Spatial assessment of the impacts of pressures on biodiversity in the EU

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Spatial assessment of the impacts of human-induced pressures on biodiversity and ecosystem condition

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Cover photo: Common reed bunting by Lawrence Jones-Walters. Occurs in wetland habitats such as reedbeds, wet willow thickets and wet meadows. It is threatened by wetland drainage of wetlands in some parts of its range, but has also adapted to other habitats including cultivated areas and young conifer plantations, hedgerows and bushes

Executive summary

Context and methods

This report presents a spatially explicit **EU-wide taxonomic group assessment** of how biodiversity is expected to respond to current pressures in Europe. It aggregates the pressure effects on species to major taxonomic groups to detect broad signals of biodiversity responses to pressures in the EU. The rationale is that understanding differential taxonomic responses along spatial pressure intensity gradients can improve insights for policy and plans aimed at recovery of Europe's biodiversity. This assessment is intended to complement the first ever **EU-wide ecosystem assessment** provided by the Mapping and Assessment of Ecosystems and their Services, hereafter the 'MAES assessment'. The MAES assessment explores a set of pressure and condition indicators at an aggregated level of major ecosystem types using a common analytical framework. A key feature of the assessment presented here and the MAES assessment is that they both assess the entire terrestrial territory of the EU rather than focusing on a narrower set of individual habitats or species. The assessments can also both be repeated at regular intervals to inform EU-level policy and monitoring. At **Member State level**, the 'State of Nature in EU' provides a well-established reporting framework to assess the trends in pressures on a set of species and habitats listed in the EU nature directives[1]. The experimental methodology developed and tested in this report provides a broader, more **aggregated EU level** assessment of taxonomic group responses to pressures.

This spatial assessment was experimental, seeking to develop and test a methodology at EU aggregated level, which could then be applied for reporting the likely trends in biodiversity with changes to pressures. The conceptual logic was founded on the assumptions that (i) different species and habitats respond variably to specific pressures, and (ii) that overall pressure-response signals of taxonomic groups can be distinguished by aggregating pressure effects on species for that taxonomic group. There is widespread agreement on the former assumption. The latter assumption is supported by recent findings from the global and regional IPBES assessments[2] and numerous meta-analyses, which show that despite variability in the pressure-responses of species within a taxonomic group, broad differential signals can be distinguished. It was also supported by 'pressure factsheets' developed for this project, which synthesized evidence from over 300 EU cases studying species-pressure effects in the peer-reviewed literature. **The pressure factsheets culminated in an 'aggregated matrix' for each pressure, describing both taxon-specific and ecosystem-specific effects for the EU**, i.e. effect categories (strongly negative, negative, neutral, positive, variable) were assessed for every combination of taxonomic group and ecosystem type. The information contained in these pressure factsheets was used as a foundation for setting knowledge rules in this spatial assessment.

The methods section of this report targets a technical audience, describing the knowledge rules and data used to undertake the spatial assessment. We made use of a participatory GIS tool (QuickScan[3]) in which knowledge rules were set according to the aggregated matrices describing taxon-specific and ecosystem-specific pressure effects. QuickScan is well-suited to experimental approaches because once it is set up, the knowledge rules can be easily changed according to new evidence or refined with expert knowledge. Spatial maps of ecosystem types and pressure intensity

[1] Article 17 of the Habitats Directive (EU 1992) and Article 12 of the Birds Directive (EU 2009)
[2] Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES); https://www.ipbes.net/
[3] http://www.quickscan.pro/quickscan

gradients were loaded into QuickScan, and combined with risk matrices of the likely negative responses of taxonomic groups along pressure intensity gradients in each ecosystem type. This produced risk maps, per taxonomic group, of the likely negative response to each pressure. Pressure hotspots and coldspots for each taxonomic group were also mapped by combining the high risk and low risk areas of these maps. Taxonomic groups assessed included: amphibians, arthropods, birds, mammals, vascular plants, non-vascular plants and fungi. We were not able to assess molluscs and reptiles owing to severe knowledge gaps on pressure effects on the species of these taxonomic groups. Ecosystem types assessed included: croplands, grasslands, heathlands and shrubs, forests, sparsely vegetated habitats and wetlands. Although we assessed the risk responses to all these ecosystem types, the pressure intensity gradients were inadequately mapped across sparsely vegetated habitats and wetlands, and we were not able to consider these ecosystem types in the spatial outputs. Pressures assessed included: agricultural intensification, habitat loss and fragmentation, atmospheric nitrogen deposition and forest management intensity. To achieve alignment with the MAES assessment, we used the same spatial layers of ecosystem types and similar pressure gradients wherever possible.

Key findings

This spatial assessment demonstrates that it is feasible to regularly evaluate the expected effects of changing pressure gradients for many taxonomic groups and pressures at EU aggregated level. The peer-reviewed literature on species effects of pressures is fraught with variation, often resulting from lack of standard metrics for measuring species response, such as different species response metrics (e.g. species richness or diversity, community composition, measures of individual fitness) and different spatiotemporal considerations (e.g. patch vs. landscape vs. regional responses; short vs. long term responses). However, when aggregated to taxon-specific and ecosystem specific pressure effects at EU level, broad signals can be distinguished, and changes in these signals over time – as pressure gradients change – can help to track successes and failures at reducing pressures on biodiversity. The pressure factsheets capture the key species-specific variability at local context that is crucial for informing restoration at local to Member State level. The spatial assessment further shows that by aggregating this information to taxonomic groups and ecosystem types, we can gain a 'helicopter view' of what is happening by the EU aggregated level. Important next steps to leverage the potential of taking this methodology from experiment to application are needed – including **application in the MAES assessment framework, application in biodiversity accounting**, **input into the EU Taxonomy Regulation (EU 2020/852)**, and **informing the EU nature restoration plan**.

Overall, the pressure effects on taxonomic groups were negative, with a small set of taxonomic groups in specific ecosystem types showing strongly negative effects. The aggregated matrices developed to summarize pressure-responses from over 300 cases in the peer-reviewed literature showed that the expected effect of each pressure according to major taxonomic group and ecosystem type was negative overall. Some taxonomic groups or ecosystem types also showed **strongly negative effects to pressures, namely**:

- Agricultural intensification effects on arthropods, vascular plants, and non-vascular plants and fungi;
- Atmospheric nitrogen deposition effects on non-vascular plants of grasslands, heathlands and shrubs, and forests; and
- Forest management intensity effects on boreal forest arthropods and non-vascular plants.

A key conclusion of this report is that spatially-explicit assessment of pressure effects on taxonomic groups is crucial. Differential responses of taxonomic groups to pressures in different ecosystem types produce divergent spatial patterns of biodiversity risk. The differential responses combine with spatial pressure intensity gradients across the EU to produce different risk profiles for each taxonomic group. For example, the proportional area in the EU under risk of a very high to high negative effect from agricultural intensification for vascular plants, non-vascular plants and fungi, and arthropods is estimated to be 1.5 times that of other taxonomic groups. Likewise, under the current atmospheric nitrogen deposition on non-vascular plants and fungi is about 3 times higher than that of vascular plants under the current pressure intensity gradients.

Another key conclusion of this report is that taxonomic risk maps emphasize the need to focus restoration efforts on lower trophic levels first (i.e., non-vascular plants and fungi, vascular plants and arthropods). Taxonomic groups at lower trophic levels display consistently higher and more widespread risk responses to pressures compared to those of higher vertebrate groups. This indicates that it will be insufficient to recover biodiversity at lower trophic levels by targeting large, charismatic species at higher trophic levels. Biophysical alterations from degrading the lower trophic levels change ecosystem functioning through, for example, altering predator-prey relations, micro-climates, and nutrient cycling. These alterations can be long-lasting and have cascading impacts on higher taxonomic groups. Several examples of these cascading impacts at local level are made explicit in the pressure factsheets. For example, atmospheric nitrogen deposition can change mineral nutrient ratios in the soil through chemical interactions from acidification. These changes result in leaf nutrient imbalances, such as calcium deficiencies, which produces arthropod larvae with calcium deficiencies, which in turn is expressed in weakened eggs, bone and flight muscles in birds. **Changes to lower trophic levels therefore have early and long-lasting impacts that need to be restored to bend the curve for biodiversity** of higher taxonomic groups. Understanding these cascading impacts is crucial for restoration interventions at site level and they are generally poorly studied in the literature.

Pressure from agricultural intensification poses by far the most widespread and severe risk, with 40-65% of area for all taxonomic groups falling into a very high or high risk category. This proportion is highest for non-vascular plants and fungi, vascular plants, and arthropods and lowest for birds and mammals, with amphibians representing a proportion between these two extremes. While the MAES assessment found that loss of habitat from outright land conversion is largely stable at EU level, the level of **habitat fragmentation** remains highly undesirable, and taxonomic group risk this pressure therefore poses the next most widespread and severe pressure, with approximately 30% of area for all taxonomic groups falling into a very high or high risk category. Active regeneration of landscape connectivity is needed to restore landscape heterogeneity and bend the curve for biodiversity. Restoring field margins, hedges, grass strips, lines of trees, patches of uncultivated land in agro-ecosystems, and green infrastructure to urban ecosystems is a matter of urgency as the EU embarks on its recovery program in terms of the EU Biodiversity Strategy 2030. Pressures from **forest management intensity** posing a very high or high risk to taxonomic groups affect 20-25% of the range in the EU. These pressures are especially widespread and high in Boreal forests, and more dispersed across the remaining forests of the EU. Pressure from **atmospheric nitrogen deposition** is decreasing in the EU, and poses very high to high risk to 5-15% of taxonomic group ranges. Non-vascular plants and fungi are most affected and attention should be given to restoring this taxonomic group, to have cascading positive effects upwards to higher trophic levels.

Broad signals of pressure hotspots and coldspots cluster interventions in the landscape into three broad opportunities for action. Pressure coldspots can be viewed as refugia for species from pressures, and should be seen as focus areas for protected area expansion – either through conventional protected areas or through land stewardship agreements. Emphasizing pressure coldspots shifts policy emphasis away from the most pressurized sites, to focus on avoiding new pressure sources in pressure refugia. There is a strong rationale for this. First, evidence suggests that species loss at early stages of pressure is more pronounced, and so prevention or early action is the best means of protection. Second, adopting a conservative approach in pressure refugia first seems logical because there is a high uncertainty in setting 'one-size-fits-all' mitigation thresholds that avoid negative impacts of pressures. Third, there are fewer remediation costs in low pressure sites**.** **Pressure hotspots** can be viewed as land use mitigation areas, where risk from multiple pressures is very high or high, and sector-specific interventions at local and Member State level are needed to manage these areas more sustainably (e.g. sustainable agricultural and forestry management practices, sustainable cities, circularity at all scales). The most feasible biodiversity gains for restoration are likely to be had in the **pressure coldspot and moderate areas**. These areas offer ideal opportunities for establishing ecological corridors or stepping stones that improve the connectivity of landscape and coherence of the protected area network. Ideally, green infrastructure and ecosystem corridors that are restored in the landscape should attempt to connect coldspot refugia through avoiding as many hotspot areas as possible. Importantly **the pressure hotspot-coldspot maps do not yet include pressures from climate change and invasive alien species**. These pressures are increasing and are viewed as major amplifiers to co-occurring pressures. It is imperative that refugia from pressures of climate change and invasive alien species are thus included in future iterations of pressure hotspot-coldspot maps.

