



Linking ecotoxicological effects on biodiversity and ecosystem functions to impairment of ecosystem services is a challenge: an illustration with the case of plant protection products

Stéphane Pesce, Annette Bérard, Marie-Agnès Coutellec, Mickaël Hedde, Alexandra Langlais-Hesse, Floriane Larras, Sophie Leenhardt, Rémi Mongruel, Dominique Munaron, Sergi Sabater, et al.

► To cite this version:

Stéphane Pesce, Annette Bérard, Marie-Agnès Coutellec, Mickaël Hedde, Alexandra Langlais-Hesse, et al.. Linking ecotoxicological effects on biodiversity and ecosystem functions to impairment of ecosystem services is a challenge: an illustration with the case of plant protection products. *Environmental Science and Pollution Research*, 2025, 32 (6), pp.2773-2785. <10.1007/s11356-023-29128-x>. <hal-04204142>

HAL Id: hal-04204142

<https://hal.science/hal-04204142v1>

Submitted on 30 Nov 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY-NC 4.0 - Attribution - Non-commercial use - International License

Accepted on 29 July 2023 in the special issue « *Key Learnings from A Collective Scientific Assessment on the Effects of Plant Protection Products on Biodiversity and Ecosystem Services Along the Land to Sea Continuum* »

Linking ecotoxicological effects on biodiversity and ecosystem functions to impairment of ecosystem services is a challenge: an illustration with the case of plant protection products

Author names and affiliations:

Stéphane Pesce* – INRAE, UR RiverLy, Villeurbanne, France.

Annette Bérard – INRAE, Avignon University, EMMAH, Avignon, France.

Marie-Agnès Coutellec – DECOD (Ecosystem Dynamics and Sustainability), INRAE, Institut Agro-Agrocampus Ouest, IFREMER, Rennes, France.

Mickaël Hedde – Eco&Sols, Univ. Montpellier, INRAE, IRD, CIRAD, Institut Agro Montpellier, Montpellier, France.

Alexandra Langlais-Hesse – Laboratoire IODE, Institut Ouest: Droit et Europe, UMR CNRS 6262, Rennes, France.

Floriane Larras – INRAE, DEPE, Paris, France / KREATIS SAS, 23 rue du Creuzat, ZAC de St-Hubert, 38080, L'Isle-d'Abeau, France.

Sophie Leenhardt – INRAE, DEPE, Paris, France.

Rémi Mongruel – Ifremer, UMR 6308 Amure, CS10070, 29280, Plouzané, France.

Dominique Munaron – MARBEC, Univ Montpellier, CNRS, Ifremer, IRD, Sète, France.

Sergi Sabater – Catalan Institute of Water Research (ICRA), Carrer Emili Grahit 101, 17003 Girona, and Institute of Aquatic Ecology, University of Girona-Montilivi Campus, 17071, Girona, Spain.

Nicola Gallai – UMR LEREPS/ENSFEA, 2 route de Narbonne, Castanet-Tolosan Cedex, 31320 Cedex, France.

* Corresponding author: stephane.pesce@inrae.fr

Keywords:

Collective scientific assessment; Ecological processes; Environmental risk assessment; Expertise; Functional traits; Pesticides.

Declarations:

Ethics approval and consent to participate: Not applicable

Consent for publication: Not applicable

Availability of data and materials: Not applicable

Competing interests: The authors declare that they have no competing interests

Funding: This collective scientific assessment received financial support from the French Office for Biodiversity (OFB) through the national ECOPHYTO plan.

Author contribution: SP, AB, MAC, MH, SB, and NG conceptualized the article. SP, AB, MAC, and NG drafted the first version of the manuscript. FL performed data curation and analysis. AP, AB, MAC, MH, ALH, FL, SL, RM, DM, SS, and NG contributed to subsequent revisions to the manuscript and approved the final submitted version.

Abstract:

There is growing interest in using the ecosystem services framework for environmental risk assessments of chemicals, including plant protection products (PPPs). Although this topic is increasingly discussed in the recent scientific literature, there is still a substantial gap between most ecotoxicological studies and a solid evaluation of potential ecotoxicological consequences on ecosystem services. This was recently highlighted by a collective scientific assessment (CSA) performed by 46 scientific experts who analyzed the international science on the impacts of PPPs on biodiversity, ecosystem functions, and ecosystem services. Here, we first point out the main obstacles to better linking knowledge on the ecotoxicological effects of PPPs on biodiversity and ecological processes with ecosystem functions and services. Then, we go on to propose and discuss possible pathways for related improvements. We describe the main processes governing the relationships between biodiversity, ecological processes, and ecosystem functions in response to effects of PPP, and we define categories of ecosystem functions that could be directly linked with the ecological processes used as functional endpoints in investigations on the ecotoxicology of PPPs. We then explore perceptions on the possible links between these categories of ecosystem functions and ecosystem services among a sub-panel of the scientific experts from various fields of environmental science. We find that these direct and indirect linkages still need clarification. This paper, which reflects the difficulties faced by the multidisciplinary group of researchers involved in the CSA, suggests that the current gap between most ecotoxicological studies and a solid potential evaluation of ecotoxicological consequences on ecosystem services could be partially addressed if concepts and definitions related to ecological processes, ecosystem functions, and ecosystem services were more widely accepted and shared within the ecotoxicology community. Narrowing this gap would help harmonize and extend the science that informs decision-making and policy-making, and ultimately help to better address the trade-off between social benefits and environmental losses caused by the use of PPPs.

1. Introduction

Environmental managers and regulators increasingly recognize biodiversity as an important protection goal in environmental risk assessment (EFSA 2016a) and sustainability programs (Glaser 2012; Bach et al. 2020; European Commission 2020; Tickner et al. 2020). In parallel, the concept of ecosystem service (Costanza et al. 1997; MEA 2005; TEEB 2010) has progressively gained currency in ecosystem management and risk assessment (e.g., Cairns and Niederlehner 1994; Forbes and Calow 2013; Maltby 2013; Forbes et al. 2017; Maltby et al. 2018; Faber et al. 2019; Galic et al. 2019). A standout example is environmental risk assessments on plant protection products (PPPs), which are defined here as synthetic and biobased pesticides (formulated products and active substances) and their transformation products. In 2010, the European Food Safety Authority (EFSA) Panel on PPPs and their residues emphasized that the ecosystem service framework was central to setting specific protection goals for this kind of substance (EFSA 2010). It served as a startpoint to the development of EFSA guidance on how to better protect biodiversity and ecosystem services against PPPs and other contaminants (EFSA 2013; 2016a). Based on these works and guidances, various scientific experts from public research, regulatory authorities and the chemicals industry have evaluated the advantages, limitations, and pitfalls of the ecosystem service framework regarding current practices in environmental risk assessment and environmental monitoring (Box 1 and references therein; Van Wensem and Maltby 2013; Arts et al. 2015; Devos et al. 2015; Van Wensem et al. 2017).

Box. 1: *Non-exhaustive list of challenges that need to be resolved to implement the ecosystem service framework in environmental risk assessments of PPP.*

- Definition of reference values for ecosystem services (Faber et al. 2019)
- Definition of acceptable vs unacceptable levels (i.e., magnitude) of PPP effects (Brown et al. 2017)
- Definition of clear and quantifiable protection goals and restoration targets for ecosystem service management (Maltby 2013)
- Identification of key taxa/communities that drive ecosystem services (Nienstedt et al. 2012)
- Development of quantifiable indicators and relevant endpoints to evaluate the effects of PPPs on ecosystem services (Faber and Van Wensem 2012; Faber et al. 2019)
- Consideration of trade-offs between ecosystem services, and possible antagonistic interactions of PPP with different services (Galic et al. 2012)
- Development and implementation of applicable strategies and procedures to address site-specific risk assessment (Forbes and Calow 2013)
- Development and implementation of applicable strategies and procedures to transpose environmental risk assessment up to landscape scales (Maltby et al. 2018)

The ecosystem service framework is pivotal to environmental risk assessment and integral to regulatory decision-making and the ecological relevance of environmental protection goals (Cairns and Niederlehner 1994; Forbes and Calow 2013; Brown et al. 2017; Munns et al. 2017; Maltby et al. 2018). Effective implementation of an ecosystem service-based environmental risk assessment of PPPs should help to protect and restore biodiversity and ecosystems against direct and indirect adverse effects of these contaminants (Maltby 2013). In this context, the ecosystem services approach has the potential to explicitly address the trade-off between social benefits and environmental losses from the use of PPPs on ecosystems, which is an issue that remains under-researched (Nienstedt et al. 2012; Brown et al. 2017).

