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Is an ecosystem services-based approach developed for setting specific protection goals for plant protection products applicable to other chemicals?

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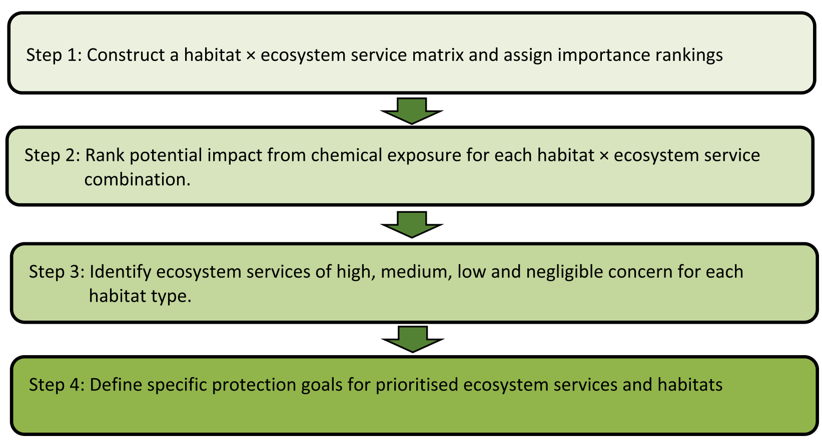
HIGHLIGHTS

- Evaluated an ecosystem services (ES) approach to environmental risk assessment.
- The ES approach was used successfully across different chemical classes
- Potentially impacted habitats and ES were prioritized in 4 case studies.
- Guidance needed on tolerable levels of change in ES and their relative importance.
- Key challenges are SPU selection and extrapolation of SPU impacts to ES change.

GRAPHICAL ABSTRACT



Stepwise process for specifying specific protection goals for use in the environmental risk assessment of chemicals.

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ABSTRACT

Clearly defined protection goals specifying what to protect, where and when, are required for designing scientifically sound risk assessments and effective risk management of chemicals. Environmental protection goals specified in EU legislation are defined in general terms, resulting in uncertainty in how to achieve them. In 2010, the European Food Safety Authority (EFSA) published a framework to identify more specific protection goals based on ecosystem services potentially affected by plant protection products. But how applicable is this framework to chemicals with different emission scenarios and receptor ecosystems? Four case studies used to address this question were: (i) oil refinery waste water exposure in estuarine environments; (ii) oil dispersant exposure in aquatic environments; (iii) down the drain chemicals exposure in a wide range of ecosystems (terrestrial and

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aquatic); (iv) persistent organic pollutant exposure in remote (pristine) Arctic environments. A four-step process was followed to identify ecosystems and services potentially impacted by chemical emissions and to define specific protection goals. Case studies demonstrated that, in principle, the ecosystem services concept and the EFSA framework can be applied to derive specific protection goals for a broad range of chemical exposure scenarios. By identifying key habitats and ecosystem services of concern, the approach offers the potential for greater spatial and temporal resolution, together with increased environmental relevance, in chemical risk assessments. With modifications including improved clarity on terminology/definitions and further development/refinement of the key concepts, we believe the principles of the EFSA framework could provide a methodical approach to the identification and prioritization of ecosystems, ecosystem services and the service providing units that are most at risk from chemical exposure.

1. Introduction

Environmental risk assessment (ERA) of chemicals is based on comparing environmental exposure with potential for adverse effects, and differentiating adverse from non-adverse effects is dependent on what it is we are trying to protect (i.e. the protection goals). Risk assessment, therefore, requires protection goals that clearly specify what to protect, where and when. Regulatory authorities worldwide face the challenge of specifying appropriate environmental protection goals and this challenge has received particular attention recently in Europe (EFSA, 2016). Current environmental protection goals for chemicals in EU legislation are generic and non-specific, including the prevention of 'unacceptable' impacts on 'biodiversity' and 'ecosystems' or the 'the environment as a whole' (Brown et al., 2016). Substantial spatiotemporal variation in environmental conditions, habitat types and species assemblages across Europe, results in generic protection goals being open to differing interpretations across regulatory regions and chemical sectors, which generates considerable uncertainty in how to achieve them (EFSA, 2010; Hommen et al., 2010; Brown et al., 2016). There is a growing consensus that environmental protection goals need to be more specific, to account for the spatial and temporal variation that is inherent in biodiversity and ecosystems (Fremier et al., 2013; Maes et al., 2013; Maltby, 2013).

One approach to accommodating spatial and temporal variation in setting protection goals is to consider what aspects of biodiversity are to be protected in different ecosystems and why? Biodiversity has intrinsic value and contributes to the natural capital that generates the many benefits that ecosystems provide to humans (Mace et al., 2012). These benefits, referred to as ecosystem services, are vital to human health and wellbeing and include provisioning services (e.g. food, clean water), regulating services (e.g. climate regulation, flood protection) and cultural services (e.g. aesthetic value, sense of place) (Costanza et al., 1997; MA, 2005). Ecosystems vary in species composition and hence in the services that can potentially be provided. Moreover, individual species may contribute to more than one ecosystem service and the interrelationships between species and hence the ecological processes they drive, may result in either positive or negative associations between services (Cardinale et al., 2012). As a consequence, the delivery of ecosystem services across a landscape varies in space and time and managing a landscape for one ecosystem service (e.g. food production) may reduce the delivery of other ecosystem services (e.g. flood protection) (Nelson and Roline, 1999; Nelson et al., 2009; Raudsepp-Hearne et al., 2010).

The EU is implementing numerous policies to enhance the sustainable use of natural resources and halt the loss of biodiversity and degradation of ecosystem services, with the EU Biodiversity Strategy to 2020 setting specific targets and policy tools for achieving this (EC, 2011). However, there is still a basic lack of understanding of how protection goals within current EU environmental legislation will ensure that these requirements for halting biodiversity loss or degradation of ecosystem services are met (EFSA, 2010; Hommen et al., 2010). To achieve the targets specified in the EU Biodiversity Strategy to 2020, it is necessary to incorporate ecosystem service thinking into regulatory policy and decision making (Haines-Young and Potschin, 2008; van Wensem and Maltby, 2013). It is also necessary to develop tools and approaches for identifying what needs to be protected and where, to enable the sustainable use of natural capital and ecosystem services (Holt et al., 2016). Aligning chemical ERA to such aims requires the establishment of protection goals and approaches for translating ecotoxicological exposure and effects information into risk management measures for ecosystem service delivery. Assessing the risk of chemical exposure to bundles of ecosystem services enables risk assessors to provide options to risk managers that incorporate the interactions (i.e. synergies and trade-offs) between relevant ecosystem services. This information will enhance the sustainable use of natural resources in multifunctional landscapes by enabling targeted risk mitigation measures and spatially-explicit risk management decisions to be implemented (Maltby, 2013).

In 2010, the European Food Safety Authority (EFSA) outlined how an ecosystem services framework could be used to develop specific protection goals (SPGs) for pesticides (EFSA, 2010), which was later extended to cover invasive species, feed additives and genetically modified organisms (EFSA, 2014; EFSA, 2016). Essentially this framework involves: (1) identifying habitats potentially exposed to the chemical or agent of interest; (2) identifying ecosystem services delivered by potentially exposed habitats; (3) identifying ecosystem components (e.g. species, functional groups, etc.) driving the services potentially affected (i.e. service providing units, SPUs); (4) identifying how service provider attributes (e.g. behaviour, biomass, function, etc.) relate to ecosystem service provision; (5) defining SPGs for SPUs and levels of impact (magnitude, spatial extent and duration) on their critical attributes that would still enable the sustainable delivery of their ecosystem service (Nienstedt et al., 2012; Maltby, 2013).

The aim of this study was to evaluate the applicability of the EFSA framework (EFSA, 2010) to a wider range of chemicals. This was achieved by exploring four case studies, selected to provide a range of chemical classes, emission scenarios and receptor habitats relevant to different chemical industry sectors: (1) oil refinery wastewater discharge exposure in estuarine environments; (2) oil dispersant exposure in ocean, coastal and estuarine environments; (3) complex mixtures of home and personal care products and pharmaceuticals that are discharged down the drain, subsequently exposing a wide range of ecosystems (terrestrial and aquatic); and (4) persistent organic pollutant (POP) exposure via atmospheric transport and condensation in remote (pristine) Arctic environments.

2. Methods

A 4-step approach, similar to that of EFSA (2010), was followed to identify habitats and ecosystem services that are potentially impacted by a variety of chemicals released into the environment. The EFSA approach was modified in order to meet the specific needs raised by each chemical case study and these modifications are highlighted below.