Spatial signals of pressure hotspots and coldspots confirm the overall patterns of threatened species (species hotspots). There are **two broad regions of pressure coldspots** where further protection is particularly warranted: (i) the pressure coldspots in the Mediterranean are especially important because the region has relatively high endemicity for many taxonomic groups compared to other parts of Europe; and (ii) the slither of central Europe just east of the Benelux region provides an arc of coldspots interspersed with hotspot/coldspot areas. Biodiversity representative of this region is under severe threat from multiple pressures and immediate action is needed for land stewardship and restoration. There are **four key pressure hotspots** evident at the European aggregated level, where multiple pressures pose very high or high risk on species: Po river basin; Benelux region; southeastern United Kingdom (UK; including the East and West midlands, Eastern England and Yorkshire); and the southern tip of the Iberian peninsula. The three pressure hotspots at EU aggregated level are already well-know. However, the methodology presented here allows regular repetition to quantitatively track how pressure hotspots and coldspots may progress as pressure gradients change. This can help to detect broad signals where increased risk to pressure coldspots may be further jeopardizing biodiversity, or where concerted efforts have managed to reduce pressure hotpots.

Pressure hotspots for taxonomic groups show that croplands and grasslands are the ecosystem types facing the highest risks from multiple pressures. This is followed by forests and heathlands and shrubs. Across biogeographic regions, taxonomic groups facing highest through to lowest proportion of pressure hotspots include: Atlantic, Continental, Mediterranean, Pannonian, Boreal and finally Alpine. The threat to biodiversity posed by multiple interacting pressures is well-known in the Atlantic and Continental, and there has been concerted effort to reduce pressures in these areas. However, **these reductions are still insufficient to bend the curve for most taxonomic groups that still remain with a high proportion of area in pressure hotspots**. The pressure hotspots of the Mediterranean biogeographic region are particularly concerning. First, the region has high species endemicity, thus implying high risk of global biodiversity extinctions should pressure trends continue. Second, the pressures from climate change and invasive alien species are expected to be particularly high in this biogeographic region and will act to amplify the interaction of multiple pressures in pressure hotspots.

There are still important knowledge gaps that constrain this assessment for some taxonomic groups, ecosystem types and pressures. Pressure effects of agricultural intensification, habitat loss and fragmentation, atmospheric nitrogen deposition and forest management intensity can be examined for all taxonomic groups except molluscs and reptiles. We **were constrained by severe knowledge gaps in the literature on how molluscs and reptiles** respond to pressures. Knowledge of pressure effects on mammals and amphibians is also limited. While it was feasible to assess the four pressures we considered here using this methodology, different aggregated approaches to exploring other pressures may be needed. For example, **pressures from invasive alien species and climate change** may require a less aggregated assessment, as these pressures require consideration of strong local context specificity (e.g. micro-climate and species interactions for climate change, recipient community interactions with invasive species). Integration of these pressure effects into the hotspot-coldspot maps developed for each taxonomic group is especially important because pressures from **climate change and invasive alien species are both increasing and act as major risk amplifiers when interacting with other pressures**. The use of the QuickScan tool allows for flexibility to include new information, should data become available through peer-reviewed literature or expert consensus (see next steps, section 5.3).

Next steps

We recommend that an iterative review process be adopted with various EU stakeholders to leverage the potential of taking this methodology from experiment to application. There are many application opportunities, which include:

- **Enhancing the species dimension of the MAES assessment framework** by including the taxon-specific risk per ecosystem type. Both assessments provide the possibility for monitoring and reporting on EUs progress towards bending the curve for biodiversity.
- **Testing the application of this approach in biodiversity accounting** in terms of the United Nation's System of Environmental Economic Accounting (SEEA).
- **Input into the EU Taxonomy Regulation (EU 2020/852)** in terms defining minimum criteria at aggregated taxon-specific and ecosystem-specific level that ensure that species composition, ecosystem structure and ecological functions are not impaired.
- **Informing the EU nature restoration plan in terms of its new 2030 Biodiversity Strategy**. Two specific applications are possible. First maps of pressure hotspots and coldspots can inform the building of a coherent Trans-European Nature Network through connecting pressure coldspots (refugia) by avoiding pressure hotspots where possible. The narrative storylines in section 4.5 provide local examples of the ways in which these maps can be used as a starting point for contextualizing with local knowledge. Second, it can facilitate repeated assessment to track how the EU progresses in its pressure reductions on taxonomic groups.

Targeting stakeholders involved in these applications would be a good point of departure. These stakeholders can be mobilised through the emerging communities of practice associated with the MAES assessment, the EU networks involved in the IPBES Regional Assessment, and the EU networks involved in the global process of experimental ecosystem accounting (SEEA-EEA). Importantly, the approach to the spatial assessment used a participatory GIS tool (QuickScan) to set up the knowledge rules and generate the maps outlined in this report. This tool can be used in collaborative workshops with experts and local stakeholders to incorporate the rich local knowledge at Member State level.

Contents

Figures

1. Introduction

1.1. Purpose of this report

The European Union (EU) has recently outlined its new Biodiversity Strategy for 2030 to set Europe's biodiversity on a path to recovery with benefits for people, the climate and the planet. This ambition will in part depend on reducing the myriad of pressures that currently threaten biodiversity in Europe. The intensities of many pressures impacting biodiversity have been mapped and monitored at various levels of resolution in Europe, with a view informing biodiversity policy and management. However, different species and habitats respond variably to specific pressure gradients across Europe, and understanding these differential responses can improve the insights for policy and plans aimed at recovery of Europe's biodiversity.

This report provides a spatial assessment of how major taxonomic groups are expected to respond to current pressure intensity gradients across different ecosystem types in Europe. The aggregation of pressure effects to major taxonomic groups and ecosystem types lends itself to EU-level policy and planning, in that it detects broad signals of how biodiversity is likely to be affected by prevailing pressures across Europe.

The spatial assessment presented here builds on a synthesis of the scientific evidence on the links between key pressures, species and ecological functioning for different ecosystem types in the EU. This synthesis produced a series of '**pressure factsheets**', one for each pressure, describing the main findings and presenting an aggregated matrix to summarize the expected effect of that pressure on each taxonomic group per ecosystem type (Nel et al. 2020). The factsheet information was then used as a basis for this spatial assessment, linking the evidence on pressure effects on taxonomic groups to spatial maps of ecosystem types and pressure intensity gradients across Europe, and thus producing maps of likely responses of different taxonomic groups to pressures. The pressure factsheets are provided as a supporting document to this spatial assessment.

1.2. Context in relation to other recent EU-wide nature assessments

The EU and its Member States recently launched its first ever EU-wide ecosystem assessment for Mapping and Assessment of Ecosystems and their Services – called the *MAES assessment* (Maes et al. 2020). The MAES assessment explores a set of pressure and condition indicators for major ecosystem types at EU aggregated level using a common analytical framework (Maes et al. 2018). By so doing it addresses how ecosystems have changed over the last decades in response to pressures and how these changes may have impacted people through altering ecosystem services. The MAES assessment 2020 provides a knowledge base at ecosystem level to support the final evaluation of targets in the EU Biodiversity Strategy 2020. A key feature is its ecosystem-level focus. This facilitates broadening the scope of EU's nature assessments to beyond protected areas, to cover the entire terrestrial and marine territory of the EU.

The work reported here is intended to complement the MAES ecosystem assessment by considering the species dimensions at EU aggregated level. It does this by mapping and assessing how major taxonomic groups are expected to respond to pressure intensity gradients across the different MAES ecosystem types in Europe. This aggregated form of species assessment also provides complementary information to other recent species-level assessments in Europe – the *State of Nature in the EU* report (Naumann et L. 2020; hereafter the 'State of Nature report') and the

Regional Assessment Report on Biodiversity and Ecosystem Services for Europe and Central Asia (IPBES 2018; hereafter 'IPBES Regional Assessment').

Every six years, the State of Nature report synthesizes data reported by Member States on the state and trends in pressures and their effects on targeted species and habitats listed in the EU nature directives[4]. The spatial assessment we apply here differs from the State of Nature in both scope and detail. It is broader in scope because it moves beyond just the species and habitats listed in the nature directives to spatially assess how major taxonomic groups across the EU are likely to respond to varying pressure intensities prevalent in different ecosystem types. However, it is less detailed because it generalizes pressure effects on species and habitat to overall responses of major taxonomic groups per ecosystem type. While the State of Nature can inform specific actions at Member State level, the form of EU aggregated assessment presented here is better suited to informing broader regional policy, such as EU policy options for restoring Europe's ecosystems. Nevertheless, we were able to leverage complementarities between this assessment and the State of Nature reporting through aggregated assessment of the most commonly-cited pressures by Member States for each taxonomic group in each MAES ecosystem type. This information is documented in Nel et al. (2020).

The spatial assessment presented here also differs to the IPBES Regional Assessment (IPBES 2018). Chapter 3 of the IPBES Regional Assessment assessed the impact of selected pressures on taxonomic groups – attributing a low, moderate or high impact. However, taxonomic group impacts were non-spatial, and presented across broad regions only (Western Europe, Central Europe, Eastern Europe and Central Asia), i.e. taxonomic group impacts to pressures could not be disaggregated per ecosystem type. However, we were able to leverage three important features in the IPBES Regional Assessment. First, we applied a similar certainty framework in assessing confidence limits of the taxonomic group responses to pressures across different ecosystem types. Second, we used the overall findings on pressure impacts per taxonomic group at EU level as a cross-check to our results. Finally, we used the IPBES Regional Assessment findings on the effects of atmospheric nitrogen deposition on mammals to fill a knowledge gap, as we were reluctant to exclude mammals because of limited data for this pressure.

1.3. Structure of this report

Chapter 2 of this report provides a high-level summary of the pressure factsheets, which summarized the peer-reviewed evidence on the pressure effects on species and ecological functions (Nel et al. 2020). It presents the overall findings across the pressure factsheets, focusing mainly on the aggregated matrices that were developed to summarize the expected pressure effects per taxonomic group and ecosystem type. **Chapter 3** outlines the methods used to undertake the spatial assessment and is intended for a technical audience. It provides a rationale for the pressures selected in the spatial assessment, describes how the evidence from the pressure factsheets was linked to pressure intensity gradients, and thus how differential taxonomic responses along pressure gradients in the EU were assessed. **Chapter 4** presents the results and discussion of this spatial assessment and targets both a technical and policy audience. It explores similarities and differences in taxonomic group responses to pressure gradients, and highlights pressure hotspots and coldspots in the EU. Illustrative examples of regional application are explored by selecting different signals

[4] Article 17 of the Habitats Directive (EU 1992) and Article 12 of the Birds Directive (EU 2009)

from the spatial outputs, which emphasize different types of landscape intervention opportunities. **Chapter 5** concludes with key findings, reflecting on knowledge gaps and next steps for regional application.

2. Summary of pressure factsheets: pressure effects on species and ecological functions

This chapter is intended as a high-level summary of the scientific evidence base on the links between key pressures, species, ecological functioning and ecosystem condition collated in the pressure factsheets (Nel et al. 2020). Here we focus mainly on the aggregated matrices that were developed to summarize the taxon-specific and ecosystem-specific effects of each pressure, because these formed a basis for this assessment. We start with an overview of the methods used to construct the aggregate matrix for each pressure. This is followed by a section that discusses some overall insights that can be gained from the aggregated matrix. Finally, we highlight some of the main common findings across all pressures. In addition to the information summarized in this chapter, we drew on specific reviews and meta-analyses to further differentiate taxonomic group responses along pressure intensity gradients. These are explained in section 3.1 when describing the knowledge rules for developing risk matrices of the likely negative responses of taxonomic groups across pressure intensity gradients for different ecosystem types.