This is why stakeholders and policymakers are increasingly demanding critical and intelligible recommendations on the possible effects of PPPs on biodiversity and ecosystem services. As an explicit recent example, in 2019, the French Ministries for the Environment, Agriculture and Research commissioned a collective scientific assessment (CSA) to deliver this goal (Pesce et al. 2021). This CSA concerned the terrestrial–freshwater–marine continuum and enlisted input from a panel of 46 experts in various spheres of research. The report of the main conclusions of the CSA underlined that the effects of PPPs on ecosystem services were only documented for a few services (Pesce et al. 2023), mainly water quality, human food quality (animal-source and plant-source), plant production, biological control, and pollination. The CSA pointed out, for instance, that services provided by soil ecosystems, as well as cultural services, have received little attention in the scientific literature dealing with the risks and effects of PPPs (Pesce et al. 2023).

The inclusion of ecosystem services in chemical risk assessment is gaining increasing currency within a prominent group of European researchers who are very active on the topic (in collaboration with a variety of stakeholders; Maltby et al. 2022), as illustrated by their recent articles (Brown et al. 2021; Faber et al. 2021; Van den Brink et al. 2021; Oginah et al. 2023). Note, however, that the consequences of ecotoxicological effects of PPPs (or other chemicals) on ecosystem services are only addressed by a handful of people within the international ecotoxicology community. To overcome this issue, the panel of experts engaged in the CSA highlighted the need for this community to have a shared set of definitions and concepts concerning both (i) the main processes governing the relationships between biodiversity, ecological processes, ecosystem functions, and ecosystem services (for which consensual definitions are proposed in Box 2) and (ii) the classification of ecosystem functions and their linkages with ecological processes investigated in ecotoxicology. A consensus set of shared definitions could

lend huge impetus to approaches advocated in recent years, which are based on the use of ecological models (Van den Brink et al. 2021) or evidence-based logic chains (Hayes et al. 2018; Maltby et al. 2021; Faber et al. 2021) to assess and predict impacts of chemicals on ecosystem services.

Box. 2: *Definitions of biodiversity, ecological processes, ecosystem functions, and ecosystem services that were adopted by the experts involved in the collective scientific assessment*

Biodiversity follows the Convention on Biological Diversity definition (United Nations 1992). As such, biodiversity is “the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems.” This definition includes the composition, structure and variety of specific species or habitats, plus the abundance and biomass of species, their functional traits, and their genetic composition and identity (Marselle et al. 2021).

Ecological processes are activities that result from interactions among organisms and between organisms and their environment (Martinez 1996).

Ecosystem functions are sets of interconnected ecological processes at work within an ecosystem. They may or may not contribute to ecosystem services (Lovett et al. 2006; Garland et al. 2021).

Ecosystem services are the socioeconomic benefits to human populations and societies provided by healthy ecosystems (adapted from MEA 2005).

The relationship between biodiversity and ecosystem functions has been extensively explored in the ecology of “natural” or “weakly anthropized” ecosystems (van der Plas 2019), but its intersection with ecotoxicological pressure has been under-researched (Rumschlag et al. 2020). Functional endpoints used in ecotoxicological studies tend to refer to ecological processes rather than to ecosystem functions. In this context, we first provide an analysis of the literature on the biodiversity–ecological processes–ecosystem functions nexus in order to propose a conceptual scheme that is specifically applicable to PPPs. We then propose a definition and classification of ecosystem functions that are potentially impacted by PPPs in an effort to address the current inconsistencies (e.g., Costanza et al. 1997; De Groot et al. 2002; Pettorelli et al. 2018; Armoškaitė et al. 2020; Garland et al. 2021). Finally, we break new ground by exploring perceptions on the possible links between these categories of ecosystem functions and ecosystem services among a sub-panel of the CSA’s scientific experts (n=17) in various fields of environmental sciences, before concluding that a shared and harmonized framework could help extend the scientific knowledge that informs decision-making and policy-making.

2. Conceptual relationships between biodiversity, ecological processes, and ecosystem functions under PPP-induced pressure

Assessment of the relationships between biodiversity and ecosystem functioning has been one of the most active fields of research in ecology (e.g., Schulze and Mooney 1993; Balvanera et al. 2006; Cardinale et al. 2006; Loreau 2010; Tilman et al. 2014; Eisenhauer et al. 2019; van der Plas 2019). At present, there is a broad consensus that the dynamics of biodiversity are not entirely governed by random processes. At community level, assembly, structure, and diversity all result from the combined effects of ecological drift and deterministic processes (Hubbell 2001; Tilman 2004; De Meester et al. 2016; Svensson et al. 2018). Likewise, at species level, population eco-evolutionary dynamics are shaped by both random (genetic drift) and non-random (selection mode and intensity, mutation rate, mating system) processes (see Hartl and Clark 1997). Environmental deterioration, such as that caused by chemical contamination (including PPPs), can drive a population to decline or even go extinct

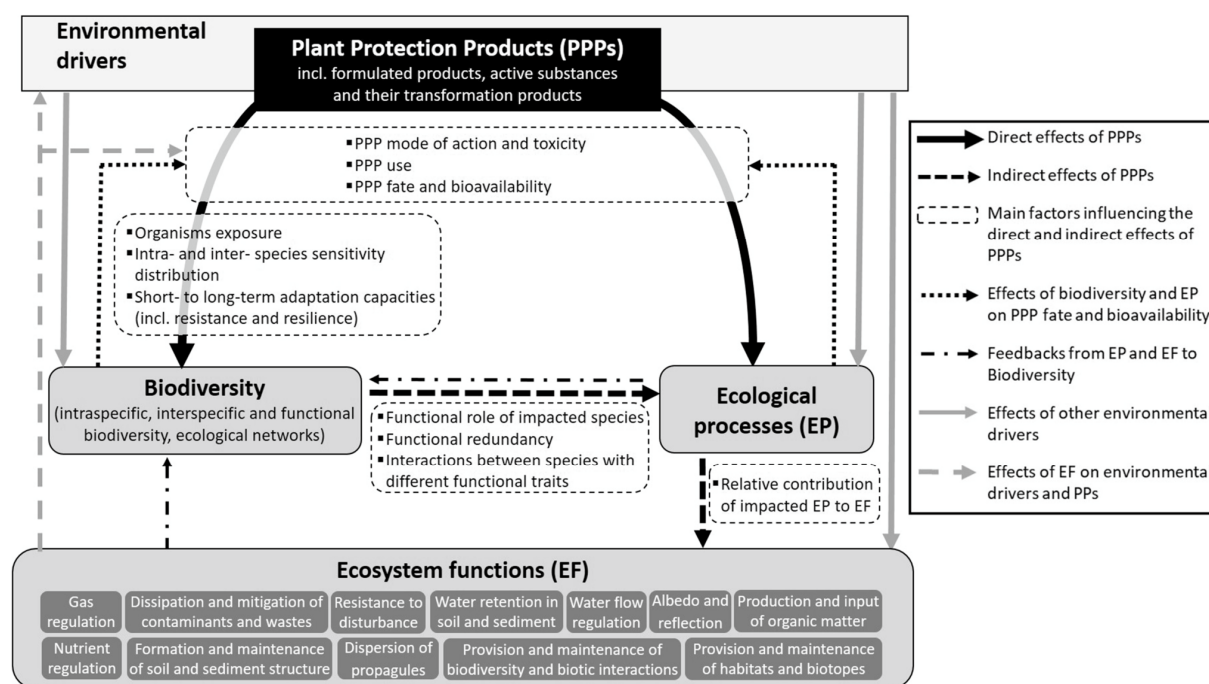
(maladaptation) or conversely to recover through plasticity, dispersion, or rapid evolutionary adaptation (e.g., antibiotic and pesticide resistance, which are two typical cases of evolutionary rescue; Bell 2017). Therefore, whatever the level of investigation, non-random (deterministic) factors and processes need to be explicitly addressed when empirically testing theoretical hypotheses related to the dynamics of biodiversity under environmental change.

Propelled by findings and lessons from a decade of intensive fundamental research, a new generation of research on biodiversity and ecosystem functioning emerged (Naeem et al. 2009) that was characterized by more functional approaches (trait-based functional diversity and mechanisms of ecosystem functioning, and the multitrophic dimension) and hypotheses (trait-based extinction probability, empirical extinction scenarios, net biodiversity effect partitioning). Today's research has also become more predictive (e.g., wider spatial and temporal scales, theory development, metacommunity dynamics) and now encompasses issues directly related to human impact and ecosystem services (Naeem et al. 2009). Recent developments now make it possible to explain the biodiversity–ecosystem functioning relationship across time and space (Isbell et al. 2018).

It is therefore patently quite clear that the impacts of PPPs on biodiversity, ecosystem functions and ecosystem services should be assessed by considering the non-random direct and indirect pressure that these impacts exert on biodiversity (De Laender et al. 2014, 2016; Halstead et al. 2014; Malaj et al. 2014; Baert et al. 2017; Rumschlag et al. 2020).