2.1. Step 1: construct a habitat × ecosystem service matrix and assign importance rankings

There are several schemes for listing and classifying ecosystem services (Haines-Young and Potschin, 2013; Maes et al., 2014), with the most widely used being that developed by the Millennium Ecosystem Assessment (MA, 2005). We followed the EFSA (2010) scheme, with some adaptations, by considering 6 provisioning services (food, fibre and fuel, genetic resources, biochemical/natural medicines, ornamental resources, fresh water), 8 regulating services (pollination, water purification/soil remediation/waste treatment, regulation of pest and disease, climate, air quality, water, erosion, natural hazards), 6 cultural services (spiritual and religious values, education and inspiration, recreation and ecotourism, cultural diversity and heritage, aesthetic values, sense of place), and 3 supporting services (primary production and photosynthesis, soil formation and retention, nutrient cycling). Ecosystems were classified into 11 broad habitat types following the MAES typology (Maes et al., 2013) and coded using the European Nature Information System (EUNIS) (EEA, 2015). The broad habitats and EUNIS codes used were: urban (J), cropland (I), grassland (E), woodland and forest (G), heathland, shrub and tundra (F), wetlands (D), rivers and lakes (C), inlets and transitional waters (X01–X03, A1–A5, A7), marine coastal (A1–A5, A7), shelf (A5, A7), open ocean (A6, A7). Each broad habitat may contain several different, and potentially interconnected, habitats. EUNIS is a hierarchical classification that divides broad habitat categories into 5282 distinct habitat types and therefore increased granularity can be incorporated into the assessment if required.

EFSA (2010) presents a relative importance ranking of ecosystem services delivered by in-crop and off-crop areas based on the expert judgement of the Panel producing the opinion. It was necessary to extend this ranking to encompass a wider range of habitat × ecosystem service combinations to account for the widespread use and distribution of the case-study chemicals. Several studies have used expert judgement to compare multiple ecosystem services across multiple habitats (UNEP, 2006; Haines-Young and Potschin, 2008; IFPRI, 2008; Vandewalle et al., 2008; EFSA, 2010; Harrison et al., 2010; Wali et al., 2010; UK National Ecosystem Assessment, 2011; Gómez-Baggethun et al., 2013). These studies were reviewed and the information integrated to produce a combined relative importance ranking for the delivery of the 23 focal ecosystem services by 11 broad habitats.

2.2. Step 2: rank potential impact from chemical exposure for each habitat × ecosystem service combination

The potential impact on each habitat × ecosystem service combination is a function of chemical exposure and the vulnerability of the ecosystem service. Only adverse impacts were considered in this analysis and they were categorized as high, medium or low. Exposure scenarios were developed for each case study based on expert knowledge and used to identify habitats potentially at risk. For each habitat at risk, the vulnerability of specific ecosystem services to chemical exposure was evaluated using knowledge of the toxic mode of action of the chemicals of concern and the toxicological sensitivity of the main taxonomic groups important for providing the ecosystem service of interest (i.e. SPUs). In addition to direct toxicity, potential for secondary poisoning through bioaccumulation was considered. For those services where ecosystem function is important, in particular regulating and supporting services, the level of ecological redundancy amongst SPUs was considered when ranking potential impacts. The major trophic groups responsible for delivering ecosystem services with a high or medium potential impact were identified. The potential importance of eco-engineers was also highlighted where appropriate.

2.3. Step 3: identify ecosystem services of high, medium, low and negligible concern for each habitat type

Ecosystem services were prioritized based on their relative importance (Step 1) and the potential level of impact of chemical exposure on ecosystem service delivery (Step 2). The two steps were linked using a pragmatic prioritization matrix (Table 1); application of which resulted in a categorization of habitat × ecosystem services combinations as high, medium, low or negligible concern. This prioritization provided a focus for the derivation of SPGs in Step 4 and was conservative, highlighting concern for ecosystem services with large relative importance in habitats with low potential impact or with small relative importance in areas of high potential impact.

EFSA (2010) adopted a taxonomic categorization for SPUs (alternatively named key drivers) potentially exposed to plant protection products (i.e. microbes, algae, non-target plants, aquatic invertebrates, non-target arthropods, terrestrial non-arthropod invertebrates, vertebrates). Broad taxonomic groups may include species that undertake different functions and therefore drive different ecosystem services. For example, non-target arthropods in agricultural areas include pollinating insects (pollination service) as well as insect predators and parasitoids of pest species (pest regulation service). A functional classification was adopted here because: (i) most ecosystem services are driven by what species do (i.e. function) rather that what they are (i.e. taxonomy) (Kremen, 2005) and (ii) there is evidence that the sensitivity of an ecosystem service to changes in biodiversity is dependent on the trophic level of the dominant species providing the service (Dobson et al., 2006). As biodiversity declines, ecosystem services provided by species in the upper trophic levels are lost before those provided by species lower in the food chain (Dobson et al., 2006). Species within broad SPU functional groups were identified for habitat × ecosystem services combinations identified as being of medium or high concern.

2.4. Step 4: define specific protection goals (SPGs) for prioritized ecosystem services and habitats

Specific protection goals for SPUs delivering ecosystem services in prioritized habitat × ecosystem services combinations (i.e. high or medium concern) were specified in five dimensions following EFSA's approach (EFSA, 2010): (i) ecological entity (e.g. individuals, (meta)populations, functional groups); (ii) attributes (process/behaviour, abundance/biomass); (iii) magnitude of impact; (iv) temporal and (v) spatial scale of impact. In order to introduce a consistent approach to defining levels of impact, magnitude and scale of impact were each assigned to 1 of 3 categories (Table 2). This categorization is offered for illustrative purposes only. Criteria for defining SPGs and the categorization of the magnitude and scale of acceptable impact, should be derived via dialogue between risk managers and risk assessors.

Table 1
Prioritization matrix based on relative importance of habitats for delivering specific ecosystem services and the potential impact of chemical exposure on service delivery.

		Importance of Ecosystem Service		
		Small	Intermediate	Large
Potential impact	Low	Negligible concern	Negligible concern	Low concern
	Medium	Negligible concern	Low concern	Medium concern
	High	Low concern	Medium concern	High concern

Table 2
Provisional definitions for categorizing impacts.

Magnitude of impact	Spatial scale of impact	Temporal scale of impact
10% reduction in SPU attribute (population abundance or function etc.)	Landscape or watershed (>10 km)	Months (<12 months)
25% reduction in SPU attribute (population abundance or function etc.)	Local to landscape (1 km to 10 km)	Weeks (<4 weeks)
50% reduction in SPU attribute (population abundance or function etc.)	Point of emission to local (<1 km)	Days (<1 week)

3. Results

3.1. Step 1: construct a habitat × ecosystem service matrix and assign relative importance rankings

The broad habitat types and ecosystem services used in this evaluation are presented in Table 3 along with their relative importance rankings. These rankings were derived from a review and integration of existing studies assessing the relative importance of multiple ecosystem services across multiple broad habitat types. EFSA (2010) evaluated the relative importance of 30 ecosystem services in five components of European agro-ecosystems: within crops, edge of field margins, terrestrial habitats away from field, small edge of field surface waters, large surface waters. The UK National Ecosystem Assessment (2011) provided information on the relative importance of 8 broad habitats (mountains, moorlands and heaths, semi-natural grasslands, enclosed farmland, woodlands, freshwaters, urban, coastal margins, marine) in delivering 16 final ecosystem services. The marine and coastal ecosystems synthesis report from the Millennium Ecosystem Assessment provides examples of the significance of ecosystem service provision by 12 coastal and marine habitats (UNEP, 2006) and ecosystem services provided by urban areas have been classified and described by Gómez-Baggethun et al. (2013). Ranking of productivity across habitats is based on Wali et al. (2010).

Haines-Young and Potschin (2008) evaluated ecosystem service provision by UK terrestrial and freshwater Biodiversity Action Plan (BAP) habitats. A questionnaire survey of BAP lead-authors was used to elicit information about the potential ecosystem services or benefits associated with each habitat. This information, which was supplemented by a literature review and a series of expert workshops, was used to identify associations between 28 services and 19 broad habitats.

The EU 6th Framework Project RUBICODE, performed a detailed review of 31 ecosystem services provided by European terrestrial and freshwater biodiversity (Vandewalle et al., 2008). The relative importance of services was first evaluated using information from an extensive literature search. The results of the literature search were then considered by international scientific experts at a workshop and via an e-conference. The agreed qualitative importance rankings for 23 ecosystem services provided by 8 broad habitat types – agro-ecosystems, forests, semi-natural grasslands, heathlands/shrublands, mountains, soil systems, rivers and lakes, wetlands – are presented in Harrison et al. (2010).

