Rea, 2015).

Most chemical prospective ERA is concerned with a single environmental compartment (e.g. soil, water) exposed to a single chemical. However ecosystems are impacted by multiple stressors – both natural and anthropogenic – and ES are often delivered across large spatial scales by multiple environmental components (UK National Ecosystem Assessment, 2011; Burkhard et al., 2014). The ability of the ES framework to integrate the ERA across multiple stressors, multiple scales and multiple environmental compartments (habitats) and hence multiple environmental policies, was considered to be a major advantage by all sectors as it offered the potential of a more holistic environmental management. However, although this added complexity increases ecological realism and can result in more intelligent and targeted testing, it also requires greater ecological understanding.

Many ES are driven by ecological processes, but current ERA tools, especially those used in prospective ERA, focus on ecological structure (see sections 3.5 and 3.6). Participants from all sectors highlighted the need to develop new tools that either measure ES directly or produce information (i.e. measurement endpoints) that can be robustly extrapolated to ES performance (i.e. assessment endpoint). The increased data requirements and the need to develop and apply new ERA tools will take time and potentially increase the cost of performing ERAs (a challenge highlighted by participants from business and academia). However, as highlighted by participants from business and government, adopting an ES approach will increase ecological realism and by considering the implications of different management decisions in multifunctional landscapes, as well as the costs and benefits of any remedial actions, applying the approach should result in more robust risk management decisions (Munns et al., 2017). The presumption that an ES approach improves environmental decision-making because it makes explicit the connection between human well being and ecosystem structures and processes, has not, however, been rigorously evaluated (Van Wensem et al., 2017).

The ES approach highlights the direct and indirect benefits that people get from nature and therefore facilitate discussion on why it is important to protect ecosystems and their biodiversity. Because stakeholder values are used to specify protection goals, participants from all sectors recognized the value of the approach for improving communication between risk assessors and risk managers, and between scientists, regulators and the general public. However, the current lack of clarity on definitions, unfamiliarity of the language and overtly anthropocentric nature of the approach (i.e. nature serving people versus nature benefiting people) can reduce the effectiveness of this communication (a challenge identified by participants from government). A similar concern about the clarity of terminology and the potential for misunderstanding or misinterpretation was identified by stakeholders asked about the use of an ES approach in European water management (Grizzetti et al., 2016). The use of the word 'services' is often perceived as particularly problematic and some authors have suggested that the language of services should be avoided altogether (Gunton et al., 2017).

3.2. What approaches could we use to account for heterogeneity in landscapes and ES delivery when undertaking prospective ERA?

Whereas retrospective ERAs may take account of environmental heterogeneity, most prospective ERAs do not. Chemicals may be released into, or applied to, a single habitat (e.g. river, arable field, forest), but then be transported, possibly over considerable distances, to other habitats. Knowledge of the properties of chemicals and the environments into which they are released, can be used to assess the likelihood of exposure for different habitat types and to target risk assessment on those habitats where the potential for impacts is greatest. In addition to spatio-temporal variation in chemical exposure, there is spatio-temporal variation in ES delivery. This variation is driven by differences in species distributions, habitats, land use and management practices (Foley et al., 2005; Anderson et al., 2009).

Workshop participants agreed that the development of a landscape scale, scenario-based approach to chemical ERA, which incorporates some of this variation and thereby reduces the uncertainty associated with the risk assessment, would improve the ecological relevance of ERAs and enable risk managers to make better informed decisions. A tiered approach was advocated for prospective risk assessment in which lower tiers would use exposure and/or effect based triggers based on conservative assumptions, whereas higher tiers would adopt standard environmental scenarios accounting for spatial and temporal variation.

Moving to a landscape scale will require consideration of the spatio-temporal variation in the distribution, abundance, impact and recovery of the species and ecological processes delivering ES (i.e. ES providers (Luck et al., 2009)) and could include the assessment of multiple stressors. Challenges in developing landscape-scale scenarios include mapping of chemical exposure and ES in space and time to identify priority areas based on the co-occurrence of chemical exposure and ES provision. The integration of exposure and ES information can be used to define environmental scenarios that represent focal regional landscapes delivering the ES of interest. These scenarios frame specific protection goals and are used to identify focal species and ecological processes for use in prospective ERA (Franco et al., 2017; Rico et al., 2017). Post-decision monitoring is recommended to develop confidence in the approach and to allow adaptive management (Faber, 2006; Vijver et al., 2017) (Fig. 1).

