The impacts of plant protection products on biodiversity and ecosystem services. Summary of the collective scientific expertise

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Summary of the collective scientific expertise - Mai 2022

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Summary of the report of the collective scientific expert study conducted by INRAE and Ifremer at the request of the Ministries responsible for the Environment, Agriculture and Research
May 2022

Each year, between 55,000 and 70,000 tonnes of plant protection product active ingredients, including those usable in organic farming and biocontrol, are sold in mainland France and its overseas territories. They are used for crop protection or the maintenance of gardens, green spaces and infrastructure (known in French as JEVI). At the same time, the report on the global assessment of biodiversity and ecosystem services established in 2019 by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) has provided an alarming assessment of an unprecedented erosion of biodiversity. Chemical pollution generated by human activities, including plant protection products (PPP), has been identified as being among the causes of this erosion. This pollution is added to other pressures, such as habitat destruction caused by urbanisation, the intensification of agricultural and forestry practices and the consequences of climate change. Faced with this observation, European regulations on the marketing of PPP have aimed for a high degree of protection, in particular on the principle of avoiding any unacceptable effect on the environment. However, this objective has not been fully achieved, due in particular to insufficient consideration of the diversity of interactions as they occur in the environment (between substances, between organisms, and with a variety of physical-chemical factors etc.).

Against this background, the French Ministries respectively responsible for the Environment, Agriculture and Research asked INRAE and Ifremer to conduct an inventory of scientific knowledge relating to the impacts of PPP on biodiversity and ecosystem services. The previous collective scientific expert study (known as an ESCo) on Pesticides, Agriculture and the Environment *was conducted in 2005. The present exercise consists of updating the results, extending them to the entire land-sea continuum and including PPP use in non-agricultural areas (JEVI). Unlike the 2005 study, this ESCo is positioned downstream of PPP use, dealing with the fate and impacts of these substances once introduced into the environment. It does not deal with agricultural practices or systems that reduce PPP use, nor with preventive strategies for regulating pests. These themes are the subject of other ongoing work, in particular another INRAE ESCo on the management of plant cover for the natural regulation of pests, the results of which are expected in autumn 2022. These two exercises are part of the Ecophyto II+ Plan, in addition to the* Pesticides and Human Health *expert study published by Inserm in 2021.*

The scope of this ESCo covers the various environments (terrestrial, atmospheric, continental and marine aquatic environments, with the exception of groundwater) in their continuity, from the site of PPP application to the ocean, in both mainland France and its overseas territories, from knowledge produced or transposable in this type of context (climate, PPP used, biodiversity present etc.). It includes all products intended for crop protection or the maintenance of JEVI, whether conventional PPP or biocontrol products or agents, when they are likely to be found in the environment due to current or past use. The analytical framework established considers biodiversity in its structural and functional dimensions, and it incorporates the issue of ecosystem services. Attention is therefore more particularly focused on work that documents the identification of risks and effects under realistic environmental conditions, and at levels of biological organisation (e.g. individual, population, community, ecosystem) likely to facilitate the link to be established with biodiversity as well as with ecosystem functions and services.

The collective scientific expert study approach (ESCo)

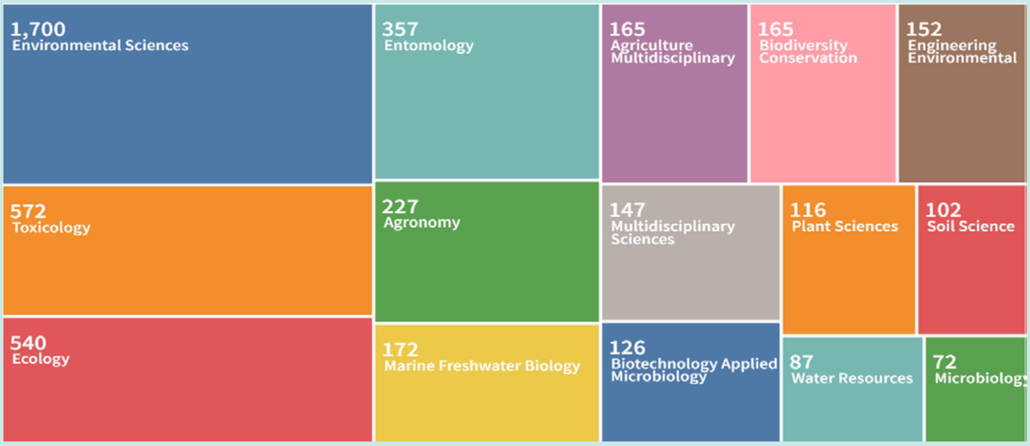
An ESCo consists of establishing an updated inventory of scientific knowledge and conducting critical analysis, taking stock of the achievements, debates and controversies that cross the scientific communities, the uncertainties which must be considered in the interpretation of results and identifying gaps that will need to be filled in the future.

An ESCo is therefore based on bibliographical references available internationally. It does not formulate opinions or recommendations. The conduct of the exercise is based on a charter of scientific expertise whose general principles are competence, impartiality, plurality and transparency.

The expert group brought together for this ESCo comprised 46 researchers (including 46% from outside INRAE and Ifremer) from 19 research organisations and higher education establishments.

The bibliographic corpus was compiled from the Web of Science™ (WoS) database, and the Scopus, Cairn, Springer and Sage platforms and databases in the fields of human and social sciences. Being an update on the state of knowledge, the initial research was centred on the period 2000-2020. The geographical scope for the inventory of contamination concerned only mainland France and its overseas territories. With regards to the effects on biodiversity, ecosystem functions and services, all the knowledge from international work on situations (type of climate, PPP, organisms etc.) transposable to the French context was considered. In addition to academic sources, non-academic sources were used, in particular institutional environmental monitoring reports and studies relating to JEVI, which have been the subject of little scientific work. In total, the corpus cited includes more than 4,000 references, 14% of which are literature reviews and meta-analyses. Seventy percent of these references were published in the past 10 years. The academic bibliography covers a wide variety of research fields, as indicated for example by the top 15 research fields in which the 3,343 references in the ESCo bibliographic corpus are classified, having been published in journals classified by WoS (Figure 1).