3.2. Step 2: rank potential impact from chemical exposure for each habitat × ecosystem service combination

Exposure scenarios were developed for each case study (Fig. 1) and used to identify the habitats for further consideration. Whilst potential impact is primarily exposure driven, it was assessed separately for each case study taking into account prior knowledge of chemical fate, behaviour and toxicity, the range of potentially impacted SPUs, and the potential for both direct and indirect chemical impacts (Tables 4–7). For example, impact on the provisioning service "food" may be considered high if any residues in foodstuffs would be considered adverse, whilst at the same exposure some other services, for example fibre and fuel, would potentially not be impacted to the same high level as some "contamination" or effects might be considered more acceptable.

Table 3
The relative importance of broad habitats for delivering ecosystem services (+ small; ++ intermediate; +++ large; ? unknown). Blank cells indicate that the habitat is not considered important for delivering the ecosystem services of interest. Letters represent EUNIS habitat codes.

Ecosystem service		Terrestrial						Freshwater	Marine			
		Urban	Cropland	Grassland	Woodland and forest	Heathland shrub and tundra	Wetlands	Rivers and lakes	Inlets and transitional waters	Coastal	Shelf	Open ocean
		J	I	E	G	F	D	C	X01–X03, A1–A5, A7	A1–A5, A7	A5, A7	A6, A7
Provisioning services	Food	++	+++	++	+	++	++	++	++	++	++	++
	Fibre and fuel	++	+++	++	+++	++	++	+	++	+	+	+
	Genetic resources	++	++	+++	+++	+++	+++	+++	+++	+++	+++	+++
	Biochemical/natural medicines	?	++	+	++	++	+	+	++	+	+	
	Ornamental resources	+	+	+	+	+	+	+	+	+		
	Fresh water	++	++	+	+++	+++	+++	+++				
Regulatory services	Pollination	++	+++	+++	++	+++	++	+	++			
	Pest and disease regulation	++	+++	+	++	+	++	++	+	++	++	++
	Climate regulation	+++	+++	++	+++	++	+++	++	++	+++	+++	+++
	Air quality regulation	+++	++	++	+++	++	+	++	+	+++	+++	+++
	Water regulation	+++	++	++	+++	++	+++	+++	+++	+		
	Erosion regulation	+	++	++	++	+++	++	++	+	++		
	Natural hazard regulation	+	++	++	++	+++	++	++	+++	+++	++	++
	Water purification/soil remediation/waste treatment	+++	+++	+++	+++	+++	+++	+++	+++	++	++	++
Cultural services	Spiritual and religious values	++	+	++	++	++	++	++	+++	+		
	Education and inspiration	+	+	++	++	++	+++	++	+++	++	+	+
	Recreation and ecotourism	++	++	+++	+++	+++	+++	+++	+++	+++		
	Cultural diversity and heritage	+	++	++	+	++	++	++	++	++		
	Aesthetic values	+++	+++	+++	+++	+++	+++	+++	+++	++		
	Sense of place	+	+++	+++	++	+++	+++	+++	+++	++		
Supporting services	Primary production and photosynthesis	++	+++	++	+++	++	+++	++	+++	++	+	+
	Soil formation and retention	++	++	++	++	++	++	++	++			
	Nutrient cycling	++	+++	++	++	++	+++	++	++	+	+	+

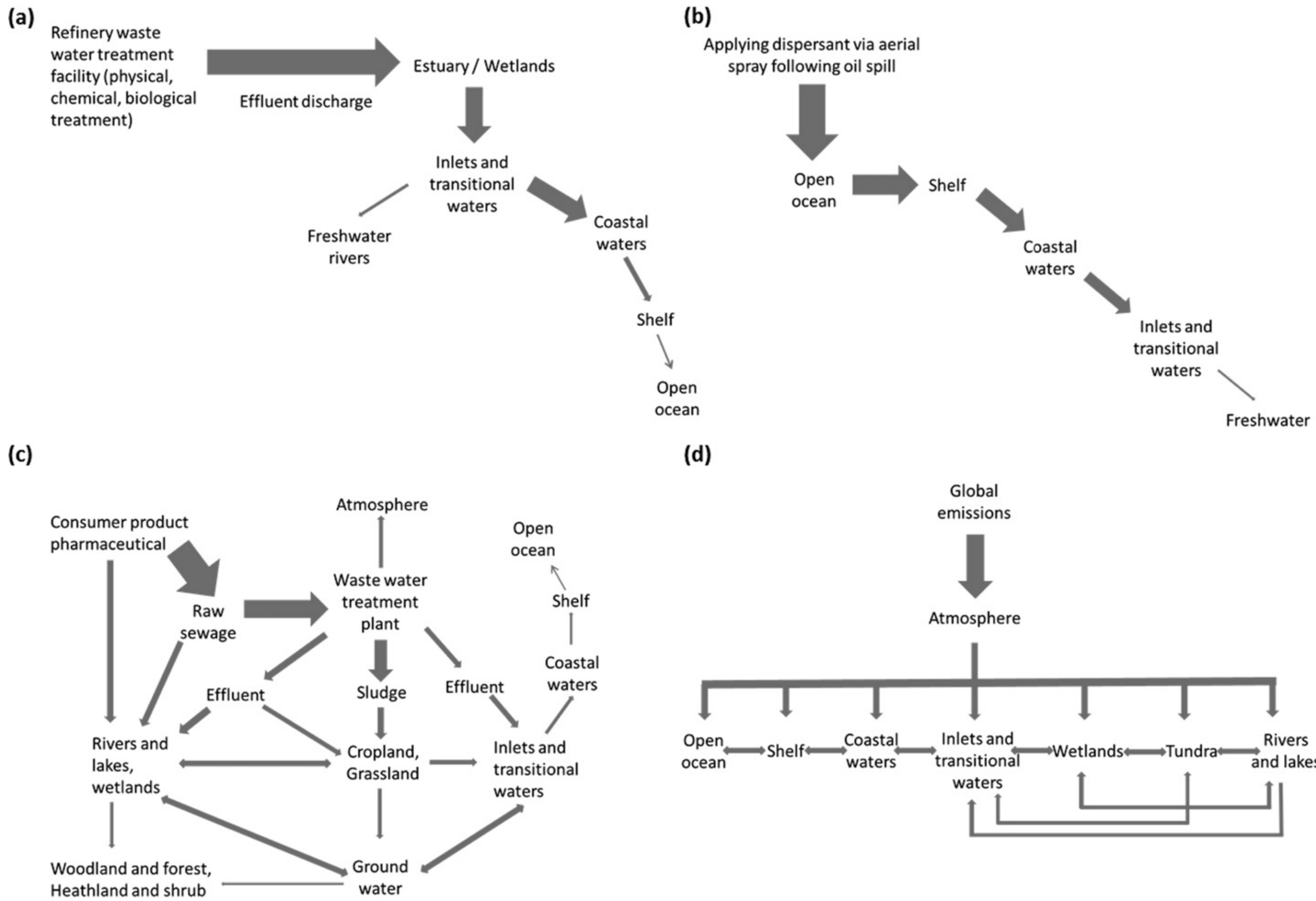


Fig. 1. Exposure scenarios and receptor habitats for: (a) oil refinery; (b) oil dispersants; (c) down the drain chemicals; (d) persistent organic pollutants. Arrow size is indicative of the level exposure.

Oil refineries are often situated in coastal locations, and effluents are complex mixtures of organic and non-organic chemicals, discharged after treatment directly into the environment (Fig. 1a). Most chemical components are hydrocarbons, with non-specific modes of action, causing baseline toxicity (narcosis). Due to this non-specific mode of action, untreated refinery effluents discharged into an estuary (as considered in this case study) has the potential for medium or high impact across all taxonomic groups and consequently a wide range of SPUs and services. As the level of exposure is reduced, the potential impact decreases and therefore dilution on reaching the open ocean reduces the impact to low. Five habitats were identified as being potentially exposed to oil refinery effluents and there was the potential for medium (yellow) or high (red) impact on all ecosystem services, except soil formation and retention (Table 4).

Dispersants are usually applied to surface oil (following release into aquatic environments). In this case study, dispersants were considered in isolation as chemical applications i.e. the impact from the oil was not considered. Dispersants rapidly dilute in the open ocean and may cause temporary impacts on sensitive marine species after application in the immediate spill vicinity. All marine habitats were identified as being potentially exposed (Fig. 1b) and the potential for medium or high impact was identified for 17 ecosystem services (Table 5).