2.1. Summary of methods used to synthesize evidence into an aggregated matrix

We synthesized the peer-reviewed literature for five key pressures on biodiversity: agricultural intensification, habitat loss and fragmentation, atmospheric nitrogen deposition, forest management intensification, and invasive alien species. These pressures were selected based on two main criteria: (i) those pressures assessed as part of the MAES assessments (MAES et al. 2018); and (ii) an assessment of the most commonly-cited pressures listed by Member States in their reporting on the state and trends of species and habitats as outlined in Nel et al. (2020). In addition, findings on wetland-related pressures and those from climate change were given explicit consideration in the literature searches as these pressures are increasingly an issue and frequently overlooked.

The synthesis of evidence included almost 300 publications (mainly in the 2010-2020 decade), comprising roughly 40-65 publications per pressure. Over 300 cases were extracted from these publications. For each pressure, cases were coded according to:

- **Eight taxonomic groups**: amphibians, arthropods, birds, mammals, molluscs, reptiles, vascular plants and non-vascular plants and fungi.
- **Six ecosystem types**: corresponding to MAES cropland, forests, grassland, heathlands and shrubs, sparsely vegetated lands, and wetlands. We did not examine pressures in the remaining MAES ecosystem types, i.e. urban ecosystems, rivers and lakes, and marine ecosystems.
- **Pressure effect on at least one metric of biodiversity**: including individual growth or reproduction, population abundance, community composition, species richness or diversity, or ecosystem process (e.g. nutrient cycling). Effects were broadly described as strongly negative, negative, neutral, positive or variable.

This information was used to construct an aggregated matrix that summarized the expected effect of each pressure according to major taxonomic group and ecosystem type (Figure 1). Confidence limits were assigned using the IPBES (2018) certainty framework, such that: **Well established** was assigned to instances where the impact included a meta-analysis, review/synthesis or at least two consistent cases; **Established but incomplete** included at least two consistent cases; **Unresolved** had at least two cases, but no consistent agreement among these; **Inconclusive** had one case only.

NITROGEN DEPOSITION (n=70)

	Croplands	Grasslands	Heathlands and shrubs	Sparsely vegetated	Wetlands	Forests	Overall effect: taxon
Amphibians					EI		EI
Arthropods	WE	WE	EI	EI		WE	EI
Birds				EI		EI	EI
Mammals							
Reptiles							
Molluscs						EI	EI
Non-vascular plants & Fungi	WE	WE	WE	EI	EI	WE	WE
Vascular plants	WE	WE	WE	WE	WE	WE	WE
Overall effect: ecosystem	EI	EI	WE	EI	WE	EI	

HABITAT FRAGMENTATION (n=94)

	Croplands	Grasslands	Heathlands and shrubs	Sparsely vegetated	Wetlands	Forests	Overall effect: taxon
Amphibians					IC	EI	UR
Arthropods	UR	UR	UR	EI	UR	UR	UR
Birds	UR	UR	IC			UR	UR
Mammals	UR	UR	IC			UR	UR
Reptiles						WE	IC
Molluscs						EI	IC
Non-vascular plants & Fungi	IC	IC	IC			WE	EI
Vascular plants	WE	WE	IC		IC	UR	UR
Overall effect: ecosystem	UR	UR	EI	IC	UR	WE	

Impact:
- Strongly negative
- Negative
- Neutral
- Variable
- No data

Confidence level:
- WE = Well established
- EI = Established but incomplete
- UR = Unresolved
- IC = Inconclusive

INVASIVE ALIEN SPECIES (n= 56)

	Croplands	Grasslands	Heathlands and shrubs	Sparsely vegetated	Wetlands	Forests	Overall effect: taxon
Amphibians							
Arthropods	IC	IC				WE	EI
Birds	WE	WE	EI	EI		WE	WE
Mammals	WE	WE	WE	WE	EI	WE	WE
Reptiles							
Molluscs					IC		IC
Non-vascular plants & Fungi						IC	IC
Vascular plants	WE	WE	WE	WE	WE	WE	WE
Overall effect: ecosystem	WE	WE	WE	WE	EI	WE	

FOREST LOGGING AND REMOVAL OF DEADWOOD (n=77)

	Boreal forest	Temperate forest	Mediterranean forest	Alpine forest	Overall effect: taxon
Amphibians					
Arthropods	WE	WE		WE	WE
Birds	UR	UR	UR	UR	UR
Mammals	EI	UR	IC	IC	UR
Reptiles					
Molluscs					
Non-vascular plants & Fungi	WE	WE		IC	EI
Vascular plants	UR	UR			UR
Overall effect: ecosystem	WE	WE	IC	UR	

AGRICULTURAL INTENSIFICATION (n=17)

	Croplands	Grasslands
Amphibians		
Arthropods	WE	WE
Birds	WE	WE
Mammals	EI	EI
Reptiles		
Molluscs		
Non-vascular plants & Fungi	WE	WE
Vascular plants	WE	WE
Overall effect: ecosystem	WE	WE

Figure 1: Synthesis of case evidence effects of nitrogen deposition, habitat fragmentation, invasive alien species and unmanaged forest logging and removal of deadwood

Numbers in brackets represent the numbers of cases per pressure

2.2. Aggregated matrix of pressure effects on taxonomic groups and ecosystem types

The information in Figure 1 highlights the following overall findings:

While there is variation in the biodiversity response for different taxonomic groups, the overall effect of every pressure examined at ecosystem type level is negative (Established but incomplete). The biodiversity response to agricultural intensification, habitat fragmentation, atmospheric nitrogen deposition, forest management intensity and invasive alien species is negative (Figure 1), despite some variation across taxonomic groups and ecosystem types (Figure 1). Even the pressures that show more variable biodiversity responses (habitat fragmentation and forest management intensity; Figure 1) are overall negative.

Pressures from atmospheric nitrogen deposition impacts on grasslands and forest management intensity in boreal forests show the strongest negative effects of all pressures examined (Established but incomplete). The strong negative response of atmospheric nitrogen deposition on grasslands is mainly a result of strongly negative impacts on vascular plants, non-vascular plants and fungi. The strong negative effect of forest management intensity in Boreal forests is mainly a result of strongly negative biodiversity responses from saproxylic arthropods, non-vascular plants (mainly mosses) and fungi.

Several knowledge gaps were prevalent (grey shaded cells in Figure 1), despite doing numerous literature searches using different terms in an attempt to fill these gaps. Indeed, we excluded further spatial assessment for reptiles and molluscs taxonomic groups because of the extensive knowledge gaps in the literature. There were also extensive knowledge gaps on the response of mammals to atmospheric nitrogen deposition, and amphibians to agricultural intensification. However, we were able to fill this gap using results from the IPBES regional assessment (IPBES 2018). Further refinements should be made by leveraging the rich local knowledge at Member State level (see next steps, section 5.3).

2.3. Synthesis of common findings across all pressures

In addition to the findings provided by the highly aggregated matrix, there were findings common across all pressures that are pertinent at the EU level. For further details see the pressure factsheets collated in Nel et al. (2020).

Increasing levels of pressure cause an overall decrease of species richness across all pressures studied (Well established). Meta-analyses show resoundingly that overall species richness declines result from intensifying any of the pressures examined, and that these declines are accompanied by higher overall declines in population abundance and alterations to species composition. This overall decline is in spite of some pressure-tolerant species that may benefit from the pressures.

Climate change is a major amplifier of all examined pressures (Well established). Nitrogen deposition is strongly moderated by warmer climate and growth days and its effects are exacerbated under climate change. The rate of climate change exceeds the migration capacity of forest plants and this is exacerbated by fragmentation. Some of Europe's worst existing invaders are expected to shift their ranges under climate and land use change. There are also strong synergistic interactions between multiple pressures, which can further exacerbate negative impacts on biodiversity.

Species richness underestimates pressure effects at landscape scale (Well established). Simply counting the number of species in a patch or landscape can mask the differential responses of species, which can drastically alter community composition and ecosystem functioning. Changes in population abundance and community composition appear to be more sensitive metrics of biodiversity effects. A selection of more appropriate metrics are included in the individual pressure factsheets, that better account for impacts at different organizational levels (e.g. individuals, populations, communities, and ecosystem functions) and at different levels of diversity (e.g. genetic, functional, and taxonomic diversity).

By the time pressure effects on above-ground species are evident, ecosystem functioning is often already impaired (Established but incomplete). This is particularly the case for below-ground ecosystem functions, such as water and nutrient cycling. This can be driven by abiotic processes (e.g. leaching of soil minerals or altered micro-climates) or biotic processes (e.g. decline of root-inhabiting mycorrhizal fungi). This can have strong implications for the delivery of ecosystem services.

Equal emphasis should be placed on pressure hotspots and coldspots ('refugia') (Well established). Species loss following a pressure is often highest in the early stages, and then the ecosystem stabilizes to a more pressure-tolerant species assemblage. This supports the need for early action to prevent and reduce pressures. It also indicates that a more balanced management emphasis be taken, which emphasizes regions undisturbed by pressure as much as regions associated with high pressure.

Differential responses of habitat specialists and generalists are highlighted across all pressures (Well established). Habitat specialists are more negatively impacted. This supports the need for a two-pronged view to nature conservation. Firstly, conventional nature protection is needed to support the conservation of habitat specialists (large core habitats with enough available resources and no edge effects). Secondly, a more nature-inclusive policy is needed to support ecosystem services and more generalist species, sustainable development, limiting of edge effects.

Recovery of biodiversity can be slow and management interventions should be informed by local ecological expertise (Established but incomplete). For example, reinforcing feedbacks occur in ecosystems from long-term exposure to excess nitrogen, such as shading, litter accumulation, production of chemicals which inhibit competitor growth, and loss of symbiotic mycorrhizal fungi. Recovery is often not only about removing nitrogen, but also restoring soil microbiota and chemistry (e.g. ratios of N:P or C:N, levels of K+, Ca2+, Mg2+ and Al). In terms of habitat fragmentation, maintaining natural or semi-natural patches of vegetation in the landscape mosaic is a more effective measure of improving landscape connectivity than constructing artificial corridors. Control of invasive alien species can lead to secondary invasions from the rapid replacement of the removed alien species by other invaders that make use of the disturbance caused by the control operations or the altered resources (e.g. sunlight).

3. Methods

We used a spatial analytical tool, QuickScan[5], to assess the spatial patterns of different taxonomic responses to pressure gradients across the EU's ecosystem types. QuickScan is a participatory and spatially explicit tool, to jointly scope policy problems with expert scientists and stakeholders, investigate the most important drivers, interactions and outcomes, and assess the state of knowledge and data of relevance to the problem (Verweij et al. in review). The workflow for QuickScan steps is shown in Figure 2. Spatial maps of ecosystem types and pressures were combined with risk matrices of the likely negative responses of taxonomic groups along pressure intensity gradients in each ecosystem type. Like the aggregated matrices, the risk matrices were taxon specific and ecosystem-specific, but they also were intensity-specific, describing risk categories (very high, high, medium, low) according to every combination of pressure intensity category, taxonomic group and ecosystem type. This produced risk maps, per taxonomic group, of the likely negative response to each pressure. The high risk and low risk areas of these maps were then combined to produce pressure hotspots and coldspots for each taxonomic group in the EU. The sections below explain these methods in more detail.