Other issues to be considered are what protection goals and hence reference conditions (Wright et al., 2000; Rutgers, 2008) should environmental scenarios represent. Most European landscapes are either urbanised or managed and it is these human-modified landscapes that should inform the reference conditions used in ERA. Non-urbanised landscapes in Europe are managed for a variety of purposes including crop and livestock production, timber, nature conservation, hunting and fishing, energy production, transport, water abstraction, flood protection or recreation. The land uses are changing, for instance, between 1990 and 2006 urban areas in Europe increased by 21% and permanent crops decreased by 13.4% (Kuemmerle et al., 2016). Changes in land use and land management will alter the ES profile even in the absence of other stressors. A commercial forest will provide a different set of ES than a native woodland, a river channel modified to alleviate flooding will provide a different set of ES than an unmodified and unconstrained river channel and a ploughed field will provide a different set of services than an unmanaged meadow (Foley et al., 2005). Environmental scenarios developed for chemical ERA should represent relevant land uses and land management practices and not default to assessing chemical effects against pristine, non-managed environments.

A key element of the problem formulation step is identifying which ES are required by stakeholders, where (and when) they need to be

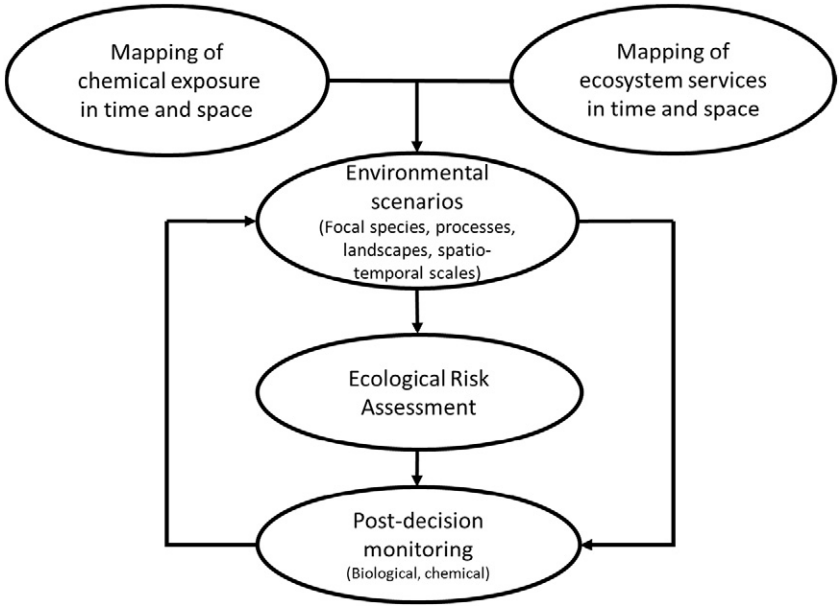

Fig. 1. Schematic representation of the links between spatially and temporally explicit exposure assessment and potentially impacted ecosystem services via environmental scenarios. Environmental scenarios represent regional landscape typologies at various scales and provide a frame for prospective ecological risk assessment. They inform, and may be refined by, field monitoring undertaken to verify the outcomes of prospective ERAs.

supplied and at what level. This requires stakeholders to be identified and consulted in order to ascertain their preferences and values whilst recognising that the areas where ES are produced (i.e. service production areas) and areas where the benefits occur (i.e. service benefit areas) may not be the same (Fisher et al., 2009). Whereas most regulating services, except for climate regulation, are produced and utilized within a catchment or region, provisioning and cultural services may be traded over large distances, making it difficult to identify and manage the potential environmental consequences of ES production and to identify appropriate stakeholders (Costanza, 2008; Villamagna et al., 2013).

The identification and valuation of human wellbeing benefits arising from ES should contextualize and be used to guide the ERA process by specifying the specific protection goals for assessment and helping to decide on focal species, processes and landscapes to be used for the environmental scenarios. The development of environmental scenarios for prospective ERA is an emerging field of research and studies have focused primarily on the ERA of pesticides (Ibrahim et al., 2014; Rico et al., 2017) or down-the-drain chemicals (Franco et al., 2017). These approaches start from a consideration of the composition of species or species traits in the reference scenario, rather than from a consideration of the ES preferences of stakeholders. However, they could be developed further to incorporate stakeholder preferences, as is currently done for some retrospective risk assessment schemes (NEN, 2010; Moore et al., 2017).