Down the drain chemical emissions were assumed to occur via municipal sewage treatment systems into surface waters (e.g. rivers, transitional or coastal waters), and the application of aqueous sewage and sludge/biosolids to land (primarily arable land and pasture) as fertiliser (Fig. 1c). Therefore, habitats likely to experience highest exposures are those closest to points of emission, with some dispersal in surface waters and/or ground waters limited by degradation, partitioning to solids, and further dilution. Concentrations of down the drain chemicals reaching the marine shelf and the open ocean are expected to become increasingly low and should represent decreasing levels of concern based on exposure. A significant proportion of down the drain chemicals include chemicals present in consumer home and personal care products and pharmaceuticals, which have the potential to impact a wide range of organisms.

A key aspect of the down the drain chemicals case study is the widespread and continuous exposure of aquatic (and to some extent terrestrial) habitats to a highly diverse range of chemicals. This broad exposure scenario means that there could be potential impacts on a wide range of SPUs. Seven broad habitats were identified as being potentially exposed, within which there would be potential medium or high impact for all ecosystem services and approximately 90% of the habitat × ecosystem service combinations (Table 6).

Persistent organic pollutants (*POPs*) can be present in gaseous form in the atmosphere or bound to the surfaces of solid particles including dust. Contamination of remote areas such as the Arctic environment can be via oceanic current and/or freshwater transport and by atmospheric transport and polar condensation in particular. The case study POP chemicals were assumed to have generic characteristics, i.e. low abiotic and biotic degradation/transformation rates, a high vapour pressure and high hydrophobicity (potential to bioaccumulate). In this case study, exposure to the Arctic environment was expected to have low but ubiquitous concentrations in all Arctic habitats, and was not

Table 4
Potential impact of oil refinery discharge on specific ecosystem services (green: low impact; yellow: medium impact; red: high impact) and service-providing units (SPU).

	Ecosystem service	Terrestrial: Urban	Terrestrial: Cropland	Terrestrial: Grassland	Terrestrial: Woodland and forest	Terrestrial: Heathland and shrub	Terrestrial: Wetlands	FW: Rivers & lakes	Marine: Inlets & trans. waters	Marine: Coastal	Marine: Shelf	Marine: Open ocean	Potentially impacted SPU[a]
Provisioning services	Food	green	green	green	green	green	yellow	yellow	red	red	yellow	green	Primary producers; Primary consumers; Secondary consumers
	Fibre and fuel	green	green	green	green	green	yellow	yellow	yellow	yellow	green	green	Primary producers
	Genetic resources	green	green	green	green	green	yellow	yellow	red	red	yellow	green	Primary producers; Primary consumers; Secondary consumers; Decomposers; Detritivores
	Biochemical / natural medicines	green	green	green	green	green	yellow	yellow	red	red	yellow	green	Primary producers; Primary consumers; Secondary consumers
	Ornamental resources	green	green	green	green	green	green	yellow	red	red	green	green	Primary producers; Primary consumers; Secondary consumers; Eco-engineers
	Fresh water	green	green	green	green	green	green	yellow	yellow	green	green	green	Primary producers; Primary consumers; Decomposers; Eco-engineers
Regulatory services	Pollination	green	green	green	green	green	yellow	green	green	green	green	green	Primary consumers
	Pest and disease regulation	green	green	green	green	green	yellow	green	yellow	yellow	yellow	green	Secondary consumers; Decomposers
	Climate regulation	green	green	green	green	green	yellow	green	yellow	yellow	yellow	green	Primary producers; Primary consumers
	Air quality regulation	green	green	green	green	green	yellow	green	yellow	yellow	green	green	Primary producers
	Water regulation	green	green	green	green	green	yellow	green	yellow	yellow	yellow	green	Primary producers; Eco-engineers
	Erosion regulation	green	green	green	green	green	yellow	green	yellow	yellow	green	green	Primary producers; Primary consumers; Eco-engineers
	Natural hazard regulation	green	green	green	green	green	yellow	green	yellow	yellow	yellow	green	Primary producers; Primary consumers; Eco-engineers
	Water purification / soil remediation / waste treatment	green	green	green	green	green	yellow	green	yellow	yellow	green	green	Primary producers; Decomposers
Cultural services	Spiritual and religious values	green	green	green	green	green	yellow	yellow	yellow	yellow	yellow	green	Primary producers; Primary consumers; Secondary consumers; Eco-engineers
	Education and inspiration	green	green	green	green	green	yellow	yellow	red	red	yellow	green	Primary producers; Primary consumers; Secondary consumers; Eco-engineers; Decomposers; Detritivores
	Recreation and ecotourism	green	green	green	green	green	yellow	yellow	red	red	yellow	green	Primary producers; Primary consumers; Secondary consumers; Eco-engineers
	Cultural diversity and heritage	green	green	green	green	green	yellow	yellow	yellow	yellow	green	green	Primary producers; Primary consumers; Secondary consumers; Eco-engineers
	Aesthetic values	green	green	green	green	green	yellow	yellow	yellow	yellow	yellow	green	Primary producers; Primary consumers; Secondary consumers; Eco-engineers
	Sense of place	green	green	green	green	green	yellow	yellow	yellow	yellow	yellow	green	Primary producers; Primary consumers; Secondary consumers; Eco-engineers
Supporting services	Primary production and photosynthesis	green	green	green	green	green	yellow	yellow	red	red	yellow	green	Primary producers
	Soil formation and retention	green	green	green	green	green	green	green	green	green	green	green	
	Nutrient cycling	green	green	green	green	green	yellow	green	yellow	yellow	yellow	green	Primary producers; Eco-engineers; Detritivores

[a]SPU key: Primary producers; Primary consumers; Secondary consumers; Decomposers; Eco-engineers; Detritivores

assumed to be due to local emissions (Fig. 1d). The persistent and bioaccumulative properties of POPs resulted in potential medium impact being identified for four cultural ecosystem services across 5 habitats and potential medium or high impact on food across 7 habitats (Table 7).

3.3. Step 3: identify ecosystem services of high, medium, low and negligible concern for each habitat type

The categorization of ecosystem services by levels of concern for each case study is presented in Table 8. All habitats where there was potential for medium or high impact on at least one ecosystem service (i.e. yellow or red coding in Tables 4–7) are presented for each case study. Both the following description of results and the SPU examples in the more detailed case study tables (Tables S1–S4 Supplementary information) focus on habitat × ecosystem service combinations for which there was high (black) or medium (dark grey) concern.

3.3.1. Oil refineries

Medium or high concern was identified for 16 ecosystems services and 17% of the 253 habitat × ecosystem service combinations considered, with the greatest concern being revealed for ecosystem services associated with inlets and transitional waters and for coastal habitats. This finding can be explained by the importance of these habitat types for the provision of certain ecosystem services (e.g. natural hazard regulation, recreation and ecotourism) and their potentially close

Table 5
Potential impact of oil dispersants on specific ecosystem services (green: low impact; yellow: medium impact; red: high impact) and service-providing units (SPU).