3.1. Risk matrices of the likely negative response of taxonomic groups to selected pressure intensities

Risk matrices were developed for four of the pressures for which we had synthesized peer-reviewed literature (Figure 1): agricultural intensification, habitat loss and fragmentation, atmospheric nitrogen deposition, and forest management intensification. The risk matrices reflect the likelihood of a negative effect of a pressure on a taxonomic group per ecosystem type, which is categorized as a very high (VH), high (H), medium (M) or low (L) risk of a negative effect. Risk matrices were compiled for six of the eight taxonomic groups considered: amphibians, arthropods, birds, mammals, vascular plants and non-vascular plants. We were unable to compile risk matrices for molluscs and reptiles because the knowledge gaps (grey cells of Figure 1) were considered too limiting to rigorously infer risk responses.

[5] http://www.quickscan.pro/quickscan

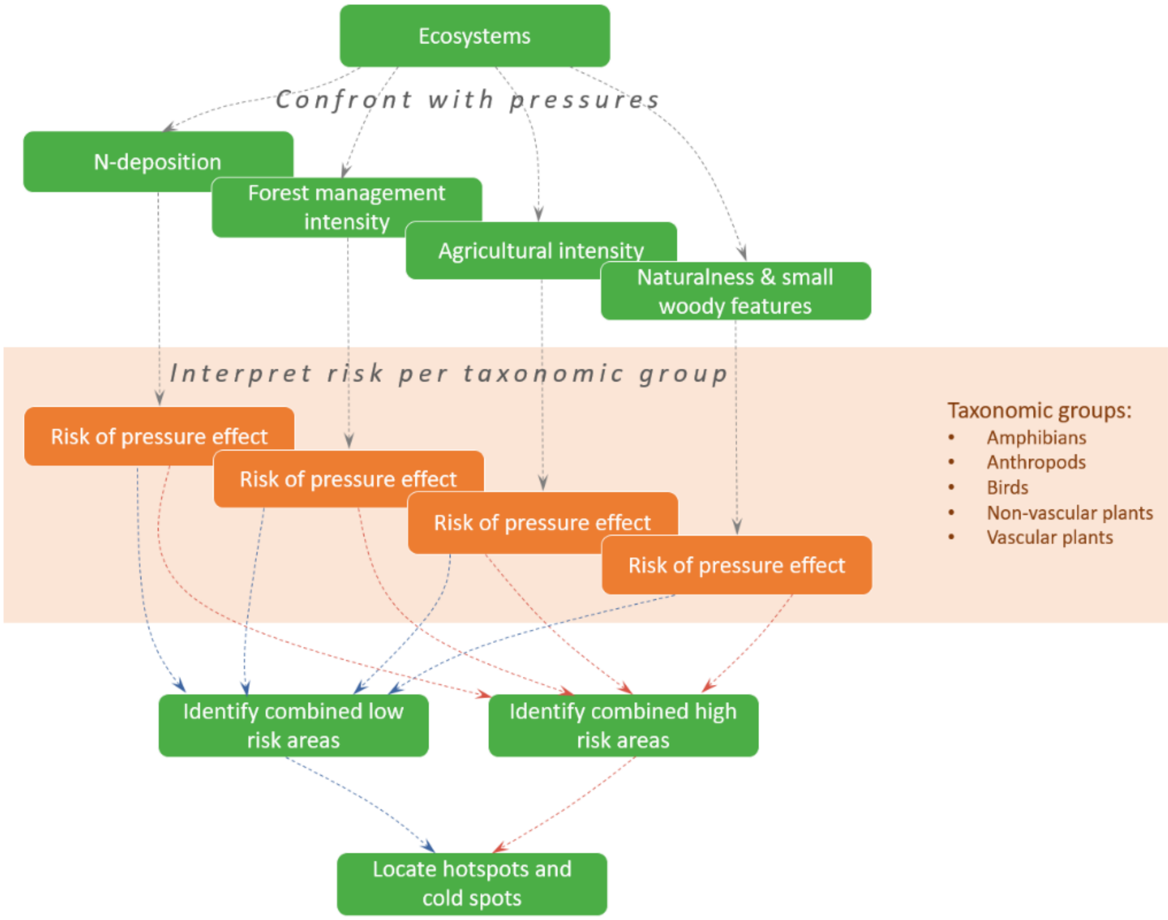

Figure 2: Summary of QuickScan steps used to develop maps that show risk of negative pressure responses per taxonomic group, and combined maps of pressure hotspot and coldspot locations

3.1.1. Agricultural intensification

We used the recently-published agricultural intensification data from Rega et al. (2020). The indicator was developed as part of the EU Horizon 2020 research and innovation programme under grant agreement No 633814 - PEGASUS project (http://pegasus.ieep.eu/). The spatial layer underwent expert review in several iterative workshops as well as in the peer-reviewed literature (Rega et al. 2020). The approach used in Rega et al. (2020) to map agricultural intensification went beyond the use of agricultural yield as a proxy for management intensity. Instead, it applied an energy-budget approach based on the amount of energy used in agricultural inputs (machinery, seeds, fertilizers, irrigation, labor) and the amount in biomass output. These factors are particularly important when considering the trade-offs and synergies among ecosystem services offered by different land uses Berbés-Blázquez et al. (2016). Farm data from the official Eurostat 2010 agricultural census were used in the Common Agricultural Regionalized Impact (CAPRI) model (Britz and Witzke 2014) to generate the energy balance. Resulting outputs at regional (NUTS2) level were downscaled to a finer spatial resolution of so-called Homogeneous Spatial Mapping Unites, i.e. pixel clusters of one or more 1 km^2 cells with similar agronomic characteristics (Rega et al. 2020). The final indicator is expressed at 1 km^2 resolution as the total amount of human-handled energy input per hectare of utilized agricultural area (MJ/ha), excluding physical human labor.

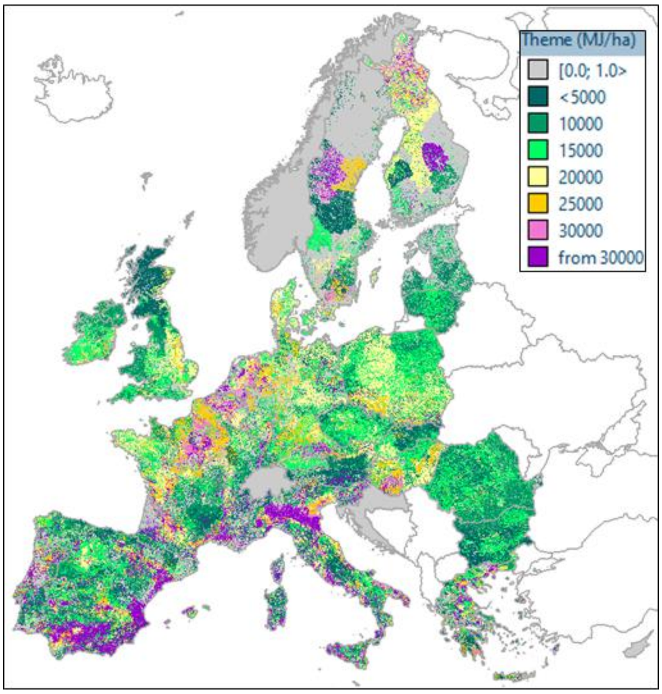

Figure 3: Pressure gradient across EU for agricultural intensification, reflecting energy input intensity; after Rega et al. (2020)

Rega et al. (2020) define categories of agricultural intensification using the following energy intensity thresholds (1000 MJ/ha/year): Very high > 20; High 15-20; Medium 10-15; Low < 10. We used these categories as a starting point to develop risk matrices for each taxonomic group. These risk matrices reflect the likelihood of a negative effect of agricultural intensification on each taxonomic group per ecosystem type (Figure 4). The aggregated matrix of synthesized evidence showed an unequivocal negative impact on biodiversity (Figure 1) – the higher the intensification, the higher the risk. We were able to disaggregate this negative response further to reflect the differential sensitivity of the taxonomic group. This was based on evidence collated in the agricultural pressure factsheet (Nel et al. 2020), which showed that taxonomic groups comprised mainly of species that are bound to the soil are more sensitive to impacts from agricultural intensification than those with species that are more mobile (Flohre et al. 2011; Guerrero et al. 2014; Carmona et al. 2020). Using this logic, the risk of agricultural intensification on vascular and non-vascular plants, and arthropods was adjusted to reflect higher sensitivity (Figure 4). Similarly, the risk of agricultural intensification on birds and mammals was adjusted to reflect lower sensitivity, and amphibians remained unchanged (i.e., a risk in between the extremes of the other sets of taxonomic groups).

Agricultural intensity (1000 MJ/ha)	Amphibians	Arthropods	Birds	Mammals	Vascular plants	Non-vascular plants
> 20	VH	VH	H	H	VH	VH
15-20	H	VH	H	H	VH	VH
10-15	M	H	M	M	H	H
< 10	L	M	L	L	M	M

Figure 4: Risk matrix to show the risk of a negative effect from agricultural intensification on taxonomic groups in agro-ecosystems (cropland and grassland)

3.1.2. Habitat loss and fragmentation

While biodiversity loss from large-scale outright land conversion from one land cover type to the another is relatively stable in Europe, there is pressure resulting from ongoing loss of landscape heterogeneity and connectivity, mainly as a consequence of urbanization and agricultural management practices (MAES et al. 2020). We therefore focused particularly on the loss of landscape heterogeneity and small natural/semi-natural features that promote landscape connectivity. Two spatial layers were used to depict this form of pressure intensity gradient for habitat loss and fragmentation:

- **'Landscape Mosaic'** layer used in the MAES assessment (MAES et al. 2020) and described in more detail in Vogt (2019). Each 100 x 100 m pixel in the Corine Land Cover 2018 is classified according to the relative proportions of the three land cover types (agriculture, natural, and developed) in a 529 ha neighborhood surrounding that location (529 ha = 23 x 23 surrounding pixels). We used the percentage natural vegetation to describe the juxtaposition of artificial/developed land and agricultural land in relation to natural land at 100 m resolution . The analysis of these three dominant land cover types simultaneously addresses landscape composition, connectivity and the degree of landscape heterogeneity.

- **'Small woody features'** layer produced by Copernicus Land Monitoring (CLMS), which maps linear structures such as hedgerows, as well as patches (200 m^2 ≤ area ≤ 5000 m^2) of woody features. This spatial layer captures small natural/semi-natural farmland features that provide crucial habitat for biodiversity in agro-ecosystems. These small woody features are not well captured in the Corine Land Cover, and are becoming increasingly important to include as the EU 2030 Biodiversity Strategy gears up for enhancing restoration activities in agricultural and urban ecosystems. There is a lot to be gained for biodiversity by restoring these features to agro-ecosystem and urban landscapes.