Figure 1. Research fields of the 3,343 references classified in WoS categories (top 15 categories).



1 PPP contaminate all environmental matrices

PPP are developed and marketed for their antagonistic properties vis-à-vis organisms that affect crops. They are applied to agricultural plots and JEVI, in direct contact with the environment within which they follow a complex dynamic of transfers and transformations throughout the land-sea continuum.

Due to insufficient data, the degree of PPP contamination of the environment is difficult to characterise quantitatively over a large scale. The diversity of the substances analysed remains limited compared to those which are potentially present (294 active ingredients and more than 1,500 commercial preparations are currently authorised in France). There is no checking for many substances, in particular the most recently placed on the market, including biocontrol products. Co-formulants and adjuvants, as well as products of transformation, resulting from the degradation of substances (each can generate several, even several dozen transformation products), are also rarely sought. The matrices are also unevenly monitored, with air and soil contamination currently being less well documented than that of inland and marine waters. This contamination also presents great temporal and spatial variability, depending on its source and the combination of various processes of transfer, retention, degradation, accumulation etc.

However, PPP contamination monitoring systems have been gradually strengthened since the 2000s, integrating a greater diversity of substances and matrices sampled. Scientifically, the main advances concern the use of integrative passive samplers, which make it possible to better identify situations of chronic exposure at low concentrations, and to quantify certain non-detectable substances on the basis of grab samples. Non-targeted analyses offer the possibility of identifying a broad spectrum of molecules, without depending on an *a priori* choice of substances sought. This type of analysis makes it possible to better characterise the contamination of environments, in particular by PPP transformation products, though these analyses are not yet deployed on a large scale.

The available data show that PPP contaminate all types of matrices (soil, air, water and sediment, as well as biota), with the impregnation of biota confirming the reality of the exposure of organisms. This contamination is also ubiquitous due to the transfer processes of PPP and the persistence of certain molecules, from the site of their application through to very distant areas such as the deep ocean or sub-polar regions. It generally results in the presence of mixtures of PPP that include several molecules (active ingredients including substances that are currently prohibited but persist in the environment, transformation products of substances, co-formulants and adjuvants).

Agriculture has been identified as the major source of introduction of PPP into the environment, with agricultural use far exceeding other uses (between 95 and 98%). Consequently, agricultural areas, including the waterways that cross them and the air masses above them, are the matrices which are most contaminated by these substances.

Figure 2 represents the overall distribution of PPP contamination in the schematised space of mainland France and its overseas territories. This representation is based on the assessment that can be made from the bibliographic corpus studied of contamination gradients for different types of substances and matrices. It shows water contamination where predominantly hydrophilic herbicides dominate, while hydrophobic compounds (a large proportion of insecticides) have a greater presence in soils and sediments, as well as in biota. Fungicides are mainly found in soil and air, but they are also present in water. From a spatial point of view, the diagram emphasises that contamination is more marked near treatment areas.

From a temporal point of view, the prohibition of some PPP considered to be among the most worrying has resulted in a reduction over the past 20 twenty years of the overall levels of concentrations of these substances. These are among the most highly monitored substances in inland surface water environments (*e.g.* DDT, lindane and diuron).

Figure 2. General scheme of environmental contamination by PPP.

Overseas territories

France's overseas territories are home to 80% of French biodiversity, both terrestrial and marine. However, this biodiversity is under particular threat, as indicated by the red list established by the International Union for the Conservation of Nature (IUCN). While monitoring networks provide information on the contamination of aquatic environments in the overseas departments, scientific studies on PPP environmental contamination in overseas territories are rare. Most of the work identified concerns chlordecone contamination in Martinique and Guadeloupe, with particular attention given to the contamination of biota. The peculiarities specific to the various overseas territories reflect the characteristics of their agricultural activities, except in the uninhabited territories located in the sub-Antarctic zone, where organochlorine PPP contamination can be found, linked to the long-distance transport of these now-prohibited molecules.

Despite proven contamination, to our knowledge there is no study documenting the effects on overseas biodiversity in the natural environment. Little work has been conducted in a manner adapted to the specificities of these territories, apart from research on chlordecone. Furthermore, these studies are mainly focused on the effects of contamination on human health, and only very marginally concern its consequences on biodiversity. It is difficult to transfer the scenarios, models and data generated in other contexts.

2 Knowledge about the effects of PPP is diversifying

The bibliographic analysis of the past 20 years has highlighted the great diversity of the direct effects of PPP, in addition to those which are classically suspected. It also shows a growing attention to indirect effects, because of their importance compared to direct effects. Finally, the need to consider other pressures (habitat destruction, climate change, other chemical pollution etc.) is increasingly emphasised, even if the integration of these aspects in the scientific approaches used is still insufficient to be able to generalise the results already obtained

2.1 Direct effects unrelated to the known mode of action of PPP

Classically, the effects of PPP are sought by focusing on species biologically close to the targeted pest and by considering biological targets (molecular or physiological) potentially sensitive to the substances under consideration. However, increasing numbers of unexpected effects with no clear relationship to the known mode of action have been highlighted, for example with regard to nervous, immune or endocrine systems, or even interactions with microbiota. Since these functions are widely shared in the living world, the effects of PPP can manifest themselves across a wide range of species.

This raises the question of the repercussions that these effects, which are most often sub-lethal, can have on the dynamics of the populations concerned. This field of research remains largely unexplored and few studies manage to describe the relationship between sub-lethal disturbances (physiological, behavioural etc.) studied mainly in the laboratory, the selective value (fitness) of individuals and population dynamics. However, some studies, carried out for example on bees sampled in open fields and therefore exposed in nature to certain individual PPP or mixtures, corroborate the results of experiments conducted under controlled conditions on the deleterious impacts of these substances, for example on feeding behaviour (lower pollen consumption, cannibalism), brood size, renewal of workers and the health or survival of breeding queens.