3.3. To what extent is the ES approach universally applicable (i.e. across different habitats, chemicals, emission/exposure scenarios, legislations etc.)?

Workshop participants agreed that, in principle, ES approaches are widely applicable across different habitats, chemicals, exposure scenarios and legislations. However, risk management decisions may vary across different legislations, chemicals and regions and insufficient understanding of which, and how, ES are provided by specific habitats may limit some applications. Participants considered the applicability of the approach to be a function of both the spatial and temporal scale of exposure: the approach being most readily applied to chemicals that had a clearly defined short-term, localised exposure (e.g. agrochemicals), followed by non-persistent chemicals from defined sources (e.g. down the drain chemicals), followed by persistent, localised chemicals (e.g. metals). They considered application of the approach to be most challenging for persistent chemicals that undergo long-range transport (e.g. POPs) where the potential spatial and temporal scales and range of exposed ecosystems are huge and, consequently, so would be the scope of the ERA.

Regulatory risk assessment in Europe is based on a threshold principle with authorisation depending on whether a specific toxicity to exposure ratio has been exceeded. However, applying an ES approach that presents risk management options incorporating trade-offs, requires a more nuanced assessment that is based on an evaluation of the magnitude of impact in ES delivery. Workshop participants acknowledged that thresholds may be required for regulatory decision making, but also acknowledged that these thresholds need not be equivalent to a no effect level. This is because a sustainable and acceptable level of ES delivery (i.e. meets beneficiaries' needs) may be achieved even if some reversible impact occurs (Luck et al., 2009).

Determining the magnitude and scale (spatial and temporal) of tolerable effects on ES providers requires knowledge of the translation function (i.e. ecological production function, EPF) linking changes in ES provider characteristics and performance to changes in the level of ecosystem service delivery (Bruins et al., 2017). Generation of robust EPFs has been identified as one of the major challenges for the implementation of an ES-based approach to risk assessment and risk management (Olander and Maltby, 2014). Workshop participants highlighted the specific need to develop tools and models that relate conventional ERA measurement endpoints (i.e. toxicity test endpoints, indicator endpoints) to ES (i.e. assessment endpoints) and the potential need for additional measurement endpoints. Moreover, in order to be able to assess fully the potential impact of chemical stressors on bundles of ES and their interactions (i.e. synergies and trade-offs), workshop participants recommended that quantitative relationships, linking chemical exposure to changes in key service provider characteristics and ES delivery, are generated. If these relationships are not known, then a precautionary approach may be adopted in which either no or only transient adverse effects on ES provider characteristics are acceptable. As a result of these discussions, workshop participants identified the need for the development of assessment criteria based on magnitude of impacts rather than binary pass/fail as in current general chemicals regulation. This will require a systems approach to evaluate the ecological consequences of predicted chemical impacts in time and space, as well as the potential recovery from such impacts (EFSA Scientific Committee, 2016b).

3.4. Assuming ES-based protection goals, how can we assess the impacts of chemicals on ES?

EFSA have led in the development of specific protection goals for market authorization framed within an ES perspective (EFSA PPR Panel, 2010; Nienstedt et al., 2012; EFSA Scientific Committee, 2016a). EFSA have identified generic ES providers (i.e. service providing units, SPU) within which vulnerable species can be identified. Specific protection goals for each SPU include the ecological entity and attribute to be protected, the spatial and temporal scale of protection, and the magnitude of acceptable effect (EFSA Scientific Committee, 2016a). For example, for aquatic organisms exposed to plant protection products, the basis for a regulatory decision is either no effect on the measurement endpoint (ecological threshold option) or some effect but full recovery after a specified period of time (ecological recovery option) (EFSA PPR Panel, 2013). The tiered approach adopted by EFSA requires calibration of lower tiers to a reference tier that captures the environmental, ecological, and where appropriate, landscape variability of the ecosystems of interest. However, in the absence of robust and quantitative EPFs linking measurement endpoints to the assessment endpoints (i.e. changes in test species attributes to changes in ecosystem service delivery), the extent to which these assessments are over- or under-protective is unknown.