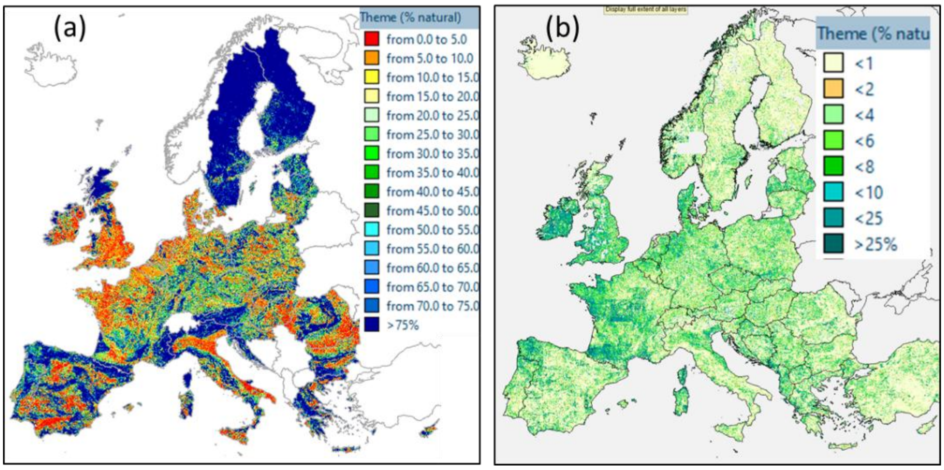

Figure 5: Pressure gradient across EU for habitat loss and fragmentation, showing (a) percentage natural land after Vogt 2019, and (b) percentage small woody features after Copernicus 2018

The aggregated matrix of synthesized evidence showed a largely negative effect of habitat fragmentation on biodiversity, with more variable impacts on grassland mammals, and arthropods of heathlands and shrubs (Figure 1). We were able to further disaggregate the overall responses in Figure 1 to reflect the differential sensitivity of taxonomic groups and ecosystem types, based on evidence collated in the agricultural pressure factsheet (Nel et al. 2020). This information stems from combining the findings of several global and European-wide meta-analyses, which quantified the effects of habitat loss and fragmentation on taxonomic groups in different ecosystem types (Figure 6 and Figure 7):

- **Taxonomic group risks in <u>forests and heathlands and shrubs</u>:** We first distinguished differential responses of taxonomic groups in these two ecosystem types, based on a meta-analysis by Banks-Leite et al. (2014). This study quantified thresholds of percentage remaining forest cover below which community composition of vertebrate taxonomic groups is severely compromised (Figure 6). While this study was for vertebrates of the Atlantic forests in Brazil, a European meta-study found similar biodiversity effects in European forests (Pfeifer et al. 2017). We therefore used remaining natural cover thresholds in Banks-Leite et al. (2014) to define risk category thresholds in forests and heathlands and shrubs. For mammals, amphibians and birds this was done using the minima and maxima depicted by the grey bars respectively in Figure 6a, b, and c, which depict the range of remaining natural cover (%) where there is a steep decline in community integrity, i.e. thresholds for mammals are at 20-30% remaining; birds 25-40%; and amphibians 15-35%. Similarly, thresholds of the remaining taxonomic groups (arthropods, vascular plants and non-vascular plants) were set using grey bar of Figure 6d, i.e. at 25-35% remaining natural cover. These ranges are depicted as the black borders in Figure 8. The top ¼ of these ranges was set to 'medium risk' (i.e. at the inflection of the downward curve where loss of community integrity is beginning); the remaining ¾ was set to 'high risk' (i.e. where the curve is at its steepest and there is exponential decline in community integrity). The 'very high' and 'low' risk categories were then set to respectively below and above this grey bar range. These risk categories are depicted in Figure 8.

- **Taxonomic group risks in remaining ecosystem types**: we inferred thresholds using meta-analyses that quantified relative ecosystem type sensitivity in Europe. For **<u>grasslands</u>**, terrestrial vertebrates (mammals, reptiles, birds and amphibians) are relatively half as sensitive to habitat loss and fragmentation compared to **<u>forests</u>**, according to a meta-study of 77 worldwide cases

(Figure 7; Keinath et al. 2017). Thus, the thresholds defining the risk categories for taxonomic groups in grassland ecosystem were halved relative to those for forests and heathlands and shrubs (Figure 8). For **wetlands**, a European meta-analysis studying 20 years of fragmentation effects showed that sharp decline of species richness begins at 30% remaining wetland habitat (Horvath et al. 2019). Biodiversity of wetland ecosystem types is thus more sensitive to habitat fragmentation than that of grasslands but less sensitive than that of forests. For **sparsely vegetated habitats and croplands**, no meta-analysis evidence exists on thresholds for biodiversity. Based on the range of evidence, we presumed these ecosystem types to be less sensitive than forests, but more sensitive than grasslands – thus a mid-point between the thresholds for these ecosystem types was adopted, making biodiversity of these ecosystem types similar in risk response to wetlands.

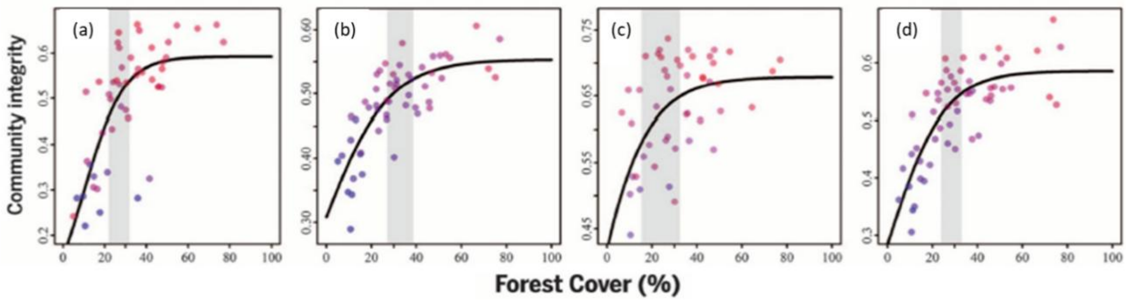

Figure 6: Community integrity responses to percentage forest cover in Brazilian Atlantic forests (red dots = forest specialists; blue dots = forest generalists) for (a) mammals, (b) birds, (c) amphibians and (d) vertebrates, after Banks-Leite et al. (2014)

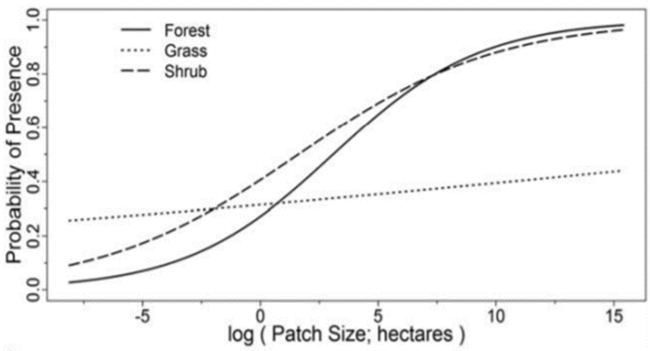

Figure 7: Species richness response in forest, shrub and grassland ecosystems, after Keinath et al. (2017), showing that the probability of presence of species in forests (solid line) and shrublands (dashed line) changed markedly with patch size, but far less so in grasslands (dotted line)

AMPHIBIANS

% natural	Cropland	Grassland	Heathland and shrubs	Sparsely vegetated	Wetlands	Woodlands and forest
<15	(VH)	(VH)	(VH)	(VH)	VH	VH
15-20	(H)	(H)	(H)	(H)	H	H
20-25	(H)	(M)	(H)	(H)	H	H
25-30	(M)	(L)	(M)	(M)	M	M
30-35	(L)	(L)	(M)	(L)	L	M
35-40	(L)	(L)	(L)	(L)	L	L
>40	(L)	(L)	(L)	(L)	L	L

ARTHROPODS

% natural	Cropland	Grassland	Heathland and shrubs	Sparsely vegetated	Wetlands	Woodlands and forest
<15	(VH)	(VH)	(VH)	(VH)	VH	VH
15-20	(H)	(H)	(H)	(H)	H	H
20-25	(H)	(M)	(H)	(H)	H	H
25-30	(M)	(L)	(M)	(M)	M	M
30-35	(L)	(L)	(M)	(L)	L	M
35-40	(L)	(L)	(L)	(L)	L	L
>40	(L)	(L)	(L)	(L)	L	L

BIRDS

% natural	Cropland	Grassland	Heathland and shrubs	Sparsely vegetated	Wetlands	Woodlands and forest
<15	VH	VH	VH	(VH)	(VH)	VH
15-20	VH	H	VH	(VH)	(VH)	VH
20-25	H	M	VH	(H)	(H)	VH
25-30	H	L	H	(H)	(H)	H
30-35	M	L	H	(M)	(M)	H
35-40	L	L	M	(L)	(L)	M
>40	L	L	L	(L)	(L)	L

MAMMALS

% natural	Cropland	Grassland	Heathland and shrubs	Sparsely vegetated	Wetlands	Woodlands and forest
<15	VH	VH	VH	(VH)	(VH)	VH
15-20	H	H	VH	(H)	(H)	VH
20-25	M	M	H	(M)	(M)	H
25-30	L	L	M	(L)	(L)	M
30-35	L	L	L	(L)	(L)	L
35-40	L	L	L	(L)	(L)	L
>40	L	L	L	(L)	(L)	L

VASCULAR PLANTS

% natural	Cropland	Grassland	Heathland and shrubs	Sparsely vegetated	Wetlands	Woodlands and forest
<15	(VH)	(VH)	(VH)	(VH)	VH	VH
15-20	(H)	(H)	(H)	(H)	H	H
20-25	(H)	(M)	(H)	(H)	H	H
25-30	(M)	(L)	(M)	(M)	M	M
30-35	(L)	(L)	(M)	(L)	L	M
35-40	(L)	(L)	(L)	(L)	L	L
>40	(L)	(L)	(L)	(L)	L	L

NON-VASCULAR PLANTS

% natural	Cropland	Grassland	Heathland and shrubs	Sparsely vegetated	Wetlands	Woodlands and forest
<15	(VH)	(VH)	(VH)	(VH)	VH	VH
15-20	(H)	(H)	(H)	(H)	H	H
20-25	(H)	(M)	(H)	(H)	H	H
25-30	(M)	(L)	(M)	(M)	M	M
30-35	(L)	(L)	(M)	(L)	L	M
35-40	(L)	(L)	(L)	(L)	L	L
>40	(L)	(L)	(L)	(L)	L	L

RISK	Low	Medium	High	Very high

Figure 8: Risk matrices to show the negative effect of habitat loss and fragmentation on taxonomic groups in different ecosystem types, with black borders indicating the medium risk threshold for overall biodiversity in each ecosystem type (see text for details)

Brackets indicate knowledge gaps that have been inferred using a mixture of global literature and overall sensitivity of ecosystem types

3.1.3. Atmospheric nitrogen deposition

We used the European Monitoring and Evaluation Programme (EMEP) data on atmospheric transport and deposition of nitrogen to map this pressure gradient at the European scale. Total Nitrogen Deposition (kg N/ha/year) was drawn from the EMEP 2018 Status reporting (EMEP 2018)[6], which reflects the modelled data for 2016 (Figure 9). This was the same data used as an indicator of atmospheric nitrogen deposition in the MAES assessment and is approximately 50 x 50 km resolutions (± depending on projected location).