These results also help put into perspective the degree of selectivity of a PPP, *i.e.* its ability to exert effects on only a narrow spectrum of targeted organisms. This property is in fact generally established from the selectivity of the known mode of action, without considering the absence of selectivity as the basis of other, unintended effects. However, the knowledge acquired in recent decades, particularly on endocrine disruption, has made it possible to integrate new types of effects into the framework of regulatory assessment, such as transgenerational effects. Finally, the selectivity of the mode of action does not predict the indirect effects resulting from the weakening or elimination of the target population.

2.2 The importance of indirect effects

The most documented indirect effects are essentially exerted through:

- The reduction of food resources, in particular following the application of herbicides for granivores and phytophagous insects and following the application of insecticides or fungicides with insecticidal properties for insectivores.
- Habitat loss, in particular following the impact of the application of herbicides on vegetation.
- Variations in the intensity of predation or competition for food, following the negative impacts of PPP on certain populations.

For example, based on data collected in European rivers, recent work has highlighted the negative correlations between the toxicity of various identified contaminants (including PPP) on photosynthetic organisms and the diversity of invertebrates populating these environments.

However, the description of these indirect mechanisms is not exhaustive due to the difficulties posed by their dynamic nature as well as by the existence of other factors, known as confunding variable, which interfere in a context where different pressures are exerted. In addition, it should be noted that the indirect effects resulting from the loss of food resources and habitats in an agricultural plot following the use of a PPP could be generated by other control methods leading to the destruction of weeds, insect pests etc. Above all, it is the scope, intensity and repetition of interventions that determine the severity of these effects.

2.3 Multifactorial contexts

The pressure exerted by exposure to PPPs and other chemical substances combines in the environment with other sources of stress, the main ones being the destruction of habitats linked to agricultural intensification and urbanisation on the one hand and consequences related to climate change and invasive species on the other. The relative role of PPPs in the erosion of biodiversity is therefore difficult to establish in a multifactorial context combining several types of chemical (including substances other than PPPs), physical and biological pressures. The intensity of the impacts of PPPs on biodiversity is therefore partly dependent on the situation under consideration and the results are difficult to generalise. It is at a local scale that all the pressures accumulated over time and space result in changes in the balance of biotic interactions. These disturbances can in turn aggravate the initial effects of PPPs (intensification of predation and/or competition, increase in vulnerability etc.). The accumulation of these effects at the local scale has repercussions for biodiversity at larger scales (see Section 3).

With regards to climate change, studies conducted on various species have highlighted the variable influence of related different environmental parameters, such as temperature, salinity or pH, which affect the sensitivity of organisms to PPPs. However, few studies at this stage combine scenarios of exposure to PPPs with scenarios that integrate a set of parameters related to climate change (evolution of territorial production systems, distribution and phenology of species etc.).

The landscape can be studied as a factor likely to modulate the effects of PPPs on organisms. It affects habitats (including refuge areas), trophic resources and biotic interactions. However, the studies carried out on this subject, in particular on the basis of field observations combined with modelling, are still limited (see Section 5).

Faced with multifactorial pressures, some species react better than others, causing the balances within ecosystems to vary. The use of PPPs can therefore induce variations that are unfavourable to crop health when the dynamic favours pests over beneficials. The consideration of evolutionary dimensions has improved the consideration of the physiological or ecological costs of adaptation at the scale of individuals (*e.g.* reduced fitness), populations or communities (*e.g.* loss of biodiversity or inhibition of certain ecological processes), which can sometimes result in increased vulnerability to other pressures.

3 PPPs contribute to the decline of certain biological groups

Since the 2005 ESCo, the knowledge acquired has strengthened the causal link between PPPs use and the decline observed for several decades in invertebrate and bird populations, particularly in agricultural areas. PPPs are also strongly suspected of contributing to the broad decline in bat and amphibian populations. The consequences of the effects observed for other biological groups (microorganisms, plants and vertebrates other than those detailed in this section) are less clearly highlighted in the scientific literature.

3.1 Terrestrial and aquatic invertebrates

The decline in the abundance and diversity of terrestrial invertebrates linked to the use of PPPs is mainly found in agricultural areas. In terrestrial ecosystems, all taxa are affected, but Lepidoptera (butterflies), Hymenoptera (honeybees, bumblebees etc.) and beetles (ladybirds, carabids etc.) are the most affected. The literature contains many studies on pollinators, especially bees. The massive use of broad-spectrum insecticides induces a decrease in the abundance of invertebrates, including beneficials. In addition to these direct effects, there are indirect effects, mainly resulting from the impacts of herbicides on the diversity and biomass of plants and their consequences on the food and habitats of terrestrial invertebrates.

Marked effects of PPP on the biodiversity of macroinvertebrates inhabiting watercourses in agricultural areas have also been observed. On a European scale, it is estimated that contamination by PPP would induce losses of up to 40% within these populations.

The impacts on the diversity of terrestrial and aquatic invertebrates have mainly been documented for insecticides, with neonicotinoids and pyrethroids the families of molecules most involved among those studied.

3.2 Birds and bats

Birds

PPP have also been identified as one of the factors in the decline of the abundance and diversity of birds in agricultural areas, in combination with the simplification of landscapes. Depending on the bird species and their diet, this impact results mainly either from a direct effect (*e.g.* ingestion of PPP-treated seeds by seed-eating birds or the ingestion of contaminated bait by raptors), or from an indirect effect (*e.g.* reduction in food resources following the decline of prey or intoxication following the consumption of prey contaminated by certain PPP).

Environmental monitoring networks in various European countries, including France, have revealed numerous cases of birds being poisoned by PPP near agricultural systems. For seed-eating birds, the cases listed since the beginning of the 2000s are mainly caused by the ingestion of seeds treated with neonicotinoid insecticides (especially imidacloprid) and more rarely with other molecules such as fungicides (thiram).