Plant protection products are applied to a known crop, at a prescribed concentration and frequency of application within a prescribed time window. However, even under such well-defined conditions the identification of ES of concern and vulnerable species within SPUs, can be challenging (EFSA PPR Panel, 2013, 2014, 2015, 2017). Workshop participants noted that the challenge is even greater for chemicals with a wider and more spatially and temporally variable exposure profile (also see section 3.3). Multiple species in multiple habitats delivering multiple ES are potentially exposed to chemicals with widespread and dispersive uses. Some prioritization is therefore required to make the assessment manageable. Ideally, this prioritization would be based on stakeholder priorities coupled with an assessment of the importance of different habitats for providing ES and their vulnerability to chemical exposure. A refined EFSA framework, incorporating a prioritization step based on chemical exposure characteristics and the importance of specific habitats for providing ES, has been applied to four case studies: oil refinery waste discharging into estuarine waters; oil dispersant exposure in aquatic environments; exposure of terrestrial and aquatic habitats to down the drain chemicals; exposure of remote pristine habitats to persistent organic pollutants (ECETOC, 2015; Maltby et al., 2017). By identifying key habitats and ES of concern, this revised framework offers the potential to incorporate greater spatial and temporal resolution and increased ecological relevance into prospective chemical ERA (Maltby et al., 2017).

For retrospective ERA, indicators for impacts of chemical exposure on species and ecological processes that drive ES could be used to derive

environmental protection goals, set environmental quality objectives/standards (EQO/EQS) or be used as assessment endpoints in site-specific risk assessments (Faber and van Wensem, 2012; Moore et al., 2017). The EU Water Framework Directive (WFD) dictates that European waters should reach 'good ecological status', which is assessed by monitoring invertebrate, fish, algal and macrophyte community structures and establishing whether they deviate from the expected reference condition (i.e. if the site was minimally impacted). The WFD also states that priority chemicals should not exceed EQS derived using toxicity information. Workshop participants thought that there could be practical advantages in setting EQS based on ES and that the CICES typology (Haines-Young and Potschin, 2013) could be used to select species and endpoints for deriving EQS. This would enable the assessment of ecological status in terms of the provision of acceptable levels of ES delivery, which may not be the same as the currently defined 'good ecological status' (Paetzold et al., 2010). However, workshop participants also acknowledged that this application of the CICES typology may require the development of tests and bioassays with functional endpoints. Paetzold et al. provide a rationale for assessing ecological quality based on ES and Vidal-Abarca et al. evaluate the ability of WFD indices to provide an assessment of ES (Paetzold et al., 2010; Vidal-Abarca et al., 2016).

European soil quality is regulated by national legislation and guidance for assessing soil quality within an ES framework has been developed in the Netherlands (NEN5737 (NEN, 2010)). NEN5737 provides a step-wise protocol for stakeholder participative assessment in which the specific land use objectives of local stakeholders (i.e. associated desired ES) set the conditions for selection of ecotoxicological endpoints. Vulnerable indicators, for use in bioassays or to be assessed through field inventory and monitoring, are selected using a triad approach: 1) chemical characterisation of soil contaminants, 2) ecotoxicological assessment of soil and 3) assessment of resident communities. Notably, indicators should be selected that are relevant for the intended land use and management practises (e.g. cropping and soil management). Recently, the approach has been used to form the basis of a more general international standard (ISO 19204:2017).

3.5. To what extent do standardised test methods and approaches provide the necessary information?

In ecotoxicology and related sciences, the most relevant standardised test methods are published by two international organisations: the OECD (Organisation for Economic Co-operation and Development) and the ISO (International Organisation for Standardization). In addition, some national organisations, most notably the ASTM (American Society for Testing and Materials), have developed their own standard methods. Most of these guidelines focus on test methods that are appropriate for prospective ERA, but some are also relevant for retrospective ERA. A review of the websites of OECD, ISO and ASTM identified 171 guidelines for ecotoxicological methods, 53% of which were published by ISO (See SI for details). The aquatic and terrestrial guidelines reviewed were applicable to a variety of species from microbes to mammals, and measured the effects of chemicals on attributes across the biological hierarchy from genes to ecosystem processes and from individuals to communities (Fig. 2). Most guidelines were for methods using invertebrates (35%), followed by microbes (28%), vertebrates (17%) and primary producers (15%). Within these major taxonomic groupings, the greatest number of guidelines were available for crustaceans, fish and plants (Fig. 2a). The majority of guidelines were for studies conducted in water ($n = 84$), followed by soil ($n = 45$) and aquatic sediment ($n = 20$). The remaining guidelines covered sludge, food and dung. In terms of ecological entity, 56% of methods are performed at the level of the individual and most of these studies measure effects on survival, development and growth (Fig. 2b,c). Sixteen percent of studies assess the effects of chemicals on ecological processes and the vast majority of these are with microbes.