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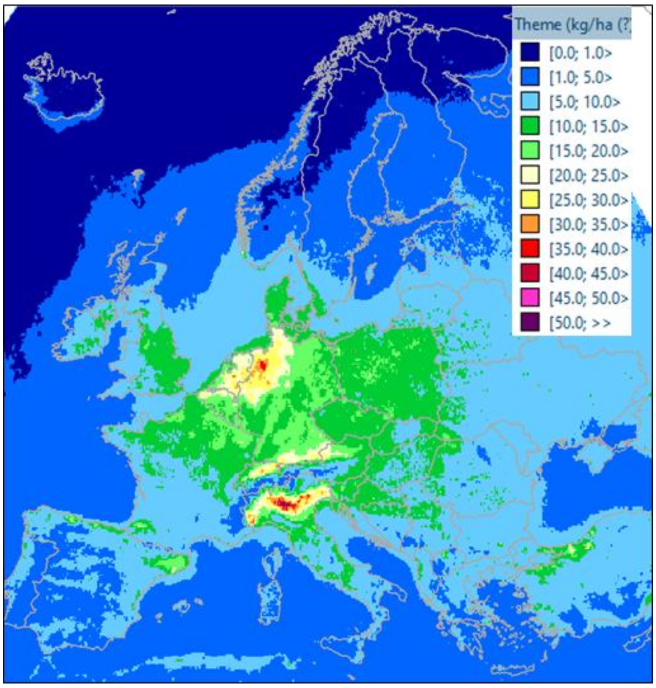


Figure 9: Pressure gradient across EU for atmospheric nitrogen deposition in kg/ha/year

Critical exceedance loads are used by the EU to provide annual nitrogen deposition thresholds that habitats can tolerate without harmful effects on associated biodiversity. Ranges for critical exceedance (in kg N/ha/year) have been defined by Bobbink et al. (2010) for EUNIS habitat types (Davies et al. 2004). These were aggregated to ecosystem types to use in this study as shown in Table 1. The upper and lower limit of these ranges was then used to define an initial category of 'medium risk' to all taxonomic groups within the respective ecosystem type, with a 'low risk' attributed to nitrogen levels below the minimum range of critical exceedance; a 'high risk' to those above the maximum critical exceedance; and a 'very high risk' to any nitrogen level above 35 kg N/ha/year.

Future spatial differentiation of broad habitat types within the ecosystem types listed in Table 1 would allow further differentiation of pressure effects for atmospheric nitrogen deposition. These include further distinction based on sensitivity differences of acidic, calcareous, alpine grassland; wet, dry, alpine heathland; moist dunes vs. remaining sparsely vegetated habitats; bogs, rich fens, poor fens and alpine fens; boreal and temperate forest

Table 1: Critical exceedance ranges aggregated to ecosystem types from Bobbink et al. (2010)

Critical exceedance ranges for Nitrogen (kg/ha/year)	**Ecosystem type**
10-30	Grassland
5-25	Heathland and shrubs
10-25	Sparsely vegetated habitats
5-35	Wetlands
5-15	Forests

Using these initial ecosystem type risk categories, we then upweighted the risk for taxonomic groups where there was strong evidence of a strongly negative impact from atmospheric nitrogen deposition as shown in Figure 1 for vascular and non-vascular plants in Grasslands, and non-vascular plants in Forests and Heathlands and shrubs. This provided a risk profile per taxonomic group and ecosystem type shown in Figure 10.

In instances where there were knowledge gaps in the aggregated matrix (the grey cells of Figure 1), information on the response to atmospheric nitrogen deposition was inferred using the critical exceedance thresholds for vascular plants. For mammals, there was no information collated in Figure 1 and instead an overall negative effect was assumed using the impact of atmospheric nitrogen deposition on mammals for Europe from the IPBES Regional Assessment (IPBES 2018), and then the critical exceedance thresholds for vascular plants was applied.

AMPHIBIANS

Nitrogen deposition level kg N/ha/yr	Cropland	Grassland	Heathland and shrubs	Sparsely vegetated	Wetlands	Woodlands and forest
< 1	(L)	((L))	(L)	(L)	L	(L)
1-5	(L)	(L)	(L)	(L)	L	(L)
5-10	(L)	(L)	(M)	(L)	M	(M)
10-15	(M)	(M)	(M)	(M)	M	(M)
15-20	(M)	(M)	(M)	(M)	M	(M)
20-25	(M)	(M)	(M)	(M)	M	(M)
25-30	(M)	(M)	(H)	(H)	M	(H)
30-35	(H)	(H)	(H)	(H)	M	(H)
>35	(VH)	(VH)	(VH)	(VH)	VH	(VH)

ARTHROPODS

Nitrogen deposition level kg N/ha/yr	Cropland	Grassland	Heathland and shrubs	Sparsely vegetated	Wetlands	Woodlands and forest
< 1	(L)	((L))	(L)	(L)	L	(L)
1-5	(L)	(L)	(L)	(L)	L	(L)
5-10	(L)	(L)	(M)	(L)	M	(M)
10-15	(M)	(M)	(M)	(M)	M	(M)
15-20	(M)	(M)	(M)	(M)	M	(M)
20-25	(M)	(M)	(M)	(M)	M	(M)
25-30	(M)	(M)	(H)	(H)	M	(H)
30-35	(H)	(H)	(H)	(H)	M	(H)
>35	(VH)	(VH)	(VH)	(VH)	VH	(VH)

BIRDS

Nitrogen deposition level kg N/ha/yr	Cropland	Grassland	Heathland and shrubs	Sparsely vegetated	Wetlands	Woodlands and forest
< 1	(L)	((L))	(L)	L	(L)	L
1-5	(L)	(L)	(L)	L	(L)	L
5-10	(L)	(L)	(M)	L	(M)	M
10-15	(M)	(M)	(M)	M	(M)	M
15-20	(M)	(M)	(M)	M	(M)	H
20-25	(M)	(M)	(M)	M	(M)	H
25-30	(M)	(M)	(H)	H	(M)	H
30-35	(H)	(H)	(H)	H	(M)	H
>35	(VH)	(VH)	(VH)	VH	(VH)	VH

MAMMALS

Nitrogen deposition level kg N/ha/yr	Cropland	Grassland	Heathland and shrubs	Sparsely vegetated	Wetlands	Woodlands and forest
< 1	(L)	(L)	(L)	(L)	(L)	(L)
1-5	(L)	(L)	(L)	(L)	(L)	(L)
5-10	(L)	(L)	(M)	(L)	(M)	(M)
10-15	(M)	(M)	(M)	(M)	(M)	(M)
15-20	(M)	(M)	(M)	(M)	(M)	(H)
20-25	(M)	(M)	(M)	(M)	(M)	(H)
25-30	(M)	(M)	(H)	(H)	(M)	(H)
30-35	(H)	(H)	(H)	(H)	(M)	(H)
>35	(VH)	(VH)	(VH)	(VH)	(VH)	(VH)

VASCULAR PLANTS

Nitrogen deposition level kg N/ha/yr	Cropland	Grassland	Heathland and shrubs	Sparsely vegetated	Wetlands	Woodlands and forest
< 1	L	L	L	L	L	L
1-5	L	L	L	L	L	L
5-10	L	L	M	L	M	M
10-15	M	M	M	M	M	M
15-20	M	M	M	M	M	H
20-25	H	H			M	H
25-30	H	H	H	H	M	H
30-35	VH	VH	H	H	M	H
>35	VH	VH	VH	VH	VH	VH

NON-VASCULAR PLANTS

Nitrogen deposition level kg N/ha/yr	Cropland	Grassland	Heathland and shrubs	Sparsely vegetated	Wetlands	Woodlands and forest
< 1	L	L	L	L	L	L
1-5	L	L	L	L	L	L
5-10	L	L	M	L	M	M
10-15	M	M	M	M	M	H
15-20	M	M	M	M	M	VH
20-25	H	H	H	M	M	VH
25-30	H	H	VH	H	M	VH
30-35	VH	VH	VH	H	M	VH
>35	VH	VH	VH	VH	VH	VH

RISK	Low	Medium	High	Very high

Figure 10: Risk matrices to show the negative effect of atmospheric nitrogen deposition on taxonomic groups in different ecosystem types

Brackets indicate inferred knowledge gaps and the stippled pattern on the mammals risk matrix indicates a knowledge gap filled from the IPBES Regional Assessment (IPBES 2018). See text for further explanation.

3.1.4. Forest management intensity

We used a map of forest management intensity (Figure 11) prepared as part of the EU Horizon 2020 research and innovation programme under grant agreement No 633814 - PEGASUS project (http://pegasus.ieep.eu/). This layer been through iterative expert workshop review as well as peer review (Nabuurs et al. 2019). The layer was compiled using a Bayesian Belief Network model (BBN), which combined statistical and expert knowledge of the relationships between drivers, management intensity and demands in the future. The following data were used: soil type, elevation, climate zoned, IUCN protection status, tree species, size of fellings, ruggedness, accessibility, population pressure, and percentage of forestry on the annual gross domestic product. Activities in the resulting forest management intensity categories are described as:

i. Strict nature management: no harvest, nature conservation objectives
ii. Close to nature management: harvest as byproduct of nature management, more remote, intention is mainly to manage for biodiversity
iii. Low intensity management: focus on timber production and nature conservation, natural regeneration, indigenous species
iv. Multifunctional management: including timber production and recreation
v. Intensive management: intensive harvest, deliberate planting, even-aged forestry, regular tree thinning and removal of deadwood
vi. Very intensive management: short rotation forestry, fertilization, use of herbicides, regular tree thinning and removal of deadwood

As a starting point to constructing the risk matrices, we assigned all taxonomic groups an overall risk based on the above forest management intensity categories, such that 'low risk' was assigned to the forest management intensity classes (i) and (ii), 'medium risk' to (iii) and (iv), 'high risk' to (v), and 'very high risk' to (vi). We further distinguished differential responses based on forest type and taxonomic group sensitivity. Forest types were classified as Boreal, Alpine, Mediterranean and Temperate forests, which were distinguished using the EU biogeographic regions[7]: the first three forest types comprised any forest in the corresponding biogeographic region, and Temperate forests comprised those in the Continental, Atlantic and Pannonian biogeographic regions. Biota in Boreal and Temperate forests were generally found to be more sensitive to forest intensification than in Alpine and Mediterranean forests (Figure 1), and were consequently upweighted in risk (Figure 11).

[7] https://www.eea.europa.eu/data-and-maps/figures/biogeographical-regions-in-europe-2

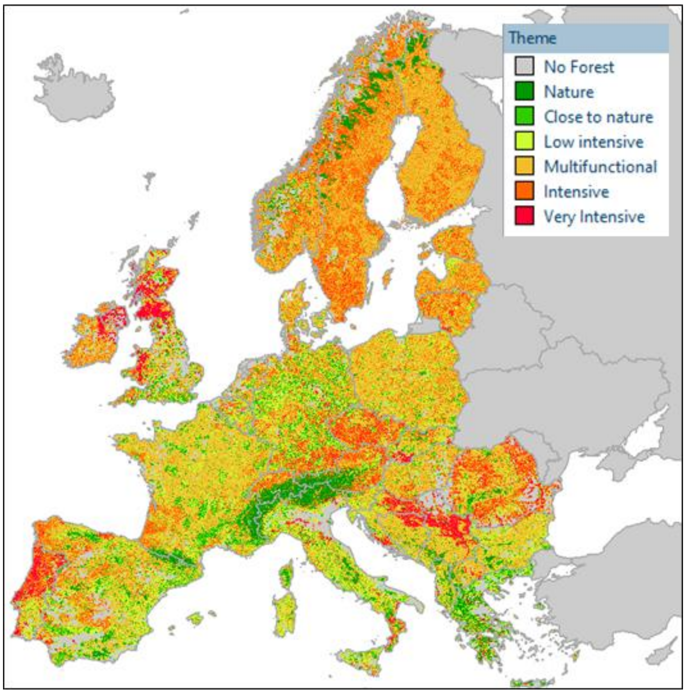


Figure 11: Pressure intensity gradient across EU for forest management intensity

ARTHROPODS, MAMMALS

Forest management intensity	Boreal	Alpine	Temperate	(M)editeranean
Nature	L	L	L	(L)
Close to nature, Low	M	L	L	(L)
Multifunctional	M	M	M	(M)
Intensive	VH	H	VH	(H)
Very Intensive	VH	VH	VH	(VH)

BIRDS

Forest management intensity	Boreal	Alpine	Temperate	(M)editeranean
Nature	L	L	L	(L)
Close to nature, Low	L	L	L	(L)
Multifunctional	M	L	M	(M)
Intensive	H	M	H	(M)
Very Intensive	VH	H	VH	(H)