	Ecosystem service	Terrestrial						FW	Marine				Potentially impacted SPU[a]
		Urban	Cropland	Grassland	Woodland and forest	Heathland and shrub	Wetlands	Rivers & lakes	Inlets & trans. waters	Coastal	Shelf	Open ocean	
Provisioning services	Food	Green	Green	Green	Green	Green	Green	Green	Red	Red	Red	Red	Primary producers; Primary consumers; Secondary consumers
	Fibre and fuel	Green	Green	Green	Green	Green	Green	Green	Yellow	Yellow	Green	Green	Primary producers
	Geneticresources	Green	Green	Green	Green	Green	Green	Green	Red	Red	Red	Yellow	Primary producers; Primary consumers; Secondary consumers; Decomposers; Detritivores
	Biochemical/natural medicines	Green	Green	Green	Green	Green	Green	Green	Yellow	Yellow	Yellow	Green	Primary producers; Primary consumers; Secondary consumers
	Ornamental resources	Green	Green	Green	Green	Green	Green	Green	Yellow	Red	Green	Green	Primary consumers; Secondary consumers; Eco-engineers
	Fresh water	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	
Regulatory services	Pollination	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	
	Pest and disease regulation	Green	Green	Green	Green	Green	Green	Green	Yellow	Yellow	Yellow	Yellow	Primary consumers; Secondary consumers; Decomposers; Eco-engineers
	Climate regulation	Green	Green	Green	Green	Green	Green	Green	Yellow	Yellow	Green	Green	Primary producers; Primary consumers
	Air quality regulation	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	
	Water regulation	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	
	Erosion regulation	Green	Green	Green	Green	Green	Green	Green	Yellow	Yellow	Green	Green	Primary producers; Primary consumers; Eco-engineers
	Natural hazard regulation	Green	Green	Green	Green	Green	Green	Green	Yellow	Yellow	Green	Green	Primary producers; Primary consumers; Eco-engineers
	Water purification/soil remediation/waste treatment	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	
Cultural services	Spiritual and religious values	Green	Green	Green	Green	Green	Green	Green	Yellow	Yellow	Yellow	Green	Primary producers; Primary consumers; Secondary consumers; Eco-engineers
	Education and inspiration	Green	Green	Green	Green	Green	Green	Green	Red	Red	Yellow	Yellow	Primary producers; Primary consumers; Secondary consumers; Eco-engineers; Decomposers; Detritivores
	Recreation and ecotourism	Green	Green	Green	Green	Green	Green	Green	Red	Red	Yellow	Yellow	Primary producers; Primary consumers; Secondary consumers; Eco-engineers
	Cultural diversity and heritage	Green	Green	Green	Green	Green	Green	Green	Yellow	Yellow	Green	Green	Primary producers; Primary consumers; Secondary consumers; Eco-engineers
	Aestheticvalues	Green	Green	Green	Green	Green	Green	Green	Yellow	Yellow	Yellow	Yellow	Primary producers; Primary consumers; Secondary consumers; Eco-engineers
	Sense of place	Green	Green	Green	Green	Green	Green	Green	Yellow	Yellow	Yellow	Green	Primary producers; Primary consumers; Secondary consumers; Eco-engineers
Supporting services	Primary production and photosynthesis	Green	Green	Green	Green	Green	Green	Green	Red	Red	Yellow	Green	Primary producers
	Soil formation and retention	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	
	Nutrient cycling	Green	Green	Green	Green	Green	Green	Green	Yellow	Yellow	Yellow	Yellow	Primary producers; Eco-engineers; Detritivores

[a]SPU key: Primary producers; Primary consumers; Secondary consumers; Decomposers; Eco-engineers; Detritivores

proximity to the point of discharge. As already mentioned under Step 2, oil refineries are often located on estuaries and are thus in direct contact with transitional waters and coastal areas, which potentially leads to high levels of exposure. Medium concern was found for a number of habitat × ecosystem service combinations. Increased concern became less frequent in habitats at greater distance from the source, i.e. shelf and particularly in the open ocean.

3.3.2. Oil dispersants

Medium or high concern was identified for 10 ecosystem services and 8% of the habitat × ecosystem service combinations considered, and was highest for ecosystem services associated with inlets and transitional waters and for coastal habitats. This finding reflects the importance of these habitat types for the provision of certain ecosystem services (e.g. genetic resources, recreation and ecotourism) and typically shallow depth of water resulting in a minimal mixing zone. Although the approval of oil dispersant applications is typically limited to marine waters, potential exists for subsequent movement of dispersants to shallower waters and estuarine environments and therefore a high level of potential exposure can be assumed for these habitats. Overall, increased concern was found for fewer habitat × ecosystem service combinations than in the oil refinery or the down the drain chemicals case studies. This is linked with the comparably lower impact of oil dispersant chemicals (Table 4) and the limited temporal and spatial occurrence of oil dispersants in (mainly marine) water bodies.

Table 6
Potential impact of down the drain chemicals on specific ecosystem services (green: low impact; yellow: medium impact; red: high impact) and service-providing units (SPU).

	Ecosystem service	Terrestrial						FW	Marine				Potentially impacted SPU[a]
		Urban	Cropland	Grassland	Woodland and forest	Heathland and shrub	Wetlands	Rivers & lakes	Inlets & trans. waters	Coastal	Shelf	Open ocean	
Provisioning services	Food	green	red	red	green	green	yellow	red	red	red	yellow	green	Primary producers; Primary consumers; Secondary consumers; Decomposers
	Fibre and fuel	green	yellow	yellow	green	green	yellow	yellow	yellow	yellow	green	green	Primary producers
	Genetic resources	green	red	red	green	green	yellow	red	red	red	yellow	green	Primary producers; Primary consumers; Secondary consumers; Decomposers; Detritivores
	Biochemical/natural medicines	green	red	red	green	green	yellow	red	red	red	yellow	green	Primary producers; Primary consumers; Secondary consumers
	Ornamental resources	green	yellow	yellow	green	green	green	red	red	red	green	green	Primary producers; Primary consumers; Secondary consumers; Detritivores; Eco-engineers
	Fresh water	green	yellow	yellow	green	green	yellow	red	yellow	green	green	green	Primary producers; Primary consumers; Decomposers; Eco-engineers
Regulatory services	Pollination	green	yellow	yellow	green	green	yellow	green	green	green	green	green	Primary consumers
	Pest and disease regulation	green	red	red	green	green	yellow	red	red	red	green	green	Secondary consumers; Decomposers
	Climate regulation	green	yellow	yellow	green	green	yellow	red	red	yellow	yellow	green	Primary producers; Primary consumers
	Air quality regulation	green	yellow	yellow	green	green	yellow	yellow	yellow	yellow	green	green	Primary producers
	Water regulation	green	yellow	yellow	green	green	yellow	yellow	yellow	yellow	green	green	Primary producers; Eco-engineers
	Erosion regulation	green	yellow	yellow	green	green	yellow	yellow	yellow	yellow	green	green	Primary producers; Primary consumers; Eco-engineers
	Natural hazard regulation	green	yellow	yellow	green	green	yellow	yellow	yellow	yellow	green	green	Primary producers; Primary consumers; Eco-engineers
	Water purification/soil remediation/waste treatment	green	yellow	yellow	green	green	yellow	red	red	yellow	green	green	Primary producers; Decomposers
Cultural services	Spiritual and religious values	green	yellow	yellow	green	green	yellow	yellow	yellow	yellow	yellow	green	Primary producers; Primary consumers; Secondary consumers; Eco-engineers
	Education and inspiration	green	yellow	yellow	green	green	yellow	red	red	yellow	yellow	green	Primary producers; Primary consumers; Secondary consumers; Eco-engineers; Decomposers; Detritivores
	Recreation and ecotourism	green	yellow	yellow	green	green	yellow	red	red	yellow	yellow	green	Primary producers; Primary consumers; Secondary consumers; Eco-engineers
	Cultural diversity and heritage	green	yellow	yellow	green	green	yellow	yellow	yellow	yellow	yellow	green	Primary producers; Primary consumers; Secondary consumers; Eco-engineers
	Aesthetic values	green	yellow	yellow	green	green	yellow	yellow	yellow	yellow	yellow	green	Primary producers; Primary consumers; Secondary consumers; Eco-engineers
	Sense of place	green	yellow	yellow	green	green	yellow	yellow	yellow	yellow	yellow	green	Primary producers; Primary consumers; Secondary consumers; Eco-engineers
Supporting services	Primary production and photosynthesis	green	red	red	green	green	yellow	red	red	red	yellow	green	Primary producers
	Soil formation and retention	green	red	red	green	green	yellow	yellow	green	green	green	green	Primary producers; Eco-engineers; Decomposers
	Nutrient cycling	green	red	red	green	green	yellow	red	red	red	yellow	green	Primary producers; Decomposers; Eco-engineers; Detritivores

[a]SPU key: Primary producers; Primary consumers; Secondary consumers; Decomposers; Eco-engineers; Detritivores

3.3.3. Down the drain chemicals

Twenty ecosystem services and 28% of the habitat × ecosystem services considered, were prioritized as being of high or medium concern. High concern was revealed particularly for freshwater habitats (rivers and lakes), transitional waters and cropland. For freshwater habitats these findings can be explained by the short distance from the point of sewage treatment plant discharge, potentially leading to a high level of exposure, and the high importance of the habitat for the provision of some services e.g. freshwater. The direct application to arable land and pasture of aqueous sewage effluent (for irrigation) and sewage sludge (as fertiliser) coincides with high importance for the provision of services such as food production. Medium concern was found for several habitat × ecosystem service combinations where habitats occurred at longer distances from the source (i.e. shelf and open ocean) and where habitats had lower importance for the delivery of an ecosystem service. For some ecosystem services (e.g. genetic resources), medium or high concern was found for a variety of habitats (i.e., terrestrial, freshwater and marine).