An illustrative mapping of the relevance of standard ecotoxicological test guidelines against ES is provided in Table 2. The mapping uses the CICES typology of ES (Haines-Young and Potschin, 2013) and is restricted to two ES sections 'Provisioning' and 'Regulation & Maintenance'. Cultural services were not considered as they either potentially apply to all species (i.e. Division 'Physical and intellectual interactions with biota, ecosystems and land-/seascapes') or are highly context dependent (i.e. Division 'Spiritual, symbolic and other interactions with biota, ecosystems and land −/seascapes). Standard test guidelines are grouped taxonomically (Fig. 2a) and for each taxon × ES combination, as assessment is made as to whether there are any directly relevant methodologies (i.e. directly relevant species and (potentially) relevant measurement endpoints) or any potential surrogate methodologies (i.e. relevant taxonomic groups).

Although no standard methods assess the effects of chemicals on ES directly, several are directly relevant for assessing the potential impacts of chemicals on ES. With respect to provisioning services, for instance, there are standard guidelines for game birds (e.g. OECD 205/206), commercial and wild fish species (e.g. OECD 210/212), honey bees (e.g. OECD 213/214), shellfish (e.g. ASTM E724-98), crop and other plant species used for food, fibre, fodder and bioenergy (e.g. OECD 227/208, ASTM E1218-04). For regulating and maintenance services, there are directly relevant standard guidelines for mediation of waste and toxics (e.g. ASTM E1688-10; ISO 11733:2004)), soil formation and composition (e.g. OECD 216), pest control (e.g. OECD 226), erosion control and flood protection (e.g. ASTM E1841-04).

Many ES are driven by ecological processes involving a range of taxonomic groups. However, almost all the standard test methods reviewed that used ecosystem processes as a measurement endpoint, were microbial studies. There is therefore a disconnect between the structural endpoints used in many guidelines (e.g. survival, growth, reproduction, biomass (Fig. 1b)) and the ecological processes driving ES of interest. Whereas protecting on the basis of structural endpoints may protect ES delivery (i.e. if structural endpoints are more sensitive than functional endpoints), this may not always be the case (Spaak et al., 2017). Workshop participants therefore identified the need for: (i) an analysis of how structural endpoints map onto different functions; (ii) an evaluation of the advantages and limitations of the use of field and mesocosm studies to provide both structural and functional effects data of relevance to ES assessments (e.g. ASTM E1197-12, OECD GD 53).

3.6. What developments are required to provide the tools and approaches needed to assess the impacts of chemicals on ES?

Workshop participants recognized the need for intelligent testing strategies informed by environmental scenarios that capture spatial and temporal heterogeneity in chemical exposures and ecological receptors. Environmental scenarios should be informed by the co-mapping of exposure patterns, environmental variables, species traits and ES delivery across landscapes so that high-risk areas can be identified. These environmental scenarios should then be used to guide the selection of test species and endpoints and to frame the models (including EPFs) developed to link measurement endpoints to assessment endpoints (Fig. 1). Trait-based approaches have a number of advantages over approaches based on species identity, including increased mechanistic understanding and increased generalization of knowledge, tools and models across communities, ecosystem and geographic regions (Van den Brink et al., 2011). The trait-based approach has been successfully applied to plant assemblages and the potential use of traits to scale from individual-level responses to ecological processes has been demonstrated (Cornwell et al., 2008; Kunstler et al., 2016). Trait-based approaches for other taxonomic groups are less well advanced, partly because of the limited availability of trait data, although this situation is improving (Moretti et al., 2017). An alternative approach to the development of environmental scenarios is to construct landscape-scale