VASCULAR PLANTS

Forest management intensity	Boreal	Alpine	Temperate	(M)editeranean
Nature	L	L	L	(L)
Close to nature, Low	L	L	L	(L)
Multifunctional	M	L	M	(M)
Intensive	H	M	H	(M)
Very Intensive	VH	H	VH	(H)

NON-VASCULAR PLANTS

Forest management intensity	Boreal	Alpine	Temperate	(M)editeranean
Nature	L	L	L	(L)
Close to nature, Low	M	L	L	(L)
Multifunctional	M	M	M	(M)
Intensive	VH	H	VH	(H)
Very Intensive	VH	VH	VH	(VH)

Figure 12: Risk matrices to show the negative effect of forest management intensity on taxonomic groups in Boreal, Alpine, Mediterranean and Temperate forests

Brackets indicate knowledge gaps that have been inferred using evidence from overall sensitivity of ecosystem types as per Nel et al. (2020)

3.2. Mapping taxonomic responses along pressure intensity gradients in the EU

The spatial distribution maps for ecosystem types were set according to those used in the MAES assessments (MAES et al. 2020). Pressure intensity gradient maps (Figure 3, Figure 5, Figure 9 and Figure 11) were loaded into QuickScan. Risk matrices describing of the likely negative response of a taxonomic group to each pressure per ecosystem type (Figure 4, Figure 8, Figure 10 and Figure 12) were linked to the associated ecosystem types and pressure intensity categories. We were not able to evaluate sparsely vegetated areas and wetlands because of limited mapping of pressure gradients in these ecosystem types. Biogeographic regions were used to further distinguish forest ecosystem types. This produced risk maps of the likely negative response of each taxonomic group to each pressure.

3.3. Mapping pressure hotspots and coldspots for each taxonomic group in the EU

The multiple pressures that impact different taxonomic groups at a single location (in this case 1 x 1 km^2 pixel) give rise to many pressure risks, ranging from very high to low. To visualize the overall risk from these multiple pressures, maps of pressure hotspots and pressures coldspots per taxonomic group were produced. This was done by extracting the 'very high/high risk' areas of each risk map per taxonomic group, as well as the 'low risk' areas. These layers were then spatially combined using knowledge rules in Figure 13 to produce maps of pressure hotspots and coldspots for each taxonomic group in the EU. For example, where ≥ 75% of the records considered for the location are very high/high risk, the location was allocated as 'Superhot'; in contrast it was 'Supercold' if ≥ 75% of the records considered for the location were low risk (Figure 13).

	No score	< 50%	50-74 %	≥ 75%	High risk from 1 pressure
No score	Remaining	Cool	Cold	Supercold	Cool
< 50%	Warm	Variable	Cool	Cold	Variable
50-74 %	Hot	Warm	Variable	Cool	Variable
≥ 75%	Superhot	Hot	Warm	Variable	Variable
High risk from 1 pressure	Warm	Variable	Variable	Variable	Remaining

Figure 13: Knowledge rules used to define pressure hotspots and coldspots per pixel by combining 'very high/high risks' and 'low risks' for each pressure risk to a taxonomic group

Hotspots comprise Superhot, Hot and Warm categories; Coldspots comprise Supercold, Cold and Cool categories. Variable is a mix of very high/high and low risks, with neither dominating. Remaining area is comprised either of pressures that are moderate or are considered urban ecosystems.

3.4. Summary statistics of pressure effects on taxonomic groups in the EU

We produced the following summary statistics using the risk maps per taxon, and the overall pressure hotspot-coldspot maps:

- Summary at **EU level** of the % area of the risk category used to describe the likely risk of a negative impact from each pressure per taxonomic group according to the Very high, High, Medium and Low risk categories.
- Summary at **EU level** of the % area of hotspot and coldspot categories for each taxonomic group
- Summary at the level of **ecosystem type** of the % area of hotspot and coldspot categories for each taxonomic group. We were not able to evaluate sparsely vegetated areas and wetlands because of limited mapping of pressure gradients in these ecosystem types.
- Summary at the level of **biogeographic region** of % area of hotspot and coldspot categories for each taxonomic group.

4. Results and discussion

4.1. Pressure effects on different taxonomic groups in the EU

4.1.1. Amphibians

There are some 85 species of amphibians in Europe (50 species of frogs and toads; 35 species of newts and salamanders), and roughly two thirds of these species are endemic to Europe (Temple and Cox 2009). Amphibians have high species diversity at intermediate latitudes (France, Germany, Czech Republic) as well as in the south (Italy, Spain and Greece) (Figure 14a). Endemic species richness is particularly prevalent in the Iberian and Italian peninsulas and central France (Temple and Cox 2009) (Figure 14b).

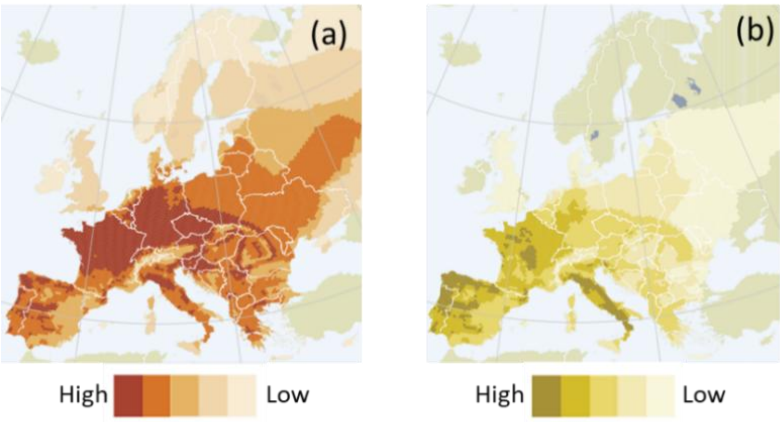


Figure 14: Patterns of amphibian species richness (a) and endemicity (b)
After Temple and Cox (2009). SOURCE: IUCN

Overall, amphibians are good indicators of environmental quality because they are very sensitive to disturbances in ecosystems. Amphibians are generally habitat specialists and tend to be more negatively affected by **agricultural intensification** (Figure 15a) and **habitat loss and fragmentation** (Figure 15b) than habitat generalists and mobile species (Kehoe et al. 2015). Amphibian biodiversity is also shown to be influenced by pond densities at the landscape level (Jeliazkov 2014), which supports findings on the negative impacts of fragmentation. The extent of the high and very risk categories for both agricultural intensification and habitat loss and fragmentation is especially concerning for the Iberian and Italian peninsulas, because of the high endemic species richness. If species in these areas are threatened with local extinction, the implication is global biodiversity loss.

Atmospheric nitrogen deposition is tolerated to the level where habitats become eutrophic (Figure 15c), with highly eutrophic waters having direct toxicity effects at the tadpole stage (Leuven et al. 1986; Nijssen et al. 2017). The risk of atmospheric nitrogen deposition of having a negative impact on amphibians is therefore similar to the risk that the ecosystem type would become eutrophic, with thresholds as defined by Bobbink et al. (2010). **Forest management intensity** is particularly threatening to amphibians in the Boreal forests of Sweden and Finland (Figure 15d), although these regions themselves are not particularly rich or endemic in amphibian species (Figure 14).

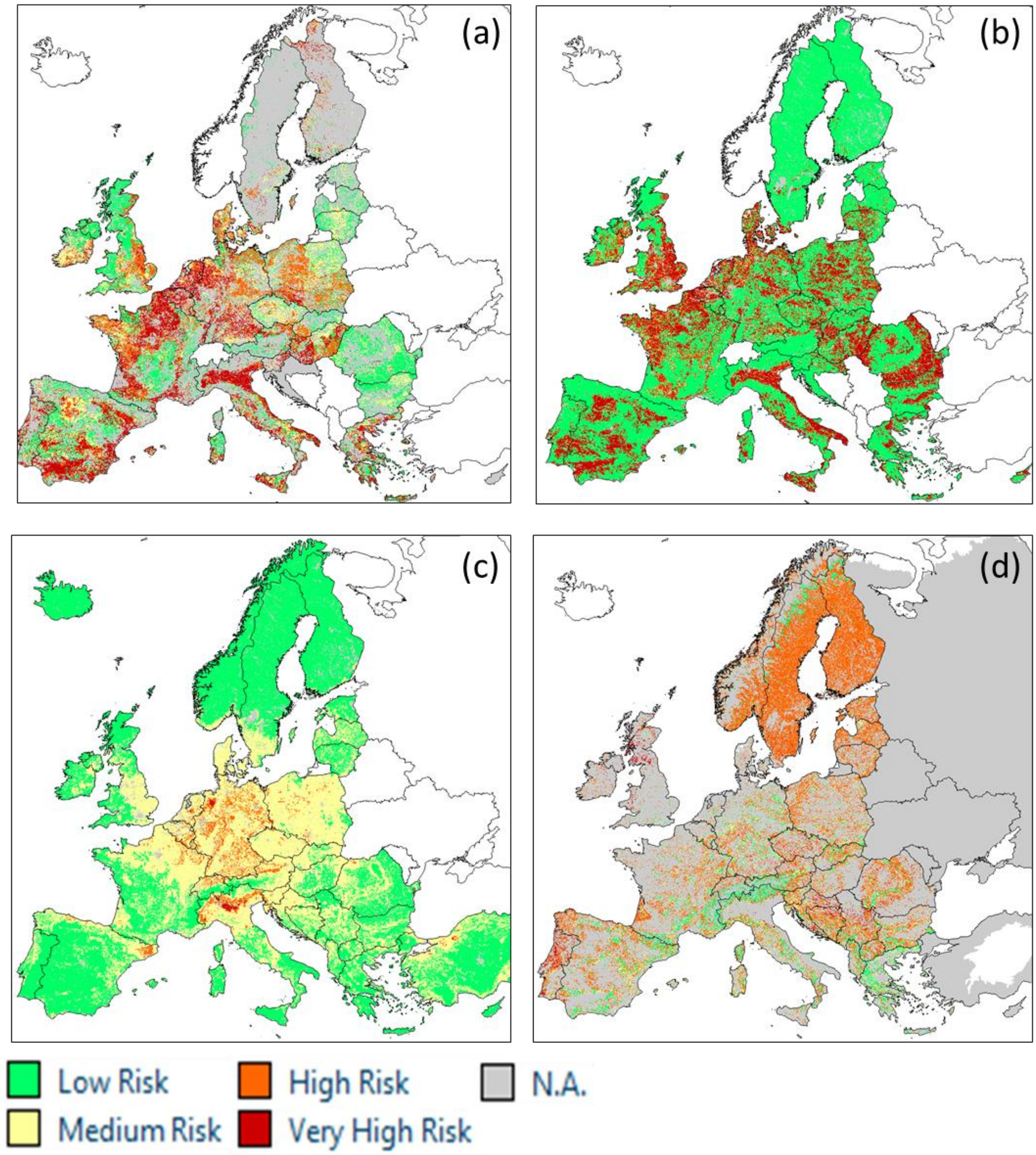


Figure 15: Maps showing the risk of a negative effect on amphibians for each pressure: (a) agricultural intensification; (b) habitat loss and fragmentation; (c) atmospheric nitrogen deposition; and (d) forest management intensity

4.1.2. Arthropods

Pressures, firstly from **agricultural management intensity** (Figure 16a) and then from **habitat loss and fragmentation** (Figure 16b) are by far the most risky and widespread pressures posed to arthropods. Moreover, these pressures interact, so that as agricultural management intensity increases, more smaller natural features are lost from the landscape. High risk categories for agricultural management intensification in the south of France coincide with an endemic hotspot for European butterflies (van Swaay, 2010). Pressures from **forest management intensity** in the Boreal forests present a widespread risk to arthropods (Figure 16d). This is largely through the effect of logging practices and deadwood removal (Lassauce et al. 2011; Lassauce et al. 2012). Arthropod biodiversity is reduced by harvesting deadwood left by forest disturbances or clearing. Some insect species (habitat specialists) thrive under a diverse patchwork of deadwood with certain wood types attracting more biodiversity than others (Gossner et al. 2016). Saproxylic beetle diversity directly benefits from of the residue left from logging.