In this context, here, we propose a conceptual scheme integrating biodiversity, ecological processes, and ecosystem functions under the effects of PPPs (Fig. 1).

Fig. 1: Expected effects of plant protection products on biodiversity, ecological processes, and ecosystem functions through inter-relationships



This scheme first integrates the direct effects of PPPs on biodiversity, including intraspecific, interspecific, and functional biodiversity, which stem from the use, fate, and bioavailability of PPPs in the environment and the resulting exposure of organisms. These effects result from the combination of the toxicity and mechanisms of action of the PPP substances and substance–substance interactions, as well as biological sensitivity and its distribution within and across species (Fig. 1; Blanck et al. 1988; Vinebrooke et al. 2004; Johnston and Roberts 2009; De Laender et al. 2014; Kattwinkel et al. 2015;

Mensens et al. 2015; EFSA 2016b). Species demonstrate adaptive capacities (acclimation, tolerance, resistance, resilience, recovery) that extend through various biological scales (populations, communities) and timescales (rapid and reversible physiological adaptation through developmental and phenotypic plasticity vs longer-term adaptation through selective evolutionary processes). Toxic effects can also have indirect consequences on biodiversity by altering species–species interactions both within and between trophic levels (Fig. 1; Fleeger et al. 2003; Halstead et al. 2014; Saaristo et al. 2018; Fleeger 2020). The non-random effects of PPPs on biodiversity therefore influence key ecological processes that mainly depend on the functional role of sensitive species and the degree of functional redundancy between species (Fig. 1; Allison and Martiny 2008; Cardinale 2012; Díaz et al. 2013; Bardgett and van der Putten 2014; De Laender et al. 2016; Baert et al. 2017). These non-random effects on biodiversity may affect ecosystem functioning to a greater (e.g., when impacting keystone species) or lower degree (e.g., where there is high functional redundancy) than random ones (De Laender et al. 2016).

Most PPPs are designed to specifically target biological groups that directly contribute to ecological processes (Fig. 1). Photosystem-inhibitor herbicides (such as triazines and phenylureas) are good examples of PPPs that directly act on photosynthesis and primary production (Black 2018). Such targeted functional effects can strongly influence biodiversity–ecosystem function relationships through mechanisms that revolves around feedback from ecological processes and ecosystem functions to biodiversity (Fig. 1). These relatively unknown feedbacks (Duncan et al. 2015; Grace et al. 2016; Qiu et al. 2018; van der Plas 2019) are an important factor for achieving biodiversity conservation objectives (Xiao et al. 2019) and enhancing our current understanding of their role in the ecological processes that affect the bioavailability of PPPs (e.g., biodegradation or bioturbation) (Fig. 1; Chaplain et al. 2011; Bundschuh et al. 2016). Moreover, there is still an unaddressed need for ecotoxicological indicators that can be linked to ecosystem functions rather than to ecological processes (Heink and Kowarik 2010; Thomsen et al. 2012; Forbes et al. 2017; Faber et al. 2019; Garland et al. 2021).

3. Definition and classification of ecosystem functions potentially impacted by PPPs

Several classifications of ecosystem functions and services have been proposed in the past (e.g., Costanza et al. 1997; De Groot et al. 2002, 2012; CGDD 2010; Banerjee et al. 2013; Liqueste et al. 2013; Pettorelli et al. 2018; van der Plas 2019; Garland et al. 2021). Certain ecosystem functions are sometimes termed “intermediate ecosystem services” (Boyd and Banzhaf 2007; Munns et al. 2016; Fisher et al. 2009; Forbes et al. 2017), but this terminology has been questioned (Potschin-Young et al. 2017). In 2021, Garland et al. proposed a classification based on an extensive meta-analysis of 268 studies dealing with ecosystem multifunctionality (Byrnes et al. 2013; Delgado-Baquerizo et al. 2016; Gamfeldt and Roger 2017). They found that research to date had considered a large number of ecosystem functions but without any attempt to harmonize the terminology and underlying concepts used (Garland et al. 2021). The resulting semantic inconsistencies have brought about redundant, ambiguous, and imprecise (if not controversial) term usage. To address this issue, we propose a classification based on 12 main categories of ecosystem functions that can be directly linked with the ecological processes used as functional endpoints in the assessment of PPP impacts in terrestrial, freshwater, and marine ecosystems (Table 1). This new classification departs from the classification published by De Groot et al. (2002) and revisited by Pettorelli et al. (2018). Following Pettorelli et al. (2018), cultural service functions were excluded on the grounds that they can be directly considered ecosystem services. The literature corpus mobilized during the CSA (i.e., about 4500 international publications) reported risks and/or effects of various PPPs on at least 8 of the 12 proposed categories (Pesce et al. 2023).

Table 1: Proposed classification of ecosystem functions potentially impacted by PPPs [adapted from De Groot et al. (2002) and Pettorelli et al. (2018)], and illustrative (non-exhaustive) list of related functional endpoints employed in ecotoxicology

	Ecosystem function category	Definition	Examples of functional endpoints used in ecotoxicology
1	Gas regulation	Production and consumption of gas and the regulation of gas exchanges among different environmental compartments and with the atmosphere	Photosynthesis, respiration, methanogenesis, methanotrophy, denitrification, nitrogen fixation, evapotranspiration
2	Dissipation and mitigation of contaminants and wastes in terrestrial and aquatic ecosystems	Filtration, buffering, sequestration and degradation of chemical and biological contaminants and wastes	Biodegradation/phytodegradation potential, enzymatic activity, exopolysaccharide production
3	Resistance to disturbance	Mitigation of and ability to resist both environmental (e.g. heatwaves, fires, storms, floods, mudflows, avalanches) and human-driven (e.g. pollution) disturbances	Aboveground (cover) and belowground (root systems) terrestrial vegetation biomass, aquatic biological-structure biomass (e.g. coral reefs, seagrasses, mangrove vegetation), pigment production, exopolysaccharide production, and mucilage production
4	Water retention in soil and sediment	Retention and storage of water in soil and sediment to preserve freshwater resources	Bioturbation by soil and sediment organisms, exopolysaccharide and mucilage production, root architecture
5	Water flow regulation	Regulation of runoff and water discharge	Bioturbation by soil and sediment organisms, exopolysaccharide and mucilage production, root architecture
6	Albedo and reflection	Local mitigation of the effects of climate change (including extreme events)	Vegetation biomass and cover, macroalgae and phytoplankton biomass, pigment production
7	Production and input of organic matter in terrestrial and aquatic ecosystems	Production and dispersion of biomass and organic matter that can serve as energy sources in food webs	Primary production, secondary production
8	Nutrient regulation in terrestrial and aquatic ecosystems	Decomposition of organic matter and nutrient transport, storage and recycling	Methanogenesis, methanotrophy, nitrification, denitrification, nitrogen fixation, sulfur oxidation/reduction, phosphorus solubilization, enzymatic activities, particulate organic matter decomposition
9	Formation and maintenance of soil and sediment structure	Role of vegetation and biota in the formation and maintenance of soil and sediment structure (including shorelines and coasts)	Bioturbation by soil and sediment organisms, aboveground (cover) and belowground (root systems and mucilage) terrestrial

			vegetation biomass, aquatic biomass (e.g. coral reefs, seagrasses, mangrove vegetation), microbial filament production and exopolysaccharide production
10	Dispersion of propagules in terrestrial and aquatic ecosystems	Role of vegetation and biota in the movement of propagules including floral gametes and seeds, aquatic/marine spores, eggs and larvae	Sexual (e.g. pollination) and vegetative reproduction of plants, spore and akinete production, transport of propagules by terrestrial and aquatic organisms
11	Provision and maintenance of biodiversity and biotic interactions in terrestrial and aquatic ecosystems	Provision and preservation of biodiversity and interactions within biotic communities to maintain ecosystem functioning, contain the impact of outbreaks/blooms (e.g. by controlling populations of potential pests and disease vectors), ensure the production and use of natural materials (i.e. biological and genetic resources) that organisms can use for health, and contribute to a self-maintaining diversity of organisms developed over evolutionary time (capable of continuing to change)	Population/community dynamics, trophic interactions, competition, facilitation, parasitism, symbiosis, genetic potential, nutrient, hormone and biocide production
12	Provision and maintenance of habitats and biotopes in terrestrial and aquatic ecosystems	Provision of suitable living space for wild biotic communities and individual species. Also includes the provision of suitable breeding, reproduction, nursery, refugia and corridors in natural and semi-natural ecosystems (connectivity)	Bioturbation by soil and sediment organisms, terrestrial and aquatic vegetation biomass (aboveground and belowground), terrestrial and aquatic biogenic structures