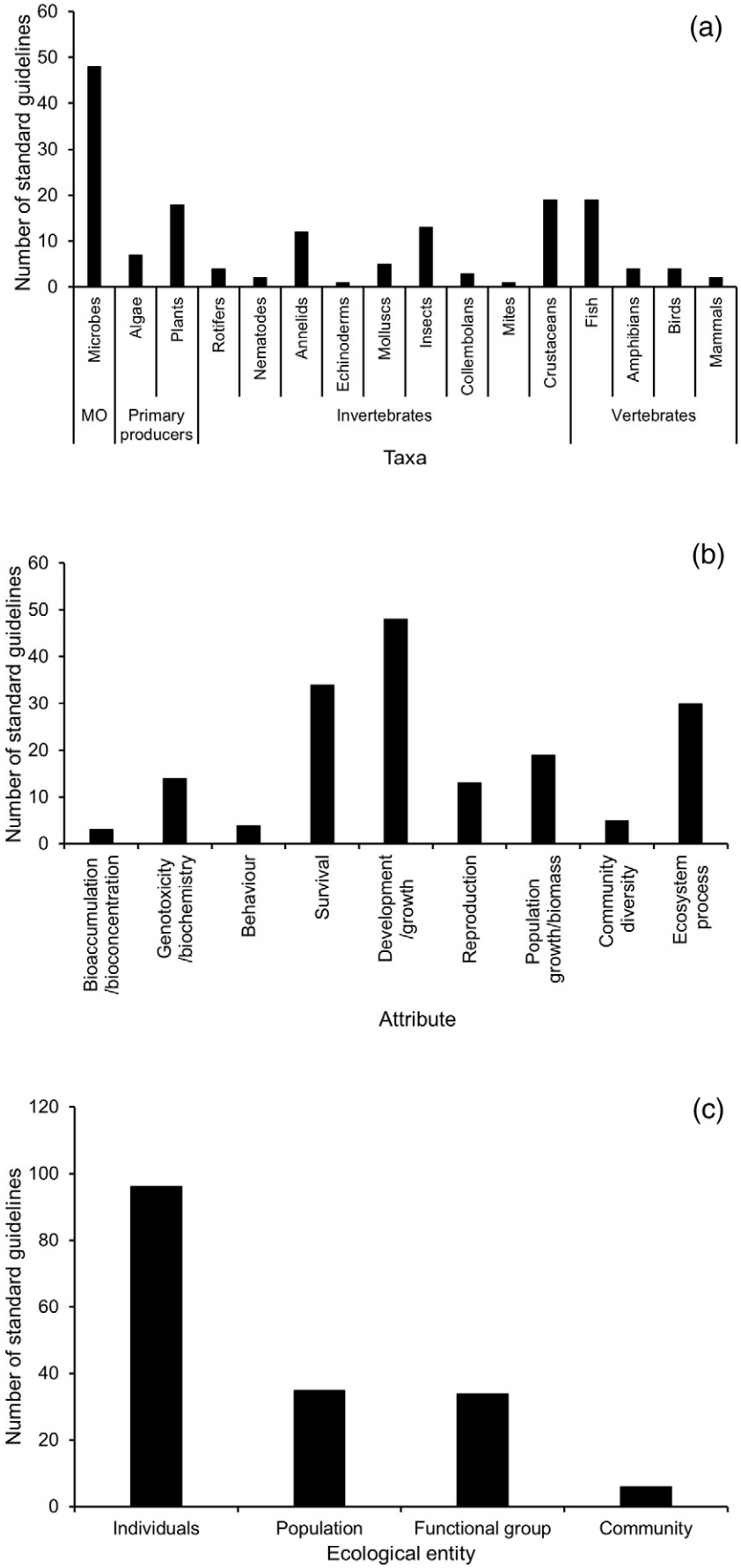

Fig. 2. Distribution of 171 OECD, ASTM and ISO standard ecotoxicity test guidelines by taxa tested (a), the attribute measured (b) and the ecological entity to which the measurement endpoints relates (c).

simulation models based on realistic landscape information (Topping et al., 2015).