For insectivorous birds, the impact of PPP is mainly indirect, through the decline in food resources. Several studies in Europe have demonstrated a relationship between the use of PPP and the concomitant decline of insect communities and bird populations. Beyond these correlations, the existence of effects via the consumption of contaminated prey has also been demonstrated in recent work, based on multi-residue analyses of the boluses of young birds in the nest. The preponderant role of neonicotinoids in the decline of certain populations has been highlighted on the basis of various works showing negative correlations between the abundance of these populations and data relating either to the use of neonicotinoids or to their concentration in surface water, while considering other factors associated with agricultural intensification (changes in land use and cultivated area, fertiliser use). Regarding these indirect effects, another insecticide, fipronil, is also strongly implicated.

In addition to the lethal effects of neonicotinoids, disruption of flight efficiency and sense of direction are sensitive and relevant symptoms of exposure and sub-lethal effects in migratory birds that use agricultural areas as staging posts. These sub-lethal effects could lead to reduced migration success.

Bats

With regard to bats, the literature generally suggests a negative impact of now banned but persistent PPP such as organochlorines (DDT and lindane), organophosphates/carbamates (such as chlorpyrifos) and pyrethroids (used both in agriculture and for wood treatments). These substances have been identified as being among the causes of the large declines observed since the middle of the 20th century in bat population dynamics and diversity. However, knowledge is currently too incomplete to be able to characterise the impacts of more recent and currently used substances on these dynamics.

The impacts described are either direct impacts during treatment or due to intoxication linked to the ingestion of contaminated items, or indirect impacts linked to the scarcity of food resources. Recent work also suggests that the alteration of bat movements by echolocation following their exposure to certain insecticides probably affects their movements and hunting activities. For example, impaired movement has been observed in the laboratory in a species of Asian bat (*Hipposideros terasensis*) following repeated exposure to imidacloprid. However, no published data were found to confirm in situ the consequences of such effects on wild bat populations.

3.3 Amphibians

Amphibians are one of the biological groups most affected by the massive reduction in biodiversity on a planetary scale. Various factors responsible for these declines have been identified, including habitat destruction, climate change, pathogens and the introduction of invasive species, alongside various pollutants (metals, nitrogen fertilisers etc.), including PPP. In particular, the decline in amphibian populations has been linked to the high prevalence of diseases, some of which could be favoured by exposure to PPP due to their direct toxic effects (immunotoxicity and endocrine disruption) and their indirect effects via the modification of pathogen and parasite dynamics and of their different vectors and hosts. Mortality episodes, developmental problems and reproductive failures following exposure to PPP have also been observed, including at low concentrations and for currently used substances.

However, the description of the mechanisms leading to the decline of amphibian populations due to the toxic effects of PPP remains difficult because of the complexity of the interacting processes. Characterising the exposure of amphibians also requires an understanding of both the phases of life in aquatic and terrestrial environments, and oral and dermal exposure routes.

Faced with the relatively limited use of laboratory testing because of the protected status of a large proportion of these species, the use of model species makes it possible to begin to understand their sensitivity to the toxicity of substances, and population models have been mentioned as an alternative, taking into account their ecological characteristics. However, such models require field data obtained in various situations, which still limits their use.

4 The effects of PPP have consequences on ecosystem functions and alter the ability of ecosystems to provide services

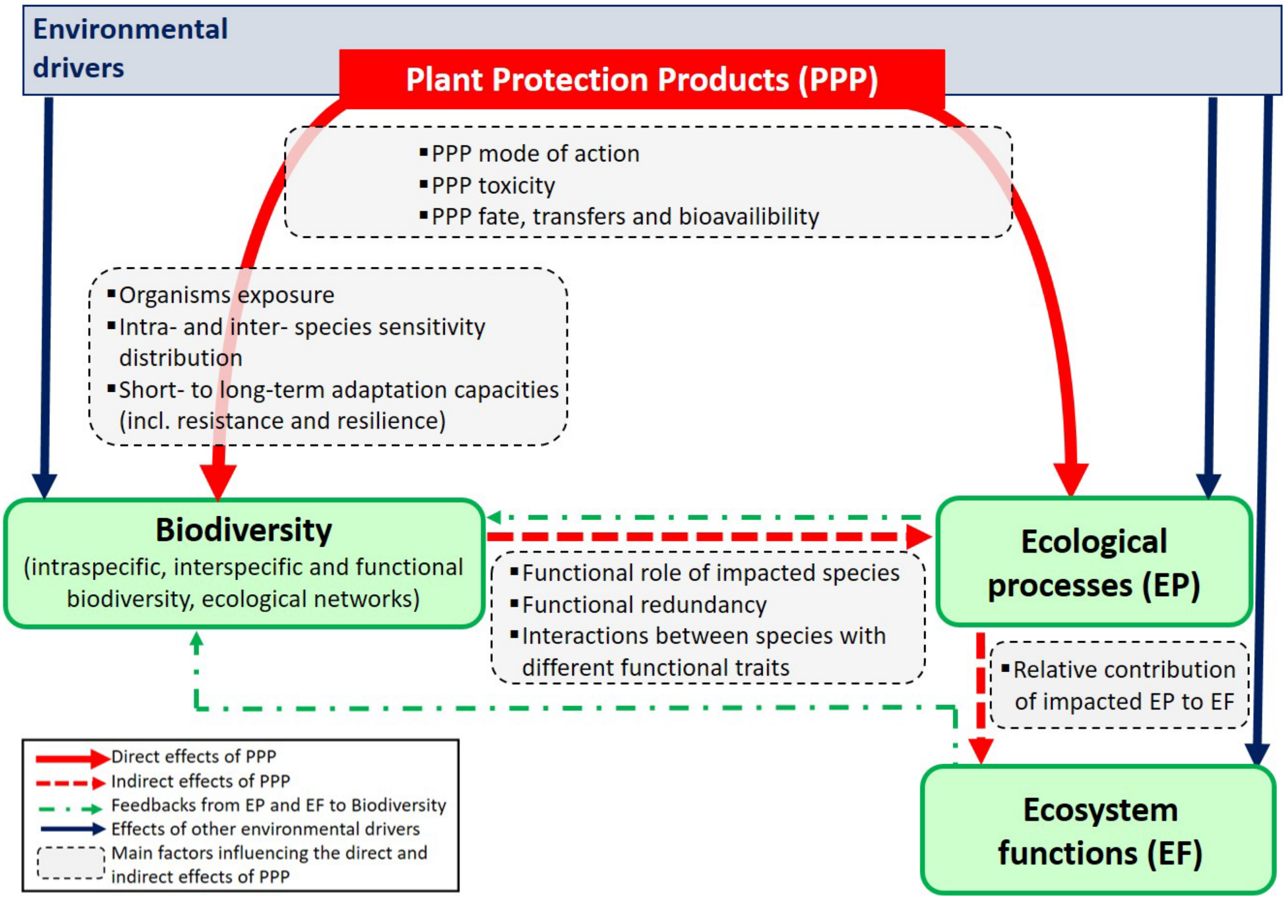
Ecosystem services are the socio-economic benefits derived by human populations and societies from their sustainable use of ecosystem functions (EFESE, 2016[1]). Different functions can contribute to the provision of an ecosystem service and one function can contribute to different services. Knowledge on the impacts of PPP on ecosystem services has been sought by bringing together the results obtained in the field of life sciences on the effects on ecosystem functions on the one hand and in the literature dealing with ecosystem services which, in addition to the life sciences, falls within the fields of research in the human and social sciences, on the other.