4. Classification of ecosystems services

The notion of ecosystem services emerged in the 1970s, where it was used by economists to conceptualize the link between the functions of nature and the benefits that society derives from it. The first author to refer to the concept was Schumacher (1973) who talked about “natural capital,” but the term “ecosystem services” itself was not coined until a few years later (see for example Westman 1977; Ehrlich and Ehrlich 1981) when it quickly became associated with advocacy for protecting ecosystems, given that most of the services they provide have no substitute (Ehrlich and Mooney 1983). Later on, seminal papers such as Daily (1997) and Costanza et al. (1997) went on to lend the “ecosystem services” concept, a multidisciplinary and global dimension, prompting the United Nations to coordinate several related projects and initiatives, such as the Millennium Ecosystem Assessment (MEA; 2000–2005), The Economics of Ecosystems and Biodiversity (TEEB; 2007–2011), and the Intergovernmental Science-Policy Platform on the Biodiversity and Ecosystem services (IPBES; 2012–today). The main objectives of these initiatives were to provide a conceptual framework for the notion of ecosystem service (MEA), to evaluate the contribution of these ecosystem services to society (TEEB), and to inform and guide government policy through evidence-based science on each of the ecosystem services previously defined by the MEA and TEEB (IPBES).

Ecosystem services have been given several more or less similar definitions. While all of these definitions converge to emphasize the contribution of ecosystem services to our well-being, they sometimes diverge on the dynamics that need to be considered. Daily (1997) asserted that ecosystem

services are processes that support our well-being, whereas Costanza et al. (1997) defined them as the goods and services resulting from these processes. As mentioned in Box 2 and in Pesce et al. (2023), the definition of ecosystem services used in our CSA (i.e., “the socioeconomic benefits to human populations and societies provided by healthy ecosystems”) is derived from that initially proposed by the MEA (2005), which defined ecosystem services as the benefits that humans derive from ecosystems (without making the distinction between the processes and the goods and services produced) and classified them into four categories, three of which directly impact human well-being (provisioning services providing food or energy, regulating services enabling, for example, air or water purification, and cultural services including recreational spaces offered by ecosystems) and a fourth that indirectly impacts it (supporting services that enable processes like nutrient cycling or soil formation to continue providing other ecosystem services). The MEA-defined scheme of ecosystem services was subsequently remobilized in international projects such as the IPBES and TEEB frameworks, but the category of “supporting” services disappeared (Díaz et al. 2015) as they were considered ecological processes (TEEB 2010).

Because most of its contributors were members of the conservation biology movement, the ecosystem services approach initially disregarded the notion of “dis-services” (Campagne et al. 2018). However, from the ecosystem services approach perspective, the impact of pests on food production is a “dis-service” of the ecosystem to humans (Rasmussen et al. 2017). A society that uses PPPs has therefore at least implicitly chosen to pursue the maximization of food production by reducing the short-term impacts of pest species on that service. It is only in the longer term that the negative impacts of PPP use on other services become apparent, notably in certain regulatory services that are useful to agriculture, such as pollination or soil formation, or cultural services that are dependent on the quality of the environment.

There is no one consensus approach for categorizing ecosystem services. Nevertheless, the approach initiated by the MEA and developed in the later IPBES and TEEB framework seems to be gaining wider adoption by the EU decision-makers. The European Environment Agency proposed a Common International Classification of Ecosystem Services (CICES; <https://cices.eu>) based on the ecosystem service cascade (Potschin and Haines-Young 2011). This system links ecological processes and functions to end-services, i.e., the MEA’s three direct-impact categories of ecosystem services (provisioning services, regulating and maintenance services, and cultural services).

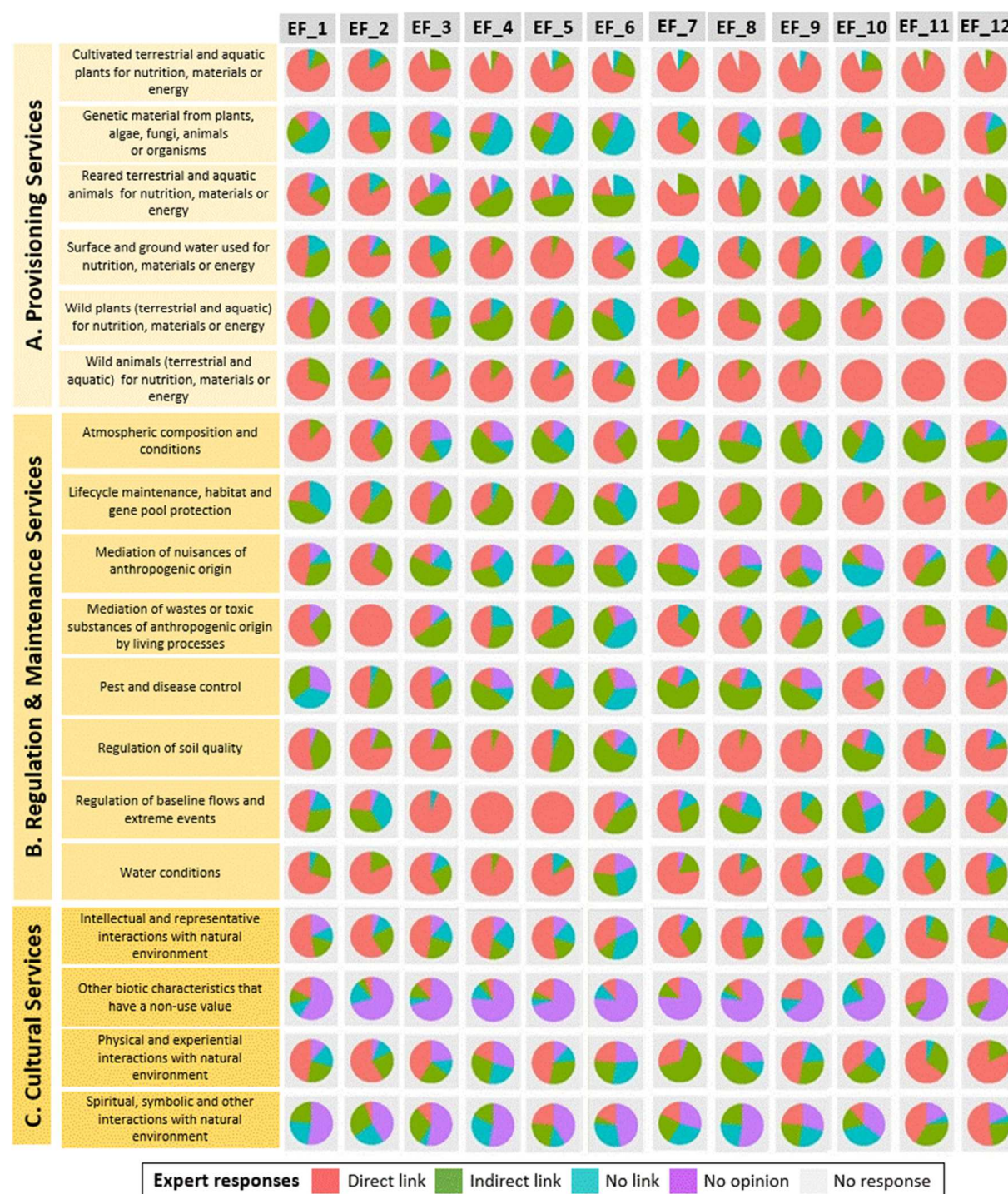
To address its aim of clearly outlining the knowledge, controversies, and gaps in understanding surrounding impacts of PPPs on ecosystem services, the expert panel working on the CSA (see Pesce et al. 2021) used the most recent version of the CICES classification (version 5.1.; Haines-Young and Potschin 2018).

5. Perceptions of the relationships between ecosystem functions and ecosystem services

Here, we used a perceptions survey to explore the possible links between the ecosystem functions potentially impacted by PPPs (based on the classification described in Table 1) and the groups of biotic and abiotic ecosystem services defined under the CICES classification (version 5.1.; Haines-Young and Potschin 2018). For that purpose, we established a sub-panel of 17 of the CSA-team scientific experts (see the acknowledgements section) covering a wide range of environmental disciplines that connect to the fate and impact of PPPs in soil and aquatic ecosystems (environmental chemistry, agronomy, microbial ecotoxicology, aquatic ecotoxicology, terrestrial ecotoxicology, ecology and evolution, and chemical fate and effect modeling). Each expert was asked to express his/her opinion, based on his/her own knowledge, experience, and perception, on ecosystem function–ecosystem service linkages. For each of the 218 combinations of ecosystem function group ($n=12$) × ecosystem service group ($n=18$), four possible responses were offered: (i) direct link, (ii) indirect link, (iii) no link, or (iv) no opinion.