Workshop participants acknowledged that moving to a more holistic ES-based landscape–scale ERA poses a number of scientific and technical challenges. These include discriminating between the influences of chemicals and other stressors in retrospective ERA and understanding and predicting how chemical impacts on the structure and functioning of ecological systems translate into changes in ES service delivery at different spatial and temporal scales. In the light of these challenges, workshop participants identified the following areas for future work:

- Development of approaches that could be used to account for heterogeneity in landscapes and ES delivery when undertaking risk assessment. In particular, there is a need to explore the potential use of mapping, environmental scenarios and trait-based approaches in assessing risks to ecosystems and ES.
- Development of tools/test methods to measure ES-relevant (functional) endpoints and EPFs that link measurement endpoints to changes in ES delivery (assessment endpoints).
- Development of a tiered risk assessment approach incorporating intelligent and prioritized testing strategies, which include standard environmental scenarios or landscape models accounting for temporal and spatial heterogeneity at higher tiers.
- Development of tools and approaches for assessing ES trade-offs.
- Illustrative case studies that evaluate the practicality and added value, in terms of decision making, of implementing an ES-based approach to ERA.

4. Conclusions

Stakeholders from across European regulatory authorities, industry and academia agreed that there were clear advantages of using an ES

Table 2
Mapping of standard ecotoxicity test guidelines against ES. Taxon × ES combinations where there are guidelines for relevant species and (potentially) relevant measurement endpoints are shaded black. Taxon × ES combinations where there are guidelines for relevant taxonomic groups are shaded grey.

Ecosystem services				*Taxonomic groups used in standard ecotoxicity tests*															
Section	**Division**	**Group**	**Class**	**Microbes**	**Algae**	**Plants**	**Nematods**	**Annelids**	**Rotifers**	**Echinoderms**	**Molluscs**	**Insects**	**Collembolans**	**Mites**	**Crustaceans**	**Mammals**	**Birds**	**Amphibians**	**Fish**
Provisioning	Nutrition	Biomass	Cultivated crops			■													
			Reared animals and their outputs								▒	■				▒	■		
			Wild plants, algae and their outputs	▒	▒	■													
			Wild animals and their outputs							■	■	■			▒	▒	■	▒	■
			Plants and algae from in-situ aquaculture		▒	▒													
			Animals from in-situ aquaculture							■	■				▒				■
	Materials	Biomass	Fibres and materials for use or processing		▒	■				▒	▒	▒				▒	▒		
			Materials for agricultural use		▒	■										▒			
			Genetic materials for industrial processes	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒
	Energy	Biomass-based energy sources	Plant-based resources		■	■													
			Animal-based resources													▒	▒		
		Mechanical energy	Animal-based energy													▒			
Regulation & Maintenance	Mediation of waste and toxics	Mediation by biota	Bioremediation	■	■	■		▒											
			Filtration/sequestration/storage/accumulation	▒	▒	▒	▒	■	▒	▒	■	■	▒	▒	■	▒	▒	▒	■
	Mediation of flows	Mass flows	Mass stabilisation and erosion control		▒	■													
		Liquid flows	Hydrological cycle, water flow maintenance			▒		▒											
			Flood protection		▒	■													
		Gaseous / air flows	Storm protection			▒													
			Ventilation and transpiration			▒													
	Maintenance of physical, chemical, biological conditions	Lifecycle maintenance, habitat and gene pool	Pollination and seed dispersal									▒			▒	▒	▒		
			Maintaining nursery populations and habitats			▒													
		Pest and disease control	Pest control				▒					▒		■		▒	▒	▒	▒
			Disease control				▒	▒						▒					
		Soil formation and composition	Weathering processes	▒				▒											
			Decomposition and fixing processes	■			■	■				■	■	▒	▒				
		Water conditions	Chemical condition of freshwaters	▒	▒	▒													
			Chemical condition of salt waters	▒	▒														
		Atmospheric composition and climate regulation	Global climate regulation by GHG reduction		▒	▒													
			Micro and regional climate regulation			▒													

approach in chemical ERA. There was agreement that a tiered approach was necessary and that ES-based ERA should be based on the magnitude of impact rather than on toxicity exposure thresholds. In principle, the ES approach has wide applicability, however the scale of the challenge of applying an ES approach to general chemicals with widespread and dispersive uses was highlighted.

A number of challenges need to be addressed before an ES approach can be implemented in chemical ERA. In particular, limitations in linking current ecotoxicity tests and indicators to ES endpoints require the development of methods to measure effects on ecological processes and the development of modelling approaches, including EPFs, to link measurement endpoints to assessment endpoints. Workshop participants recognized the value of developing a standard set of environmental scenarios (species or trait-based) that can be combined with spatial information on exposure, ES delivery and ES provider vulnerability, to frame the chemical ERA.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2017.10.094.

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