[1] EFESE (2016). L'essentiel du cadre conceptuel (The essence of the conceptual framework). Théma (https://www.ecologie.gouv.fr/sites/default/files/Th%C3%A9ma%20-%20Efese%20-%20L%E2%80%99essentiel%20du%20cadre%20conceptuel.pdf)

4.1 Impacts on ecosystem functions

Variations in populations and the physiological state or fitness of the individuals that compose them have repercussions on the ecological processes in which these populations are involved and on the ecosystem functions that these processes support. Figure 3 illustrates the theoretical relationship of the links between PPP use, biodiversity, ecological processes and ecosystem functions.

Figure 3. Conceptual representation of the possible effects of PPP on biodiversity, ecological processes and ecosystem functions through their interrelationships (adapted from Pesce et al., 2022[2]).



This representation highlights in particular the importance of the functional role of the species impacted by the effects of PPP, of the degree of functional redundancy, *i.e.* of substitutability between impacted and non-impacted species to fulfil the same function, as well as interactions between species. Ecosystem functions are based on balances, optimums and complementarities, more than on monotonic positive or negative relationships with the abundance of a given species or group. Nevertheless, specific richness is not enough to guarantee the functional resilience of an ecosystem, for example when certain functions are provided only by species that are impacted by the pressure exerted (absence of functional redundancy).

Moreover, due to their mode of action, PPP directly affect certain ecological processes, such as primary production affected by herbicides that inhibit the photosystem II (triazines or phenylureas). These targeted functional effects can strongly influence the relationships between biodiversity and ecosystem functioning through feedback mechanisms linking ecological processes and ecosystem functions with biodiversity. These feedbacks have received little attention and therefore remain relatively unknown.

The available knowledge makes it possible to highlight, in terrestrial and aquatic environments, the impact of different PPP on most categories of ecosystem functions as they were established in the initial framework of the ESCo and which are presented in Figure 4 (see next section). Those for which the effects are most firmly demonstrated (marked in bold) are the regulation of gaseous exchanges (F1), the dissipation of contaminants (F2), resistance to disturbances (F3), production of organic matter (F7), regulation of nutrient cycles (F8), dispersal of propagules (F10), provision and maintenance of biodiversity and biotic interactions (F11) and provision and maintenance of habitats and biotopes (F12) .

These functional impacts arise from effects on different biological groups. For example, variations in the populations of photosynthetic organisms and microorganisms will more particularly influence gaseous exchanges and the dissipation of contaminants. Plants are also linked to the production of organic matter and the maintenance of habitats. Effects on invertebrates have greater implications for propagule dispersal and biotic interactions, although the latter by definition encompass all biological groups.