Direct or indirect links did not carry any mention of whether the ecosystem function–ecosystem service relationship had to be positive or negative. Figure 2 illustrates the results obtained for the provisioning services (Fig. 2A), regulating and maintenance services (Fig. 2B), and cultural (Fig. 2C) services.

Fig. 2: Perceptions of a panel of experts in environmental sciences (n=17) on the links between the ecological function (EF) categories proposed in Table 1 and A provisioning services, B regulating and maintenance service, and C cultural services, as classified in CICES version 5.1. (Haines-Young and Potschin 2018)



Whatever the proposed combination, at least two experts identified possible direct and/or indirect links between the ecosystem service categories and the ecosystem function categories. Moreover, the majority of the experts consulted (i.e., at least 9/17) considered that about 55% of the combinations

concerning provisioning services (Fig. 2A) and regulating and maintenance services (Fig. 2B) were characterized by direct links with the proposed categories of ecosystem functions. This percentage reached 95% when also considering the indirect links.

However, a general consensus (i.e., identical responses among experts) emerged in very few cases ($n=9$, <5% of the total combinations), and only in three categories of provisioning services (i.e., “Genetic material from plants, algae, fungi, animals or organisms,” “Wild plants (terrestrial and aquatic) for nutrition, materials or energy,” and “Wild animals (terrestrial and aquatic) for nutrition, materials or energy”; Fig. 2A) and two categories of regulating and maintenance services (“Regulation of baseline flows and extreme events” and “Mediation of wastes or toxic substances of anthropogenic origin by living processes”; Fig. 2B). Furthermore, each time, the consensus was always towards the existence of direct links.

There was much higher variability in the responses on cultural services (Fig. 2C), for which a high percentage of “no opinion” responses was observed, in particular for the categories “Spiritual, symbolic and other interactions with the natural environment” and “Other biotic characteristics that have a non-use value.”

The results of this exercise indicate that it is possible to establish potential relationships between ecosystem functions and services, but that further efforts are needed to clarify the direct vs indirect nature of these links, and that there is still a great deal of subjectivity that can sometimes generate very different perceptions among experts. Moreover, the general picture of expert perception shows that the nature of the link is mainly profiled by service rather than by function (i.e., in most cases presented in Fig. 2, the percentages obtained are fairly homogeneous in the rows but more heterogeneous in the columns). This suggests that few services are linked to only part of the functions, and that it is above all the nature of the service that determines whether the link with most of the functions is direct or indirect. In terms of risk prevention, this implies that prioritizing particular services would in no way lead to prioritizing particular functions, given that each service relies on a set of functions and each function has consequences on a set of services.

6. Conclusions

Effective implementation of ecosystem service-based environmental risk assessments on PPPs could lead to better protection for ecosystems affected by the direct and indirect adverse effects of PPP contaminants. This topic is increasingly being discussed in the recent scientific literature, but there is still a substantial gap between most ecotoxicological studies and the evaluation of potential ecotoxicological consequences on ecosystem services. Several authors have recently proposed to develop ecological models or evidence-based logic chain approaches, but it is likely that the ecotoxicology community can only appropriate these approaches if it learns to accept and shares a backbone set of concepts and definitions related to ecological processes, ecosystem functions, and ecosystem services. A shared set of concepts and definitions could help harmonize and extend the science that informs decision-making and policy-making, and ultimately help to better address the trade-off between social benefits and environmental losses caused by the use of PPPs on ecosystems. In addition, the development of shared and standardized methods could make it possible to establish quantifiable indicators and relevant endpoints to evaluate the effects of PPPs on ecosystem services. With this in mind, the recent establishment of a working group at the International Organization for Standardization (ISO) to specifically focus on the assessment of soil functions and related-ecosystem services (ISO/TC 190/WG3), with the aims of proposing definitions and conceptual Framework (ISO/CD 18718) as well as indicators and methods (ISO/CD 18721), offers promising prospects for filling the knowledge gaps pointed out by the CSA about the effects of PPPs on soil ecosystem services (Pesce et al. 2023).

Acknowledgments

The authors thank (i) all the experts involved in the CSA that served for this paper, and especially those who, together with some of the authors, gave their perception of the links between ecosystem functions and services, namely Drs Marcel Amichot, Philippe Berny, Stéphane Betoulle, Michael Coeurdassier, Olivier Crouzet, Laure Mamy, Sylvie Nelieu, Wilfried Sanchez, Sabine Stachowski-Haberkorn, and Julien Tournebize; (ii) the French Ministries for the Environment, Research and Agriculture, who commissioned this CSA; (iii) the INRAE directorate for science strategy, and the Ifremer general directorate; (iv) Guy Richard, head of the INRAE Directorate for Expertise, Foresight and Advanced Studies (DEPE); and (v) the librarians responsible for compiling the bibliographic corpus (Anne-Laure Achard, Morgane Le Gall, and Sophie Le Perchec).

References

- Allison SD, Martiny JBH (2008) Resistance, resilience, and redundancy in microbial communities. *Proc Natl Acad Sci USA* 105:11512–11519. <https://doi.org/10.1073/pnas.0801925105>
- Armoškaitė A, Puriņa I, Aigars J, Strāķe S, Pakalniete K, Frederiksen P, Schrøder L, Hansen HS (2020) Establishing the links between marine ecosystem components, functions and services: an ecosystem service assessment tool. *Ocean Coast Manag* 193:105229. <https://doi.org/10.1016/j.ocecoaman.2020.105229>
- Arts GHP, Dollinger M, Kohlschmid E, Maltby L, Ochoa-Acuna H, Poulsen V (2015) An ecosystem services approach to pesticide risk assessment and risk management of non-target terrestrial plants: recommendations from a SETAC Europe workshop. *Environ Sci Pollut Res* 22:2350–2355. <https://doi.org/10.1007/s11356-014-3637-6>
- Bach EM, Ramirez KS, Fraser TD, Wall DH (2020) Soil biodiversity integrates solutions for a sustainable future. *Sustainability* 12:2662. <https://doi.org/10.3390/su12072662>
- Baert JM, De Laender F, Janssen CR (2017) The consequences of nonrandomness in species-sensitivity in relation to functional traits for ecosystem-level effects of chemicals. *Environ Sci Technol* 51:7228–7235. <https://doi.org/10.1021/acs.est.7b00527>
- Balvanera P, Pfisterer AB, Buchmann N, He J, Nakashizuka T, Raffaelli D, Schmid B (2006) Quantifying the evidence for biodiversity effects on ecosystem functioning and services. *Ecol Lett* 9:1146–1156. <https://doi.org/10.1111/j.1461-0248.2006.00963.x>
- Banerjee O, Crossman ND, de Groot RS (2013) Ecological processes, functions and ecosystem services: inextricable linkages between wetlands and agricultural systems. In: Wratten S, Sandhu H, Cullen R, Costanza R (eds) *Ecosystem services in agricultural and urban landscapes*. John Wiley, Hoboken, NJ, pp 16–27. <https://doi.org/10.1002/9781118506271.ch2>
- Bardgett RD, van der Putten WH (2014) Belowground biodiversity and ecosystem functioning. *Nature* 515:505–511. <https://doi.org/10.1038/nature13855>
- Bell G (2017) Evolutionary rescue. *Ann Rev Ecol Evol Syst* 48:605–627. <https://doi.org/10.1146/annurev-ecolsys-110316-023011>
- Black CC (2018). Effects of herbicides on photosynthesis. In: Duke SO (Ed), *Weed Physiology: Volume 2: Herbicide Physiology*. CRC Press, 2018. pp. 1-36
- Blanck H, Wängberg S-A, Molander S (1988) Pollution-induced community tolerance – a new ecotoxicological tool. In: Cairns J Jr, Pratt Jr (Eds), *Functional Testing of Aquatic Biota for Estimating Hazards of Chemicals* (pp. 219–230). ASTM STP 988, Philadelphia. <https://doi.org/10.1520/STP26265S>
- Boyd J, Banzhaf S (2007) What are ecosystem services? The need for standardized environmental accounting units. *Ecol Econ* 63:616–626. <https://doi.org/10.1016/j.ecolecon.2007.01.002>
- Brown AR, Whale G, Jackson M, Marshall S, Hamer M, Solga A, Kabouw P, Galay-Burgos M, Woods R, Nadzialek S, Maltby L (2017) Toward the definition of specific protection goals for the environmental risk assessment of chemicals: a perspective on environmental regulation in Europe. *Integr Environ Assess Manag* 13:17–37. <https://doi.org/10.1002/ieam.1797>
- Brown AR, Marshall S, Cooper C, Whitehouse P, Van den Brink PJ, Faber JH, Maltby L (2021) Assessing the feasibility and value of employing an ecosystem services approach in chemical environmental risk assessment under the Water Framework Directive. *Sci Total Environ* 789:147857. <https://doi.org/10.1016/j.scitotenv.2021>
- Bundschuh M, Schletz M, Goedkoop W (2016) The mode of bioturbation triggers pesticide remobilization from aquatic sediments. *Ecotox Environ Saf* 130:171–176. <https://doi.org/10.1016/j.ecoenv.2016.04.013>