3.3.4. Persistent organic pollutants

None of the 23 ecosystem services considered were identified as being of high concern; indeed, medium concern was only determined for 4 ecosystem services and 4% of habitat × ecosystem service combinations considered. This can be explained by the assumed low impact of POP-type chemicals on most ecosystem services due to the expected low concentrations in pristine areas (Fig. 1d). When high impact on a

Table 7
Potential impact of persistent organic pollutants on specific ecosystem services (green: low impact; yellow: medium impact; red: high impact) and service-providing units (SPU).

	Ecosystem service	Arctic Terrestrial			Arctic FW	Marine				Potentially impacted SPU[a]
		Urban	Heathland shrub and tundra	Wetlands	Rivers & Lakes	Inlets and trans. waters	Coastal	Shelf	Open ocean	
Provisioning services	Food	Green	Red	Yellow	Yellow	Red	Red	Red	Red	Primary consumers; Secondary consumers
	Fibre and fuel	Green	Green	Green	Green	Green	Green	Green	Green	
	Genetic resources	Green	Green	Green	Green	Green	Green	Green	Green	
	Biochemical/natural medicines	Green	Green	Green	Green	Green	Green	Green	Green	
	Ornamental resources	Green	Green	Green	Green	Green	Green	Green	Green	
	Fresh water	Green	Green	Green	Green	Green	Green	Green	Green	
Regulatory services	Pollination	Green	Green	Green	Green	Green	Green	Green	Green	
	Pest and disease regulation	Green	Green	Green	Green	Green	Green	Green	Green	
	Climate regulation	Green	Green	Green	Green	Green	Green	Green	Green	
	Air quality regulation	Green	Green	Green	Green	Green	Green	Green	Green	
	Water regulation	Green	Green	Green	Green	Green	Green	Green	Green	
	Erosion regulation	Green	Green	Green	Green	Green	Green	Green	Green	
	Natural hazard regulation	Green	Green	Green	Green	Green	Green	Green	Green	
	Water purification/soil remediation/waste treatment	Green	Green	Green	Green	Green	Green	Green	Green	
Cultural services	Spiritual and religious values	Green	Green	Green	Yellow	Yellow	Yellow	Yellow	Yellow	Primary consumers; Secondary consumers
	Education and inspiration	Green	Green	Green	Yellow	Yellow	Yellow	Yellow	Yellow	Primary producers; Primary consumers; Secondary consumers; Eco-engineers
	Recreation and ecotourism	Green	Green	Green	Yellow	Yellow	Yellow	Yellow	Yellow	Primary consumers; Secondary consumers
	Cultural diversity and heritage	Green	Green	Green	Yellow	Yellow	Yellow	Yellow	Yellow	Secondary consumers; Primary consumers
	Aesthetic values	Green	Green	Green	Green	Green	Green	Green	Green	
	Sense of place	Green	Green	Green	Green	Green	Green	Green	Green	
Supporting services	Primary production and photosynthesis	Green	Green	Green	Green	Green	Green	Green	Green	
	Soil formation and retention	Green	Green	Green	Green	Green	Green	Green	Green	
	Nutrient cycling	Green	Green	Green	Green	Green	Green	Green	Green	

[a]SPU key: Primary producers; Primary consumers; Secondary consumers; Decomposers; Eco-engineers; Detritivores

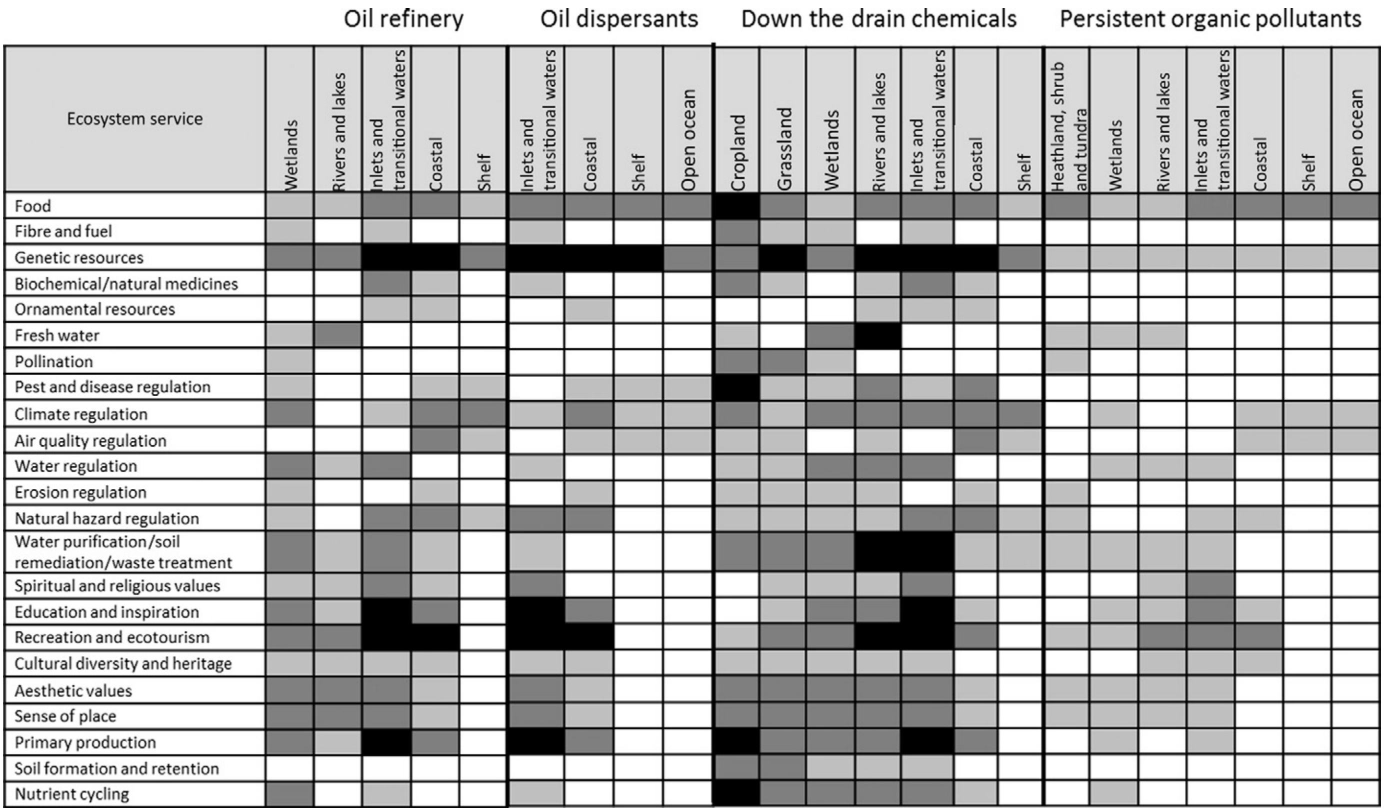
certain ecosystem service was assumed (e.g. in the case of food provision), this resulted in only medium concern because the respective habitats were considered to be of no more than intermediate importance for delivery of this service.

3.4. Step 4: define specific protection goals (SPGs) for prioritized ecosystem services and habitats

Table 9 gives a ranking of ecosystem services based on the number of chemical case studies that identified an ecosystem service as being of high concern (i.e. black cells, Table 8) and the number of habitats delivering that ecosystem service. Specific protection goals were developed for the three ecosystem services identified as being of high concern across multiple case studies and multiple habitats. These were: genetic resources, recreation and ecotourism and primary production (Table 10).

Genetic resources were identified as a priority ecosystem service at risk of impact from oil dispersants, down the drain chemicals and from oil refinery emissions. Transitional/marine habitats were likely to be exposed in all three cases, but over differing exposure periods (e.g. continuous low level exposure to down the drain chemicals versus short-term and locally relatively high exposure to dispersants). Table 10 indicates SPGs that reflect the likely worst case exposure scenario, i.e. continuous exposure from down the drain chemicals. Genetic resources (i.e. genetic material used for breeding or biotechnology) are derived from a variety of organisms including plants, algae, microorganisms, fish, shellfish and terrestrial vertebrates. The SPG for the protection of genetic resources in ecosystems focusses on populations or metapopulations and the attributes of interest are abundance and genetic diversity.

Table 8
Ecosystem services of concern. Black: high concern; dark grey: medium concern; light grey: low concern; white: negligible concern.