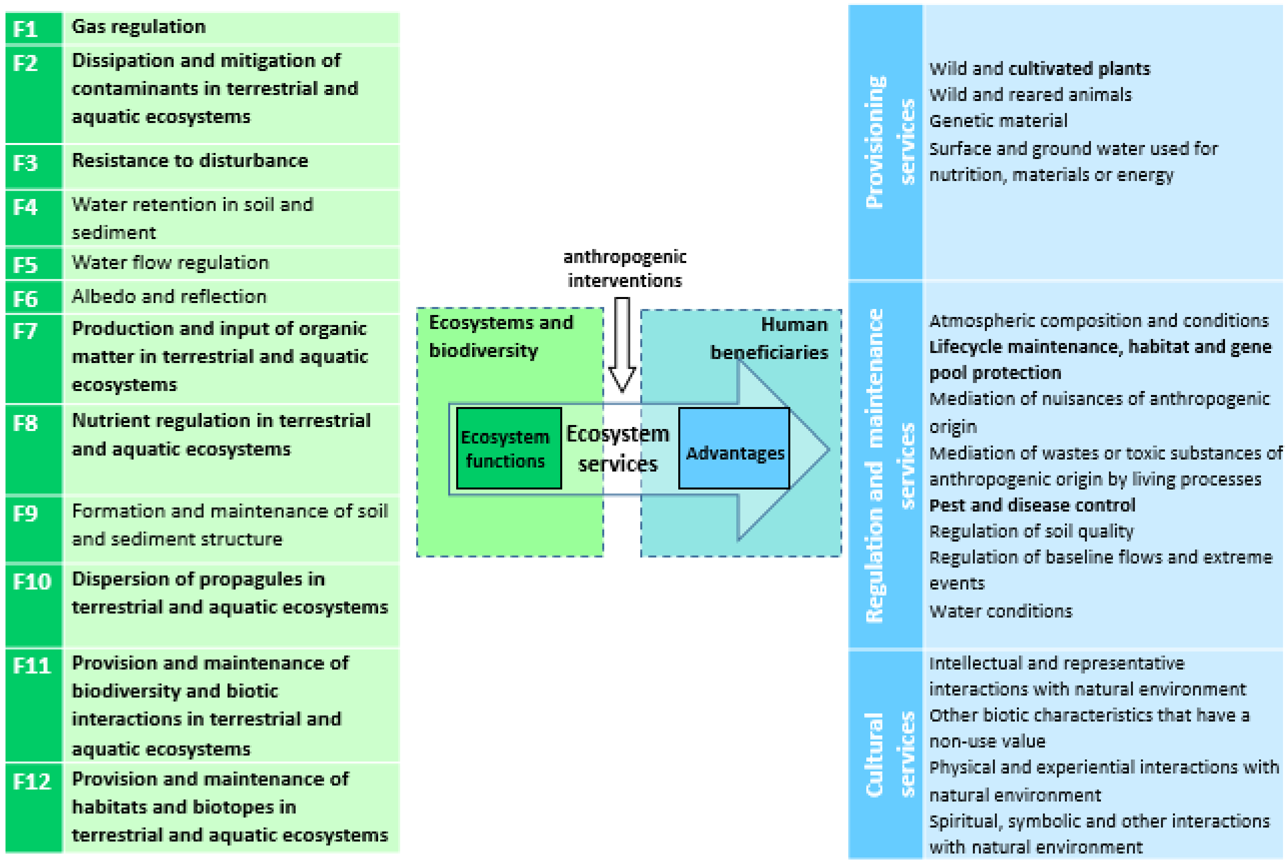
[2] Pesce S, Bérard A, Coutellec M-A, Hedde M, Langlais-Hesse A, Larras F, Leenhardt S, Mongruel R, Munaron D, Sabater, S, Gallai N, 2022. Linking the effects of plant protection products on biodiversity and ecological processes to potential impairment of ecosystem functions and services–A multidisciplinary conceptual framework. https://doi.org/10.32942/osf.io/46ab5

4.2 Impacts on ecosystem services

To bring together the results that document the impacts of PPP on ecosystem services, the classification established by CICES (*Common International Classification of Ecosystem Services*, version 5.1; Haines-Young and Potschin, 2018[3]) into three categories of services was used: supply, regulation and maintenance, and cultural services. The bibliography relating to ecosystem services is mainly positioned at a more global level than the analysis of the consequences specifically attributable to PPP and no study identified compares all of the ecosystem services delivered with and without PPP in the short or longer term. Work published on the subject over the past decade shows that the operational modalities for mobilising the concept of ecosystem services for the assessment of risks related to PPP have not yet been established.

The link between PPP and ecosystem services has only been studied for a few services. This results in very marked imbalances in terms of the knowledge available; it is clearly more developed for plant production, biological control and pollination. The soil quality regulation and maintenance service has received little attention. However, given the effects highlighted on certain functions provided by terrestrial microorganisms and invertebrates, which contribute in particular to the degradation of organic matter and soil structure, this service should be given more attention. Cultural services have also received little attention.

Figure 4. Links between functions and ecosystem services (in **bold**: functions and services documented in the bibliographic corpus in connection with PPP).Translated and adapted from EFESE 2016[1].



The work analysed highlights a tension between the production of cultivated plant biomass and other services. Indeed, the contribution of conventional PPP (excluding biocontrol) intervenes in the production process to eliminate a dis-service (*i.e.*, a disadvantage of biodiversity for humans), represented by the actions of pests. However, by replacing the ecosystem service of biological control, PPP also contribute to degrading it, as well as other regulatory services that depend on the activity of organisms. For example, insecticides favour cultivated plants by eliminating phytophagous pests, but they also affect the predators which provide biological control and the pollinators essential to fertilisation and therefore to the formation of fruits and grains for a large number of cultivated plants. The few studies dealing with the service of regulating and maintaining soil quality suggest the same negative impacts of PPP. The rare works conducted on cultural services call for better consideration of them. For example, economic losses are documented in connection with the degradation of water quality, having repercussions on tourism and recreational activities.

So, even if studies concerning the impacts of PPP on ecosystem services are small in number, their results suggest that PPP degrade the capacity of ecosystems to provide services.

[3] Haines-Young, R. and M.B. Potschin (2018). Common International Classification of Ecosystem Services (CICES) V5.1 and Guidance on the Application of the Revised Structure. (www.cices.eu)

5 Levers for action exist to partially limit contamination and the effects of using PPP

As indicated in the 2005 ESCo, the first lever for reducing contamination is the reduction in the quantity of PPP used, which is the subject of the work in progress mentioned in the introduction (ESCo on the natural regulation of pests, *Growing and protecting crops differently* Priority Research Programme). Downstream of PPP use, other levers for action make it possible to intervene in the transfer of PPP in the environment. These mainly consist of limiting PPP dispersion at the time of application and reducing transfers after application by developments at the plot and supra-plot scales (watershed). Research has intensified over the past 20 years to better understand transfer dynamics and to improve the effectiveness of mitigation measures by optimising various implementation parameters (sizing, positioning etc.). This work tends to underline the necessary combination of different complementary levers and the fact that no mitigation measure can completely neutralise the effects of PPP. The role of the more global characteristics of the landscape, not only on transfers but also on the vulnerability of organisms and the resilience capacity of ecosystems vis-à-vis PPP, is also increasingly being addressed.