- Byrnes JEK, Gamfeldt L, Isbell F, Lefcheck JS, Griffin JN, Hector A, Cardinale BJ, Hooper DU, Dee LE, Duffy JE (2013) Investigating the relationship between biodiversity and ecosystem multifunctionality: challenges and solutions. *Methods Ecol Evol* 5:111–124. <https://doi.org/10.1111/2041-210X.12143>
- Cairns J, Niederlehner BR (1994) Estimating the effects of toxicants on ecosystem services. *Environ Health Perspect* 102:936–939. <https://doi.org/10.1289/ehp.94102936>
- Campagne CS, Roche PK, Salles JM (2018) Looking into Pandora's Box: ecosystem disservices assessment and correlations with ecosystem services. *Ecosyst Serv* 30:126–136. <https://doi.org/10.1016/j.ecoser.2018.02.005>
- Cardinale BJ (2012) Biodiversity loss and its impact on humanity. *Nature* 486:59–67. <https://doi.org/10.1038/nature11148>
- Cardinale BJ, Srivastava DS, Duffy JE, Wright JP, Downing AL, Sankaran M, Jouseau C (2006) Effects of biodiversity on the functioning of trophic groups and ecosystems. *Nature* 443:989. <https://doi.org/10.1038/nature05202>
- Chaplain V, Mamy L, Vieublé-Gonod L, Mougin P, Benoit P, Barriuso E, Nélieu S (2011) Fate of pesticides in soils: toward an integrated approach of influential factors. In: Stoytcheva M (Ed.), *Pesticides in modern world – Risks and benefits* (ch. 29, 26 pp.), Intech.
- Commissariat Général au Développement Durable (CGGD) (2010) *Projet de caractérisation des fonctions écologiques des milieux en France. Études Doc* 20:70
- Costanza R, d'Arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill RV, Paruelo J, Raskin RG, Sutton P, Van Den Belt M (1997) The value of the World's ecosystem services and natural capital. *Nature* 387:253–260. <https://doi.org/10.1038/387253a0>
- Daily GC (1997) *Nature's services: societal dependence on natural ecosystems*. Island Press, Washington, DC
- De Groot RS, Wilson MA, Boumans RMJ (2002) A typology for the classification, description and valuation of ecosystem function, goods and services. *Ecol Econ* 41:393–408. [https://doi.org/10.1016/S0921-8009\(02\)00089-7](https://doi.org/10.1016/S0921-8009(02)00089-7)
- De Groot R, Brander L, Van Der Ploeg S, Costanza R, Bernard F, Braat L, Christie M, Crossmang N, Ghermandi A, Hein L, Hussain S, Kumar P, McVittie A, Portela R, Rodriguez LC, ten Brink P, van Beukering P (2012) Global estimates of the value of ecosystems and their services in monetary units. *Ecosyst Serv* 1:50–61. <https://doi.org/10.1016/j.ecoser.2012.07.005>
- De Laender F, Melian CJ, Bindler R, Van den Brink PJ, Daam M, Roussel H, Juselius J, Verschuren D, Janssen CR (2014) The contribution of intra- and interspecific tolerance variability to biodiversity changes along toxicity gradients. *Ecol Lett* 17:72–81. <https://doi.org/10.1111/ele.12210>
- De Laender F, Rohr JR, Ashauer R, Baird DJ, Berger U, Eisenhauer N, Grimm V, Hommen U, Maltby L, Meliàn CJ, Pomati F, Roessink I, Radchuk V, van den Brink PJ (2016) Reintroducing environmental change drivers in biodiversity–ecosystem functioning research. *Trends Ecol Evol* 31:905–915. <https://doi.org/10.1016/j.tree.2016.09.007>
- De Meester L, Vanoverbeke J, Kilsdonk LJ, Urban MC (2016) Evolving perspectives on monopolization and priority effects. *Trends Ecol Evol* 31:136–146. <https://doi.org/10.1016/j.tree.2015.12.009>
- Delgado-Baquerizo M, Maestre FT, Reich PB, Jeffries TC, Gaitan JJ, Encinar D, Berdugo M, Campbell CD, Singh BK (2016) Microbial diversity drives ecosystem multifunctionality in terrestrial ecosystems. *Nat Commun* 7:10541. <https://doi.org/10.1038/ncomms10541>
- Devos Y, Romeis J, Luttik R, Maggiore A, Perry JN, Schoonjans R, Streissl F, Tarazona JV, Brock TC (2015) Optimising environmental risk assessments: accounting for ecosystem services helps to translate broad policy protection goals into specific operational ones for environmental risk assessments. *EMBO Rep* 16:1060–1063. <https://doi.org/10.15252/embr.201540874>
- Díaz S, Purvis A, Cornelissen JHC, Mace GM, Donoghue MJ, Ewers RM, Jordano P, Pearse WD (2013) Functional traits, the phylogeny of function, and ecosystem service vulnerability. *Ecol Evol* 3:2958–2975. <https://doi.org/10.1002/ece3.601>
- Díaz S, Demissew S, Carabias J, Joly C, Lonsdale M, Ash N, Larigauderie A, Adhikari JR, Arico S, Báldi A, Bartuska A, Baste IA, Bilgin A, Brondizio E, Chan KM, Figueroa VE, Duraipappah A, Fischer M, Hill R et al (2015) The IPBES conceptual framework — connecting nature and people. *Curr Opin Environ Sustain* 14:1–16. <https://doi.org/10.1016/j.cosust.2014.11.002>
- Duncan C, Thompson JR, Pettorelli N (2015) The quest for a mechanistic understanding of biodiversity–ecosystem services relationships. *Proc R Soc B Biol Sci* 282:20151348. <https://doi.org/10.1098/rspb.2015.1348>
- Ehrlich P, Ehrlich A (1981) *Extinction: the causes and consequences of the disappearance of species*, Random House, New York
- Ehrlich PR, Mooney HA (1983) Extinction, substitution, and ecosystem services. *BioScience* 33:248–254. <https://doi.org/10.2307/1309037>
- Eisenhauer N, Schielzeth H, Barnes AD, Barry K, Bonn A, Brose U, Bruehlheide H, Buchmann N, Buscot F, Ebeling A, Ferlian O, Freschet GT, Gilling DP, Hättenschwiler S, Hillebrand H, Hines J, Isbell F, Koller-France E, König-