Specific protection goals for recreation and ecotourism are driven by the interaction people have with the environment. This will often be linked to an appreciation of the aesthetics of landscapes/waterbodies where aspects of environmental quality, diversity and landscape patterning may be important, or to hunting and fishing where sustainable populations may be key. The ecological entity will generally be at the population, metapopulation or community level, but in some cases (e.g. endangered species, vertebrates) there may be a specific requirement to protect individual organisms.

In the case of primary production, primary producers obviously play a major role, particularly in crop and grassland terrestrial habitats and in a range of fresh and salt water habitats. In this example, the key biological attribute providing the ecosystem service was plant biomass/production.

Table 9
Ranking of ecosystem services based on the number of chemical case studies that identified an ecosystem service as being of high concern.

Ecosystem service	Number of chemical scenarios (case studies)	Number of habitats
Genetic resources	3	5
Recreation & ecotourism	3	3
Primary production	3	2
Water purification/soil remediation/ waste treatment	1	2
Education & inspiration	3	1
Food	1	1
Fresh water	1	1
Pest & disease regulation	1	1
Nutrient cycling	1	1

4. Discussion

The methodological approach underpinning the EFSA framework (EFSA, 2010) to define SPGs could be applied to the four case studies from the wider chemical industry. However, further modification of the framework, including greater clarity on terminology and definitions is necessary before it could be applied generally across the chemical sector. One key modification required when applying the framework to non-agricultural chemicals is an expansion of the range of habitats considered and the diversity of ecosystem services they provide. The habitat × ecosystem service matrix (Step 1) provides a very useful tool for selecting relevant ecosystem services within the habitats of interest and the EUNIS (European Nature Information System, eunis.eea.europa.eu) typology was considered a good, multi-level hierarchical classification with which to construct the matrix. This habitat classification system is used by European regulators (Strachan, 2015) and EU member states are required to use EUNIS when reporting data under the INSPIRE Directive 2007/2/EC (EC, 2007; EC, 2013). The eleven broad habitat types used for the case studies were selected to be compatible with those used in the EU Mapping and Assessment of Ecosystem and their Services (MAES) project (Maes et al., 2013), which is tasked with developing methodologies for assessing ecosystems under Action 5 of the EU Biodiversity Strategy to 2020 (EC, 2011). Although case studies applied a similar hierarchical level of classification across all habitats, the system is flexible and different levels of resolution could be applied if required. For example, all fresh water habitats could be considered as a single habitat (i.e. rivers and lakes) or subdivided into different types of lotic and lentic habitats depending on the specific chemical emissions being assessed. In deriving the habitat × ecosystem service matrix we followed the approach taken by EFSA (2010) and adopted the Millennium Ecosystem Assessment

Table 10
Illustrative examples defining SPGs for three ecosystem services: genetic resources; recreation and ecotourism; primary production.

Ecosystem service	Habitat group	Key SPUs	Ecological entity	Attribute	Scale[a]			Specific protection goal	Legal requirement (legal instrument)
					Magnitude of impact	Spatial scale of impact	Temporal scale of impact		
Genetic resources	Terrestrial (crop/grassland) Freshwater (lakes and rivers) Transitional/Marine (estuaries/inlets, coastal waters)	Primary producers Terrestrial plants Primary consumers Terrestrial livestock and beneficial wild fauna Secondary consumers Aquaculture fish and shellfish Primary producers Microalgae/cyanobacteria, macroalgae Primary consumers Shellfish	Population/ metapopulation	Abundance and genetic diversity	10% reduction in SPU attribute	Landscape or watershed (≥10 km)	Weeks to months	No >10% reductions in genetic diversity across landscape/watershed for >weeks to months	Protection of non-target organism populations/metapopulations (BPR, MPHU, MPVU PPPR, REACH, HD), or key species populations (BD)
Recreation and ecotourism	Terrestrial (grassland) Freshwater (wetlands, rivers, lakes) Marine (estuaries/inlets, coastal waters)	Primary producers Terrestrial and aquatic plants Primary consumers Wild coarse/game fish/non-edible shellfish	Population/ metapopulation/ community	Abundance/diversity/ spatial distribution	Locally up to 25% reduction in SPU attribute but up to10% reduction in SPU attribute at watershed/landscape scale	Point of emission/local (<1 km) Landscape or watershed scale (≥10 km)	Weeks to months (growing season)	Locally up to 25% reduction in populations/metapopulations. Up to 10% reduction at watershed/ landscape scale for >weeks to months	Protection of non-target organism populations/metapopulations/ communities (HD, MSFD, OSPAR) or good ecological status (WFD)
Primary production	Terrestrial (crop/grassland) Freshwater Rivers, lakes, wetlands Transitional/marine (estuaries/inlets, coastal waters)	Primary producers Terrestrial and aquatic plants	Population/ metapopulation	Production (process)/biomass	10% reduction in SPU attribute	Landscape or watershed scale (≥10 km)	Weeks to months (growing season)	No more than negligible biomass reductions in field crops/grasses across landscape scale for >weeks to months	Protection of non-target organism populations/metapopulations (BPR, MPHU, PPPR, REACH, MPVU), key species populations (BD), communities (HD)

[a] Measures of scale are suggestions for illustrative purposes and not based on any regulatory criteria.

classification of ecosystem services (MA, 2005). The use of all types of ecosystem services, including supporting and other intermediate services, was important to ensure that the assessment was comprehensive, transparent and unbiased.

There have been several attempts to assess the ecosystem service potential of broad habitat types by drawing together information from the literature and expert workshops (Haines-Young and Potschin, 2008; Harrison et al., 2010). Information from several sources was collated to produce relative importance rankings for 23 ecosystem services across the 11 broad habitat types (Table 3). When constructing this matrix, it was clear that guidance is required both in terms of the types of services and habitats to be considered and the level of importance assigned to each habitat × ecosystem service combination. Currently there is limited information for the ecosystem services delivered by some habitat types and most assessments of service provision have been based on qualitative information (Burkhard et al., 2009; Burkhard et al., 2014).

The treatment of biodiversity within an ecosystem services framework and the interpretation of the ecosystem service of genetic resources are areas of particular uncertainty. There is considerable ambiguity in the literature on the definition of the provisioning service 'genetic resources'. The Millennium Ecosystem Assessment defines 'genetic resources' as "genes and genetic information used for animal and plant breeding and biotechnology" (MA, 2005). This implies that "genetic resources" are those organisms that are currently utilized in breeding or biotechnology activities. Article 2 of the Convention of Biological Diversity defines genetic resources as "genetic material of actual or potential value" (CBD, 1992). A liberal and uncritical interpretation of 'potential value' can result in 'genetic resources' being equated with 'biodiversity'; the rationale being that all organisms have the potential to provide genetic material that may be of use to humans in the future. There is considerable debate over whether biodiversity should be considered as an ecosystem service (Mace et al., 2012). The Convention on Biological Diversity's definition of biodiversity includes diversity within species, between species and of ecosystems (CBD, 1992). Although this definition has been adopted by the EU Biodiversity Strategy to 2020 (EC, 2011), it is too generic and all-encompassing to be useful for scientific risk assessment and consequently EFSA adopted an ecosystem services framework for developing specific protection goals (Nienstedt et al., 2012; Devos et al., 2016). As Haines-Young and Potschin state "the blanket assertion that all habitats are important for biodiversity is not particularly helpful in terms of understanding the relative contributions that different habitats make, or in understanding the significance of the impacts and pressures upon them" (Haines-Young and Potschin, 2008).

A key finding from our case studies was that familiarity with ecosystem services definitions and other terms, and consistency in their use, is an important requirement if the ecosystem services framework is to be applied correctly and efficiently. The application of an ecosystem services approach to risk assessment needs to be based on agreed ecosystem service definitions and habitat typology. The Common International Classification of Ecosystems and Services (CICES) typology has been used to collect EU-wide and national indicators to map and assess ecosystem services (Maes et al., 2014) and could be used to develop an EU framework for assessing the risk of chemicals to ecosystem services.

A robust characterisation of the possible exposure pathways for the chemicals of interest was essential for an effective assessment of potential impact (Step 2). Assessing the level of potential impact due to chemical exposure was difficult for some ecosystem services, particularly cultural services, where there can be differences in how different sections of society perceive and value ecosystem services (Petrosillo et al., 2007; Pan et al., 2016).