At the plot scale

How PPP are applied is decisive in dictating transfers to the environment. Different elements need to be considered in a coherent way, integrating the type of formulation of the product used and the performance of the application equipment, as well as weather conditions, avoiding extreme temperatures, humidity and wind.

Soil management, one of the first filters to reduce PPP transfers, is an essential control lever. The parameters that play a major role are soil cover, organic matter content, structure and water content.

The remediation of environments contaminated by PPP has also been the subject of research but remains underdeveloped in the absence of regulatory obligations. Most experiments act on plant cover and on the inhibition/stimulation of microbial biodegradation capacities.

At the watershed scale

The measures that can be employed around plots to promote the interception and degradation of PPP are dry buffer zones (hedges, grass strips etc.) or wet ones (ponds, ditches, storm or drainage water collection basins etc.). Extensive field trials and modelling work have been jointly conducted to improve their effectiveness. This depends on the size of these facilities, but also relies heavily on their positioning in the geography of the catchment area. These parameters must therefore be considered together on a case-by-case basis.

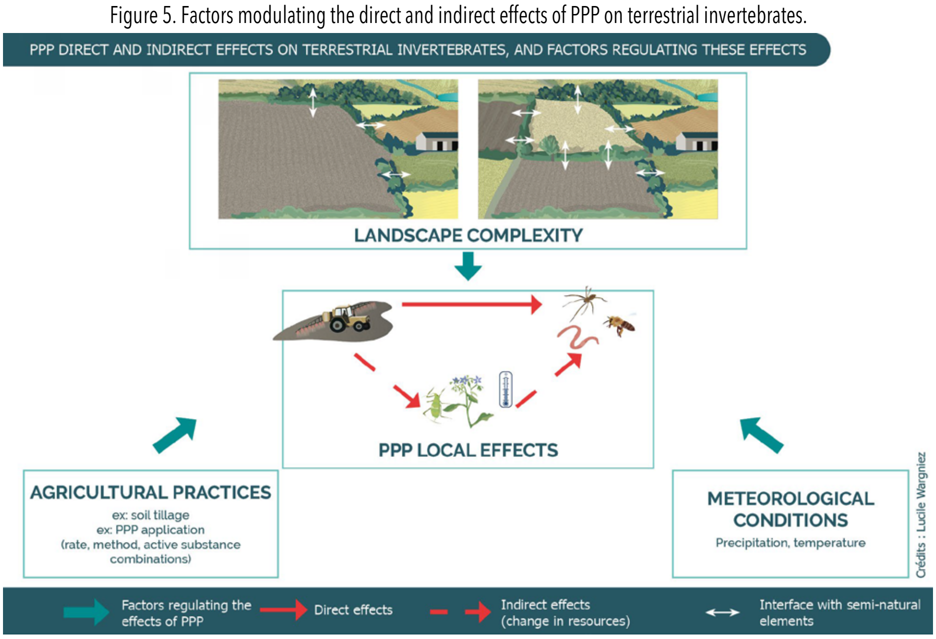
Landscape characteristics

In addition to their influence on PPP transfers, landscape characteristics are mentioned in many studies as a major factor in modulating PPP impacts on biodiversity, aggravating the situation in the case of simplified landscapes and mitigating it in the case of landscape mosaics multiplying the interfaces between treated and untreated areas, and ensuring the connectivity of refuge areas (Figure 5). The landscape therefore acts on both direct effects, limiting the exposure of organisms through the interception of molecules, and on indirect effects, preserving food resources and habitats.

This influence is highlighted in particular in modelling work that combines the dynamics of contamination and effects, integrating a typology of landscape characteristics to assess their modulating effects. But such approaches are still rather ad hoc and it is necessary to develop large-scale field observation systems.

In studies concerning non-agricultural areas (JEVI), the landscape and the dynamics of reducing PPP in these spaces interact at different levels. Greater acceptance of spontaneous vegetation has gradually been established in the urban landscape, whether in gardens or alongside roads, sometimes accompanied by a more global redesign of management methods and the use of these spaces. Biodiversity may have been the lever for this redesign, particularly with regard to the choice of species planted to ensure plant occupation of the land that is compatible with its use. For example, experiments have been initiated on the rail network to plant selected plant species along the lines in order to limit weed invasion of the tracks.

Figure 5. Factors modulating the direct and indirect effects of PPP on terrestrial invertebrates.



6 Regulatory PPP evaluation processes cannot cover all effects

The PPP regulatory framework seeks to avoid any use leading to unacceptable effects on the environment. With this in mind, in addition to the substances banned before 2005 (*e.g.* DDT, chlordecone and atrazine), a series of the most toxic substances have been withdrawn from the market over the past 15 years. However, although they are gradually being updated, the processes and guidance documents for risk assessments included in regulatory frameworks are based on methods (*e.g.* monospecific tests) which do not take sufficient account of the complexity of the effects of the most recent substances on the environment and living organisms, nor that of the economic and social issues related to the supervision of PPP use. Many articles deal with these limits and paths for improvements are sometimes suggested.

Paths for methodological improvements

Several suggestions concern the evaluation system as it currently stands, seeking to identify scientifically ways of improving the consideration of the impacts of PPP on biodiversity. Among these ideas, some concern the choice of species used for the tests. For example, recent work proposes relevant focal species better targeted for cereal crops (granivorous birds including grey partridges) by integrating agricultural practices (presence before or after sowing, for example). In addition, some proposals relate to experimental test protocols which could be adapted in terms of the biological and physiological traits of the species used, exposure routes and the duration and rate of exposure, in order to arrive at a more realistic evaluation. Regarding the establishment of causal links, AOP-type approaches (Adverse Outcome Pathway) are often mentioned to better link experimental data and field observations in response to exposure measured at different levels of biological organisation. At the landscape scale, some authors recommend that future risk assessments use multiple scenarios representative of a wide range of agricultural practices and pedoclimatic contexts.