- Ries B, Jochum M (2019) A multitrophic perspective on biodiversity–ecosystem functioning research. *Adv Ecol Res* 61:1–54. <https://doi.org/10.1016/bs.aecr.2019.06.001>
- European Food Safety Authority (EFSA) (2010) EFSA panel on plant protection products and their residues (PPR): scientific opinion on the development of specific protection goal options for environmental risk assessment of pesticides, in particular in relation to the revision of the Guidance Documents on Aquatic and Terrestrial Ecotoxicology (SANCO/3268/2001 and SANCO/10329/2002). *EFSA J* 8:1821. <https://doi.org/10.2903/j.efsa.2010.1821>
- European Food Safety Authority (EFSA) (2013) EFSA panel on plant protection products and their residues (PPR): guidance on tiered risk assessment for plant protection products for aquatic organisms in edge-of-field surface waters. *EFSA J* 11:3290. <https://doi.org/10.2903/j.efsa.2013.3290>
- European Food Safety Authority (EFSA) (2016a) EFSA Scientific Committee: guidance to develop specific protection goals options for environmental risk assessment at EFSA, in relation to biodiversity and ecosystem services. *EFSA J* 14:4499. <https://doi.org/10.2903/j.efsa.2016.4499>
- European Food Safety Authority (EFSA) (2016b) EFSA Scientific Committee: recovery in environmental risk assessments at EFSA. *EFSA J* 14:4313. <https://doi.org/10.2903/j.efsa.2016.4313>
- European Commission (2020) EU Biodiversity Strategy for 2030. Bringing nature back into our lives. COM/2020/380 final (<https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0380>; accessed 4 May 2023)
- Faber JH, Van Wensem J (2012) Elaborations on the use of the ecosystem services concept for application in ecological risk assessment for soils. *Sci Total Environ* 415:3–8. <https://doi.org/10.1016/j.scitotenv.2011.05.059>
- Faber JH, Marshall S, Van den Brink PJ, Maltby L (2019) Priorities and opportunities in the application of the ecosystem services concept in risk assessment for chemicals in the environment. *Sci Total Environ* 651:1067–1077. <https://doi.org/10.1016/j.scitotenv.2018.09.209>
- Faber JH, Marshall S, Brown AR, Holt A, van den Brink PJ, Maltby L (2021) Identifying ecological production functions for use in ecosystem services-based environmental risk assessment of chemicals. *Sci Total Environ* 791:146409. <https://doi.org/10.1016/j.scitotenv.2021.146409>
- Fisher B, Turner RK, Morling P (2009) Defining and classifying ecosystem services for decision making. *Ecol Econ* 68:643–653. <https://doi.org/10.1016/j.ecolecon.2008.09.014>
- Fleeger JW (2020) How do indirect effects of contaminants inform ecotoxicology? A review. *Processes* 8:1659. <https://doi.org/10.3390/pr8121659>
- Fleeger JW, Carman KR, Nisbet RM (2003) Indirect effects of contaminants on aquatic ecosystems. *Sci Total Environ* 317:207–233. [https://doi.org/10.1016/S0048-9697\(03\)00141-4](https://doi.org/10.1016/S0048-9697(03)00141-4)
- Forbes VE, Calow P (2013) Use of the ecosystem services concept in ecological risk assessment of chemicals. *Integr Environ Assess Manag* 9:269–275. <https://doi.org/10.1002/ieam.1368>
- Forbes VE, Salice CJ, Birnir B, Bruins RJF, Calow P, Ducrot V, Galic N, Garber K, Harvey BC, Jager H, Kanarek A, Pastorok R, Railsback SF, Rebarber R, Thorbek P (2017) A framework for predicting impacts on ecosystem services from (sub)organismal responses to chemicals. *Environ Toxicol Chem* 36:845–859. <https://doi.org/10.1002/etc.3720>
- Galic N, Schmolke A, Forbes V, Baveco H, van den Brink PJ (2012) The role of ecological models in linking ecological risk assessment to ecosystem services in agroecosystems. *Sci Total Environ* 415:93–100. <https://doi.org/10.1016/j.scitotenv.2011.05.065>
- Galic N, Salice CJ, Birnir B, Bruins RJF, Ducrot V, Jager HI, Kanarek A, Pastorok R, Rebarber R, Thorbek P, Forbes VE (2019) Predicting impacts of chemicals from organisms to ecosystem service delivery: a case study of insecticide impacts on a freshwater lake. *Sci Total Environ* 682:426–436. <https://doi.org/10.1016/j.scitotenv.2019.05.187>
- Gamfeldt L, Roger F (2017) Revisiting the biodiversity–ecosystem multifunctionality relationship. *Nat Ecol Evol* 1:0168. <https://doi.org/10.1038/s41559-017-0168>
- Garland G, Banerjee S, Edlinger A, Oliveira Hagen E, Herzog C, Wittwer R, Philippot L, Maestre FT, van der Heijden M (2021) A closer look at the functions behind ecosystem multifunctionality: a review. *J Ecol* 109:600–613. <https://doi.org/10.1111/1365-2745.13511>
- Glaser G (2012) Base sustainable development goals on science. *Nature* 491:35. <https://doi.org/10.1038/491035a>
- Grace JB, Anderson TM, Seabloom EW, Borer ET, Adler PB, Harpole WS, Hautier Y, Hillebrand H, Lind EM, Partel M, Bakker JD, Buckley YM, Crawley MJ, Damschen EI, Davies KF, Fay PA, Firn J, Gruner DS, Hector A et al (2016) Integrative modeling reveals mechanisms linking productivity and plant species richness. *Nature* 529:390–393. <https://doi.org/10.1038/nature16524>
- Haines-Young R, Potschin MB (2018) Common International Classification of Ecosystem Services (CICES) V5.1 and Guidance on the Application of the Revised Structure. Available at www.cices.eu ; accessed 5 May 2023)

- Halstead NT, McMahon TA, Johnson SA, Raffel TR, Romansic JM, Crumrine PW, Rohr JR (2014) Community ecology theory predicts the effects of agrochemical mixtures on aquatic biodiversity and ecosystem properties. *Ecol Lett* 17:932–941. <https://doi.org/10.1111/ele.12295>
- Hartl DL, Clark AG (1997) Principles of population genetics. Sinauer, Sunderland, MA
- Hayes F, Spurgeon DJ, Lofts S, Jones L (2018) Evidence-based logic chains demonstrate multiple impacts of trace metals on ecosystem services. *J Environ Manag* 223:150–164. <https://doi.org/10.1016/j.jenvman.2018.05.053>
- Heink U, Kowarik I (2010) What are indicators? On the definition of indicators in ecology and environmental planning. *Ecol Indic* 10:584–593. <https://doi.org/10.1016/j.ecolind.2009.09.009>
- Hubbell SP (2001) The unified neutral theory of biodiversity and biogeography. Princeton University Press, Princeton, NJ
- Isbell F, Cowles J, Dee LE, Loreau M, Reich PB, Gonzalez A, Hector A, Schmid B (2018) Quantifying effects of biodiversity on ecosystem functioning across times and places. *Ecol Lett* 21:763–778. <https://doi.org/10.1111/ele.12928>
- Johnston EL, Roberts DA (2009) Contaminants reduce the richness and evenness of marine communities: a review and meta-analysis. *Environ Pollut* 157:1745–1752. <https://doi.org/10.1016/j.envpol.2009.02.017>
- Kattwinkel M, Liess M, Arena M, Bopp S, Streissl F, Römbke J (2015) Recovery of aquatic and terrestrial populations in the context of European pesticide risk assessment. *Environ Rev* 23:382–394. <https://doi.org/10.1139/er-2015-0013>
- Liquete C, Piroddi C, Drakou EG, Gurney L, Katsanevakis S, Charef A, Egoh B (2013) Current status and future prospects for the assessment of marine and coastal ecosystem services: a systematic review. *PLoS One* 8:e67737. <https://doi.org/10.1371/journal.pone.0067737>
- Loreau M (2010) Linking biodiversity and ecosystems: towards a unifying ecological theory. *Philos Trans R Soc Lond B Biol Sci* 365:49–60. <https://doi.org/10.1098/rstb.2009.0155>
- Lovett GM, Jones CG, Turner MG, Weathers KC (2006) Ecosystem function in heterogeneous landscapes. In: Lovett GM, Jones CG, Turner MG, Weathers KC (eds) *Ecosystem function in heterogeneous landscapes*. Springer, New York, pp 1–4
- Malaj E, von der Ohe PC, Grote M, Kühne R, Mondy CP, Usseglio-Polatera P, Brack W, Schäfer RB (2014) Organic chemicals jeopardize the health of freshwater ecosystems on the continental scale. *Proc Natl Acad Sci USA* 111:9549–9554. <https://doi.org/10.1073/pnas.1321082111>
- Maltby L (2013) Ecosystem services and the protection, restoration and management of ecosystems exposed to chemical stressors. *Environ Toxicol Chem* 32:974–983. <https://doi.org/10.1002/etc.2212>
- Maltby L, van den Brink PJ, Faber JH, Marshall S (2018) Advantages and challenges associated with implementing an ecosystem services approach to ecological risk assessment for chemicals. *Sci Total Environ* 621:1342–1351. <https://doi.org/10.1016/j.scitotenv.2017.10.094>
- Maltby L, Brown R, Faber JH, Galic N, Van den Brink PJ, Warwick O, Marshall S (2021) Assessing chemical risk within an ecosystem services framework: implementation and added value. *Sci Total Environ* 791:148631. <https://doi.org/10.1016/j.scitotenv.2021.148631>
- Maltby L, Brown R, Wilkinson H (2022) Applying ecosystem services principles to the derivation of freshwater environmental quality standards. *Front Environ Sci* 10:932161. <https://doi.org/10.3389/fenvs.2022.932161>
- Marseille MR, Harting T, Cox DTC, Bell S, Knapp S, Lindley S, Triguero-Mas M, Böhning-Gaese K, Braubach M, Cook PA, de Vries S, Heintz-Buschart A, Hofmann M, Irvine KM, Kabisch N, Kolek F, Kraemer R, Markevych I, Martens D et al (2021) Pathways linking biodiversity to human health: a conceptual framework. *Environ Int* 150:106420. <https://doi.org/10.1016/j.envint.2021.106420>
- Martinez ND (1996) Defining and measuring functional aspects of biodiversity. In: Gaston KJ (ed) *Biodiversity: a biology of numbers and difference*. Blackwell Science, Oxford, pp 114–148
- Mensens C, De Laender F, Janssen C, Sabbe K, De Troch M (2015) Stressor-induced biodiversity gradients: revisiting biodiversity-ecosystem functioning relationships. *Oikos* 124:677–684. <https://doi.org/10.1111/oik.01904>
- Millennium Ecosystem Assessment (MEA) (2005) *Ecosystems and human wellbeing: synthesis*. Island Press, Washington (DC), p 137
- Munns WR, Rea AW, Suter GW, Martin L, Blake-Hedges L, Crk T, Davis C, Ferreira G, Jordan S, Mahoney M, Barron MG (2016) Ecosystem services as assessment endpoints for ecological risk assessment. *Integr Environ Assess Manag* 12:522–528. <https://doi.org/10.1002/ieam.1707>
- Munns WR, Poulsen V, Gala WR, Marshall SJ, Rea AW, Sorensen MT, von Stackelberg K (2017) Ecosystem services in risk assessment and management. *Integr Environ Assess Manag* 131:62–73. <https://doi.org/10.1002/ieam.1835>
- Naeem S, Bunker DE, Hector A, Loreau M, Perrings C (2009) *Biodiversity, ecosystem-functioning, and human wellbeing*. Oxford University Press, New York