There was a high level of concern for ecosystem service delivery in many habitats exposed to down the drain chemicals (Step 3), resulting in a broad range of SPGs across seven habitats. Making a risk assessment with sufficient scope to include this range of SPGs would require considerable further research and development to determine what battery of test species and ecological models (including landscape scale models) are needed to represent the wide range of SPUs identified via the assessment framework. Notwithstanding this challenge, the use of an ecosystem services approach to deriving SPGs provides a useful indication of the scope of knowledge required to make a spatially referenced and ecologically relevant assessment and represents a major advance from the current generic use of application factors aimed at protecting all species in all habitats. The other three case studies resulted in greater specificity of SPUs and SPGs, influenced primarily by the narrower exposure scenarios and, to a lesser extent, the range of ecosystem services potentially impacted.

Across all four case studies, the ecosystem services identified as being of highest concern were genetic resources, recreation and ecotourism and primary production (Table 9). Marine genetic resources were prioritized for three case studies (down the drain chemicals, oil refinery, oil dispersants) and freshwater and terrestrial (i.e. grassland) genetic resources were prioritized in one case study (down the drain chemicals). All habitats, except urban and cropland, are identified in Table 3 as having a large relative importance for genetic resources. As discussed above, there is considerable uncertainty in these rankings, which may be based on perceptions of biological diversity and its potential to provide useful genetic resources in the future, rather than current provision of a service. For example, Harrison et al. (2010) rank semi-natural grasslands as being of 'key importance' for genetic resources but qualify this assessment with a statement that "knowledge is limited on the full potential of genetic resources".

Many ecosystems provide opportunities for people to rest, relax and undertake recreational activities (De Groot et al., 2005). Recreation and ecotourism was prioritized for inlets and transitional waters in three cases studies (down the drain chemicals, oil refinery, oil dispersants), for coastal habitats in two case studies (oil refinery, oil dispersants) and for freshwater habitats in one case study (down the drain chemicals). Recreation and ecotourism was identified as having high relative importance in all habitats, except urban and cropland. Cultural services are particularly challenging to assess (Milcu et al., 2013; Baulcomb et al., 2015) and there is considerable uncertainty associated with their relative importance rankings. The capacity or suitability of a habitat for a particular recreational or ecotourism activity cannot be derived solely from an understanding of ecological processes and functions, and must be assessed alongside an understanding of what people require from that habitat, which will be location- and activity-specific (Petrosillo et al., 2007; Paetzold et al., 2010). One way forward is to consider a scenario-based approach where mapping techniques (Paracchini et al., 2014) are used to identify bundles of activities for use in the risk assessment. For instance, a library of scenarios could be generated based on regional land use plus ecological and ecosystem service mapping information, possibly building on the work of the EU MAES project (Maes et al., 2013) and other pan-European mapping activities (Maes et al., 2011; Liquete et al., 2015). The EU Biodiversity Strategy to 2020 requires Member States to map and assess ecosystem services and several activities are ongoing across Europe to map ecosystem services at multiple scales (UK National Ecosystem Assessment, 2011; Maes et al., 2014; Rabe et al., 2016). Risk assessors could use such a library to select an appropriate range of scenarios for evaluating chemicals with widespread exposures.

Primary production was prioritized in inlets and transitional waters in three case studies (down the drain chemicals, oil refinery, oil dispersants) and in cropland for one case study (down the drain chemicals). In the Millennium Ecosystem Assessment typology, supporting services, including primary production, are regarded as underpinning the other service groups (provisioning, regulating, cultural). As such, they do not contribute directly to human well-being and it is difficult to untangle them from ecosystem functions (Maes et al., 2013). Primary production in cropland, inlets and transitional waters will influence food production, although the relationship between them may not be straightforward (Friedland et al., 2012). Moreover, it has been argued that ecosystem services directly associated with primary production (e.g. timber for wood, fuel or fibre), are more resilient to species loss than ecosystem services that are predominantly dependent on rare species or keystone species (e.g. ornamental resources, cultural services) (Dobson et al., 2006).

The final step (Step 4) is to identify key SPUs for each prioritized habitat × ecosystem service combination and then derive specific protection goals for each SPU. A functional approach based on trophic levels was taken for categorizing SPUs. This differs from the approach adopted by EFSA (2010), which identifies seven categories of SPUs (key drivers) based on taxonomy. A functional approach is consistent with the fact that most ecosystem services are derived from ecological processes and are therefore driven by functional diversity rather than taxonomic diversity (Cadotte et al., 2011). A trophic-level classification was adopted as there is evidence that the sensitivity of an ecosystem service to changes in biodiversity is dependent on the trophic level of the dominant species providing the service (Dobson et al., 2006) and that multiple trophic levels are required to sustain multifunctional ecosystems (Soliveres et al., 2016). Functional categorizations have the advantage that assessments are applicable across locations that have the same functional profile, but have different species assemblages; this is particularly useful for prospective risk assessments for large geographical areas (e.g. Europe). The resolution of the risk assessment can be refined spatially by adopting a scenario-based approach and refined ecologically by adopting more detailed trait-based approaches (de Bello et al., 2010). Examples of taxonomic groups within each main functional group × habitat category can be identified to help guide the risk assessment. A functional approach is least relevant where ecosystem services are provided by specific taxa or species, such as genetic and ornamental resources and charismatic species linked to cultural services.

Ultimately, an important aspect in setting SPGs for ecosystem services and their key SPUs is understanding the interdependencies between SPUs and the ecological processes that support them. Supporting ecological processes can be considered in a risk assessment either indirectly by including them in the SPGs for final ecosystem services (Munns et al., 2015) or directly by deriving SPGs for relevant supporting ecosystem services (EFSA, 2016). Ecological production functions translate changes in SPU attributes to changes in ecosystem service delivery and outcomes that people use or value (Bruins et al., 2016). Their development will aid identification of relevant supporting functions and the types of taxonomic groups providing them, thereby enabling a comprehensive range of SPGs to be obtained (Munns et al., 2016).

EFSA defines SPGs using five interrelated dimensions: ecological entity, attribute, magnitude, temporal scale and spatial scale (EFSA, 2016). 'Magnitude', 'temporal scale' and 'spatial scale' relates to the level and scale of change that can be tolerated resulting from the use of regulated products. What can be 'tolerated' will depend on the ecological properties of the SPU (including resilience and capacity for recovery), the landscape context (including food web structure and environmental complexity) and legal and societal requirements (Brown et al., 2016; EFSA, 2016), and therefore should be defined by risk managers in collaboration with risk assessors. Acceptable impacts should also consider practical aspects such as the natural variability in the functional group/endpoint. Specific protection goals are important for guiding the risk assessment process and aiding decision making by risk managers. However, their derivation is challenging and there is a lack of detailed guidance and knowledge in deciding ecological entities, attributes and especially scale of potential impact. Robust ecological production functions are essential for the successful application of an ecosystem services-based approach to protection goal development (Olander and Maltby, 2014).

5. Conclusions and future needs

i. The EFSA framework represents a top-down approach for deriving SPGs for habitats expected to be exposed to anthropogenic chemicals. With modifications, clarity on terminology/definitions and further development, the framework could provide a methodical approach for the identification and prioritization of ecosystems and services that are most at risk from exposure to chemicals from all sectors.
ii. The development of SPGs requires an agreed definition of 'tolerable' levels of change in ecosystem service delivery. As this is not wholly a scientific judgement, there is a need for risk managers to specify acceptable levels of ecosystem service delivery or change.
iii. Many chemicals occur across different habitats and have the potential to impact multiple ecosystem services. Prioritising at each step in the assessment process was important in order to manage time and effort requirements. The relative importance of specific habitats for the delivery of individual ecosystem services is a key component of the prioritization process, but is also subject to considerable uncertainty. Greater understanding of the use and value of ecosystem services delivered by different habitats would reduce uncertainty and improve prioritization.
iv. Changes in ecosystem service delivery are driven by changes in the performance of SPUs. Identifying key SPUs for multiple habitat × ecosystem service combinations is particularly challenging for prospective risk assessments applied over large geographic scales. Defining SPUs using functional groups rather than taxonomic groups has the advantage that the classification is more closely aligned to the ecological functions driving many ecosystem services and is less sensitive to spatial variation in species composition. However, some taxonomic detail is required to be of practical use in risk assessment.
v. Extrapolating chemical-induced changes in key SPU attributes to changes in ecosystem service delivery remains a challenge that requires the further development of modelling approaches, including ecological production functions and landscape-scale models that integrate multiple ecosystem services.
vi. Applying the ecosystem services concept to derive environmental SPGs brings the potential for greater transparency and greater spatial resolution in chemical risk assessment, i.e. SPGs can be derived for specific land uses or landscape typologies. This would be aided by the development of a library of assessment scenarios, based on regional land use, ecological and ecosystem service mapping information, for use by risk assessors.

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Appendix A. Supplementary data

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