Significant work has been developed in the field of modelling, in particular to predict transfer processes based on the physical-chemical characteristics of substances combined with scenarios integrating different types of crop, climate and soil. Developments have also been noted in the prediction of the effects of multiple stressors on bees, on the basis of scientific knowledge (ecology, demography, physiology and bee behaviour, and PPP toxicity), in interaction with an *in-situ* monitoring programme, and in the estimation of the effects of PPP mixtures. Modelling is repeatedly mentioned as a potential solution for integrating processes involved at different scales of space and time. The coupling of different models is often invoked, for example between ecotoxicological models, which describe the effects of PPP, and ecological models, which provide information on the interactions between organisms and on the functions in which they intervene. In particular, so-called spatially explicit models integrate the contamination of organisms, the toxicity of a PPP and its demographic effects, taking into account the variability of the landscape structure and that of exposure. However, modelling remains dependent on the collection of appropriate data and metadata (for the development of models and the testing of their performance), including large scales of space and time, which often represents a major obstacle to their development.

The employment of these approaches in regulatory processes requires implementation protocols and shared interpretation frameworks. Intermediate degrees of harmonisation could be considered, such as the recent possibility of pre-validating methods, like that offered by the PEPPER platform (public-private platform for the pre-validation of testing methods on endocrine disruptors) to trial relevant toxicology and ecotoxicology testing methods for characterising endocrine disrupting properties.

Biocontrol

Within the framework of this ESCo, biocontrol is understood in the sense of natural substances, organisms and semiochemicals used in the context of Integrated Pest Management. Natural substances, microorganisms and semiochemicals are subject to a pre-marketing assessment in the same way as other PPP, although some of them benefit from a simplified procedure. However, macroorganisms come under a specific regulatory framework, particularly with regard to the risk of introducing invasive species. In the field of biocontrol, the literature is mainly focused on the development of new solutions, *i.e.* on the intended effects (modes of action of existing and potential solutions, efficacy), with unintended effects rarely addressed. Very few studies concern the presence of biocontrol products in the environment and their impacts on biodiversity, except for the organisms that have been used the longest, and most often from the angle of their interactions with other biocontrol agents. The use of living organisms (micro- and macroorganisms) in biocontrol brings a specific dimension compared to conventional PPP because they can multiply, move and colonise other environments. For example, the escape of the harlequin ladybird (*Harmonia axyridis*) has led to a decline in the biodiversity of native ladybird species. Concerning natural substances, the few existing results indicate that while most of them have low ecotoxicity, others (abamectin and spinosad) have a toxicity equivalent to or greater than that of their synthetic counterparts. Knowledge of the unintended effects of biocontrol solutions has proved to be very incomplete in the bibliographic corpus analysed but remains necessary to ensure their sustainability.

Paths for regulatory improvements

Other work has demonstrated the role played by coalitions of actors (researchers, beekeepers, NGOs, politicians advocating environmental action and companies) in the production and mobilisation of research work for interventions in the regulatory arena and to develop the scope of knowledge considered in decisions concerning the status of substances. Some proposals consist of extending the sources of information considered in the assessment to types of actors and knowledge beyond that resulting from standardised protocols. We can find mentions of a broader consideration of the academic bibliography in the life sciences, including human and social sciences, on the one hand and the knowledge of use among PPP users and field observations on the other. These proposals raise the question of how we qualify such knowledge in order to delimit the scope of what must be taken into account.

It should be emphasised that published work on these issues largely predates the recent publication of the European Parliament and Council's EU Regulation 2019/1981 of 20 June 2019 on the transparency and sustainability of EU risk assessment in the food supply chain, the purpose of which is to overcome some of the limitations that have been highlighted.

For example, it provides for the publication of the scientific data included in the file of an application for authorisation, with the exception of data considered confidential, and the possibility for any actor (scientific community, NGO, citizen etc.) to conduct a parallel analysis of these data, which must be part of the dossier studied by the European Food Safety Authority (EFSA).

7 Perspectives and research needs

The analysis of research work conducted over the past two decades shows that there are still significant gaps in knowledge regarding the environmental contamination by PPP and its effect on biodiversity and ecosystem functions and services, whether in terms of types of PPP (biocontrol), products of transformation, types of organisms (amphibians, reptiles, less studied symbiotic organisms such as corals, mycorrhizae, lichens, microbiota etc.), types of environments and territories (marine, overseas etc.), or types of effects (sub-lethal, synergistic, cumulative etc.). Scientific approaches address increasingly diverse levels of organisation and interactions, but the proliferation of studies is generally reflected at this stage in great heterogeneity. It is therefore necessary to promote more integrated research strategies to consider the complex reality of PPP exposure and its effects. Sets of indicators should be combined to integrate the direct ecotoxicity of substances and their indirect effects, depending on the characteristics of the system considered (landscape, agroecosystem etc.). To this end, work based on different climate scenarios, different scenarios of space and use and the spatial heterogeneity of contamination or effects could be developed.

Assessing the effects of PPP on biodiversity and ecosystem functions and services therefore requires a paradigm shift in research practices. The definition of precise, cognitive objectives can be combined with the mobilisation and pooling of resources around these objectives and dedicated experiments, allowing different scientific communities to combine their specific contributions. If research networks, such as France's ECOTOX network, are a first step in this direction, it would be relevant to rely on instrumented study sites and/or long-term monitoring, such as certain sites associated with the LTER network (Long Term Ecological Research network) or certain French long-term observatory or experimental sites. The study of the impacts on living organisms of anthropogenic pressures and their consequences on ecosystem functions and services involves multidisciplinary approaches based on the cross-referencing of knowledge relating in particular to the functioning of living organisms, social functioning, associated economic issues, corresponding legal concepts, in order to consider action in terms of public policies. From this perspective, the literature review shows that the hybridisation between tools and concepts specific to each of the disciplinary fields dealing with the same objects appears clearly insufficient.

For more information

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