- Nienstedt KM, Brock T, Jv W, Montforts M, Hart A, Aagaard A, Alix A, Boesten J, Bopp SK, Brown C, Capri E, Forbes V, Köpp H, Liess M, Luttik R, Maltby L, Sousa JP, Streissl F, Hardy AR (2012) Development of a framework based on an ecosystem services approach for deriving specific protection goals for environmental risk assessment of pesticides. *Sci Total Environ* 415:31–38. <https://doi.org/10.1016/j.scitotenv.2011.05.057>
- Oginah SA, Posthuma L, Maltby L, Hauschild M, Fantke P (2023) Linking freshwater ecotoxicity to damage on ecosystem services in life cycle assessment. *Environ Int* 171:107705. <https://doi.org/10.1016/j.envint.2022.107705>
- Pesce S, Mamy L, Achard AL, Le Gall M, Le Perchec S, Réchauchère O, Leenhardt S, Sanchez S (2021) Collective scientific assessment as a relevant tool to inform public debate and policymaking: an illustration with the effects of plant protection products on biodiversity and ecosystem services. *Environ Sci Pollut Res* 28:38448–38454. <https://doi.org/10.1007/s11356-021-14863-w>
- Pesce S, Mamy L, Sanchez W et al (2023) Main conclusions and perspectives from the collective scientific assessment of the effects of plant protection products on biodiversity and ecosystem services along the land–sea continuum in France and French overseas territories. *Environ Sci Pollut Res*. <https://doi.org/10.1007/s11356-023-26952-z>
- Pettorelli N, to Bühne HS, Tulloch A, Dubois G, Macinnis-Ng C, Queiros AM, Keith DA, Wegmann M, Schrodt F, Stellmes M, Sonnenschein R, Geller GN, Roy S, Somers B, Murray N, Bland L, Geijzendorffer I, Kerr JT, Broszeit S et al (2018) Satellite remote sensing of ecosystem functions: opportunities, challenges and way forward. *Remote Sens Ecol Conserv* 4:71–93. <https://doi.org/10.1002/rse2.59>
- Potschin MB, Haines-Young RH (2011) Ecosystem services: exploring a geographical perspective. *Prog Phys Geogr Earth Environ* 35:575–594. <https://doi.org/10.1177/0309133311423172>
- Potschin-Young M, Czúcz B, Lique C, Maes J, Rusch GM, Haines-Young R (2017) Intermediate ecosystem services: an empty concept? *Ecosys Serv* 27:124–126. <https://doi.org/10.1016/j.ecoser.2017.09.001>
- Qiu K, Xie Y, Xu D, Pott R (2018) Ecosystem functions including soil organic carbon, total nitrogen and available potassium are crucial for vegetation recovery. *Sci Rep* 8:760. <https://doi.org/10.1038/s41598-018-25875-x>
- Rasmussen LV, Christensen AE, Danielsen F, Dawson N, Martin A, Mertz O, Sikor T, Thongmanivong S, Xaydongvanh P (2017) From food to pest: conversion factors determine switches between ecosystem services and disservices. *Ambio* 46:173–183. <https://doi.org/10.1007/s13280-016-0813-6>
- Rumschlag SL, Mahon MB, Hoverman JT, Raffel TR, Carrick HJ, Hudson PJ, Rohr JR (2020) Consistent effects of pesticides on community structure and ecosystem function in freshwater systems. *Nat Commun* 11:6333. <https://doi.org/10.1038/s41467-020-20192-2>
- Saaristo M, Brodin T, Balshine S, Bertram MG, Brooks BW, Ehlman SM, McCallum ES, Sih A, Sundin J, Wong BBM, Arnold KO (2018) Direct and indirect effects of chemical contaminants on the behaviour, ecology and evolution of wildlife. *Proc R Soc B Biol Sci* 285:20181297. <https://doi.org/10.1098/rspb.2018.1297>
- Schulze ED, Mooney HA (eds) (1993) Biodiversity and ecosystem function. Springer-Verlag, Berlin, Germany
- Schumacher EF (1973) Small is beautiful: economics as if people mattered. Blond and Briggs, London
- Svensson EI, Gómez-Llano MA, Torres AR, Bensch HM (2018) Frequency dependence and ecological drift shape coexistence of species with similar niches. *Am Nat* 191:691–703. <https://doi.org/10.1086/697201>
- TEEB (2010) The economics of ecosystems and biodiversity: ecological and economic foundations. Pushpam Kumar (ed.), Earthscan, London & Washington.
- Thomsen M, Faber JH, Sorensen PB (2012) Soil ecosystem health and services – evaluation of ecological indicators susceptible to chemical stressors. *Ecol Indic* 16:67–75. <https://doi.org/10.1016/j.ecolind.2011.05.012>
- Tickner D, Opperman J, Abell R, Acreman M, Arthington AH, Bunn SE, Cooke SJ, Dalton J, Darwall W, Edwards G, Harrison I, Hughes K, Jones T, Leclère D, Lynch AJ, Leonard P, McClain ME, Muruven D, Olden JD et al (2020) Bending the curve of global freshwater biodiversity loss: an emergency recovery plan. *BioScience* 70:330–342. <https://doi.org/10.1093/biosci/biaa002>
- Tilman D (2004) Niche tradeoffs, neutrality, and community structure: a stochastic theory of resource competition, invasion, and community assembly. *Proc Natl Acad Sci USA* 101:10854–10861. <https://doi.org/10.1073/pnas.0403458101>
- Tilman D, Isbell F, Cowles JM (2014) Biodiversity and ecosystem functioning. *Annu Rev Ecol Evol Syst* 45:471–493. <https://doi.org/10.1146/annurev-ecolsys-120213-091917>
- United Nations (1992) Convention on biological diversity [WWW document]. (<https://www.cbd.int/doc/legal/cbd-en.pdf> ; accessed 5 May 2023)
- Van den Brink PJ, Alix A, Thorbek P, Baveco H, Agatz A, Faber JH, Brown AR, Marshall S, Maltby L (2021) The use of ecological models to assess the effects of a plant protection product on ecosystem services provided by an orchard. *Sci Total Environ* 798:149329. <https://doi.org/10.1016/j.scitotenv.2021.149329>
- van der Plas F (2019) Biodiversity and ecosystem functioning in naturally assembled communities. *Biol Rev* 94:1220–1245. <https://doi.org/10.1111/brv.12499>

- Van Wensem J, Maltby L (2013) Ecosystem services: from policy to practice. *Integr Environ Assess Manag* 9:211–213. <https://doi.org/10.1002/ieam.1412>
- Van Wensem J, Calow P, Dollacker A, Maltby L, Olander L, Tuvendal M, Van Houtven G (2017) Identifying and assessing the application of ecosystem services approaches in environmental policies and decision making. *Integr Environ Assess Manag* 13:41–51. <https://doi.org/10.1002/ieam.1836>
- Vinebrooke RD, Cottingham KL, Norberg J, Scheffer M, Dodson SI, Maberly SC, Sommer U (2004) Impacts of multiple stressors on biodiversity and ecosystem functioning: the role of species co-tolerance. *Oikos* 104:451–457. <https://doi.org/10.1111/j.0030-1299.2004.13255.x>
- Westman WE (1977) How much are nature's services worth? *Science* 197:960–964. <https://doi.org/10.1126/science.197.4307.960>
- Xiao H, McDonald-Madden E, Sabbadin R, Peyrard N, Dee LE, Chadès I (2019) The value of understanding feedbacks from ecosystem functions to species for managing ecosystems. *Nat Commun* 10:3901. <https://doi.org/10.1038/s41467-019-11890-7>