High and very high risks of **atmospheric nitrogen deposition** are found scattered throughout central Europe and in the Po river catchment, just south of the Italian alps (Figure 16c). These areas are associated with agricultural intensity and urbanization. The effects of atmospheric nitrogen deposition (Figure 16c) mainly impact the larval stages of arthropods through changes in microclimate resulting from vegetation compositional changes, or changes in nutrient balances in leaf foliage (Nijssen et al. (2017). These impacts on arthropod communities cascade through the food chain to higher trophic level taxa like birds (Siepel 1990; Graveland et al. 1994).

4.1.3. Birds

Agricultural intensification poses severe pressure to farmland birds (Figure 17a). This concurs with MAES et al. (2020) which reported a 33% decline in the farmland bird index since 1990, representing 13.5% decrease per decade. **Habitat loss and fragmentation** constitutes a widespread and high risk for birds across much of the EU (Figure 17b). While outright land conversion has a stable signal at EU level (MAES et al. 2020), there are small natural features (e.g. field margins, hedges, grass strips, lines of trees, patches of uncultivated land), which were not assessed, and these constitute important connectivity corridors for farmland bird species. **Forest management intensity** places a widespread and high risk of negative impact on Boreal forests birds (Figure 17d). The high risk in the southernmost Boreal region is particularly concerning as it coincides with a region where endemic species richness is high for bird species (Birdlife International 2015). Logging practices and deadwood clearing in these intense areas can destroy nesting habitat, food sources and refuges for many bird species (Thorn et al. 2016). Forest bird specialists dependent on mature forest and dead wood are therefore often threatened or heavily depleted (Birdlife International 2015). **Atmospheric nitrogen deposition** impacts birds through cascading effects on nesting site availability that limit breeding success, or prey nutrient deficiencies (brought on through leaf foliage nutrient imbalances) that pose physiological problems such as weak egg shells, bones and muscles (Nijssen et al. 2017).

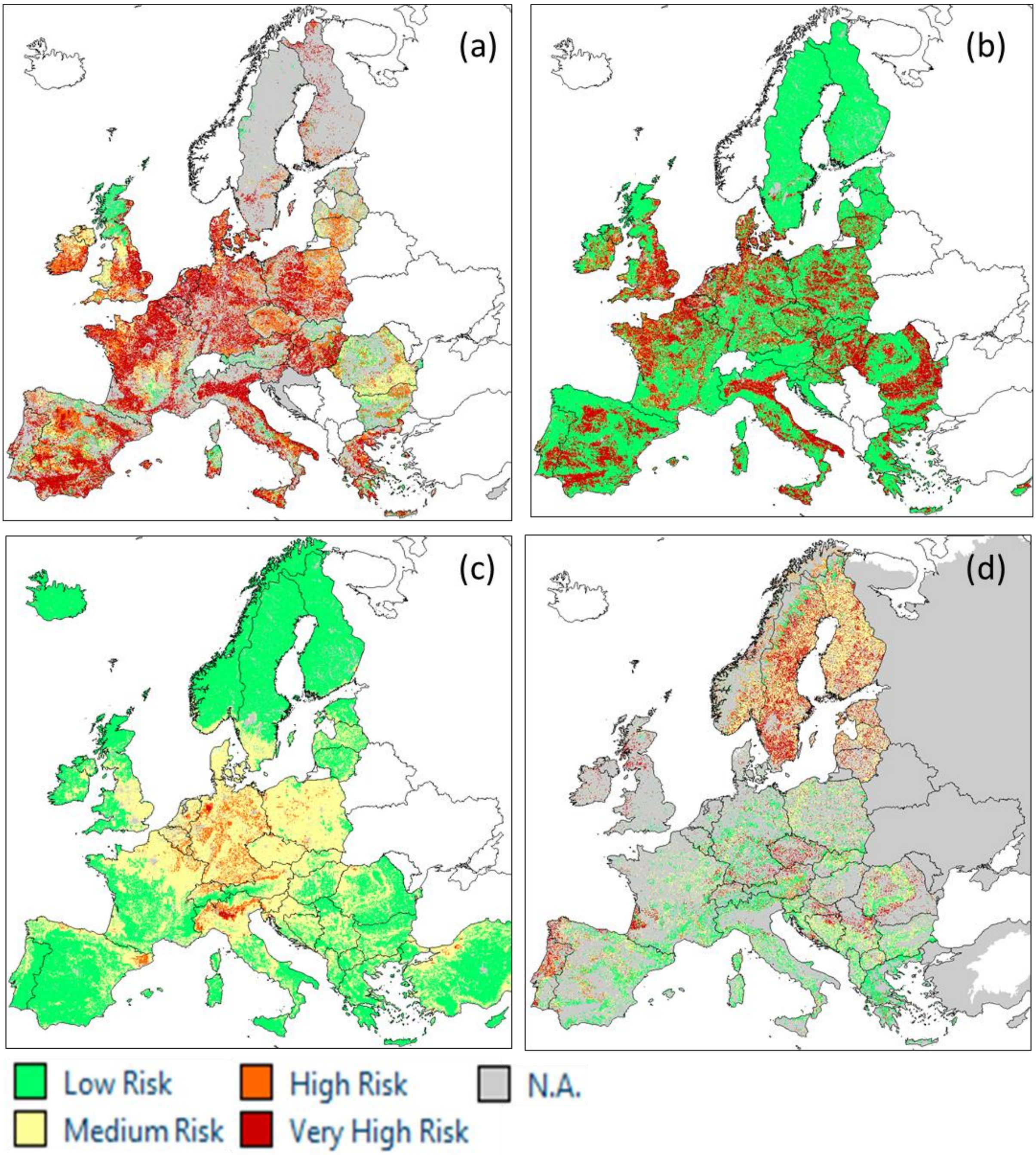


Figure 16: Maps showing the risk of a negative effect on arthropods for each pressure (a) agricultural intensification; (b) habitat loss and fragmentation; (c) atmospheric nitrogen deposition; and (d) forest management intensity

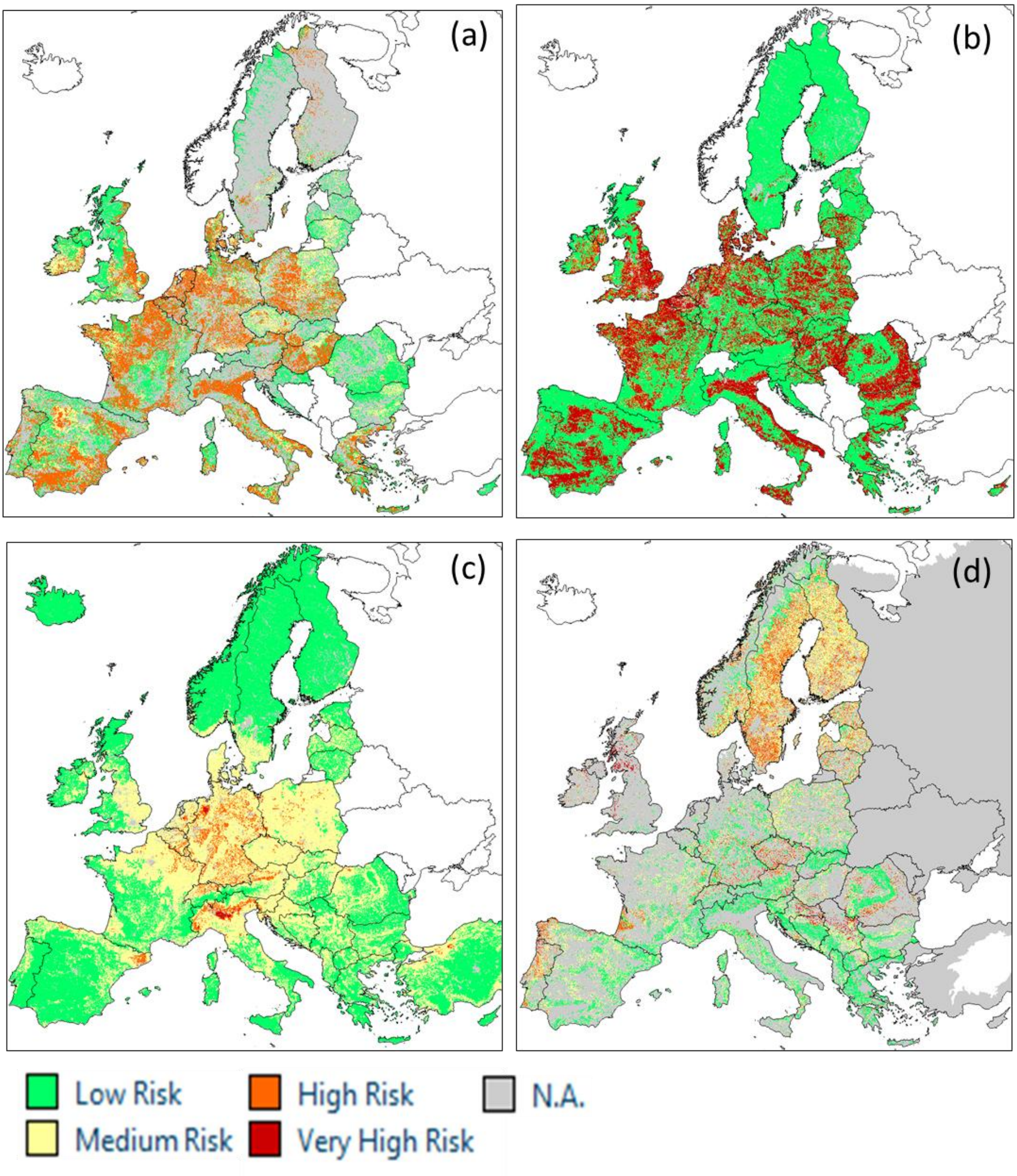


Figure 17: Maps showing the risk of a negative effect on birds for each pressure (a) agricultural intensification; (b) habitat loss and fragmentation; (c) atmospheric nitrogen deposition; and (d) forest management intensity

4.1.4. Mammals

Some 25% of terrestrial mammals are endemic to Europe (Temple and Terry 2009). Endemism is relatively high in southern Europe, especially the northern and eastern Iberian peninsula, the Italian peninsula and southern France. Endemicity is generally higher in the small, non-flying mammals than large ranging mammals and bats.

Similar to birds, **agricultural intensification** and **habitat loss and fragmentation** constitute widespread and high risk for mammals across much of the EU (Figure 18a and Figure 18b). The high risk in the Po river catchment and Iberian peninsula are concerning because these are endemic species hotspots (Temple and Terry 2009). As for birds, **forest management intensity** in Boreal forests, poses a widespread and high risk of negative impact (Figure 18d). There is a knowledge gap on the impact of **atmospheric nitrogen deposition** on mammals, and expert knowledge from the IPBES Regional Assessment (IPBES 2018) was used to develop the risk map (Figure 18c).

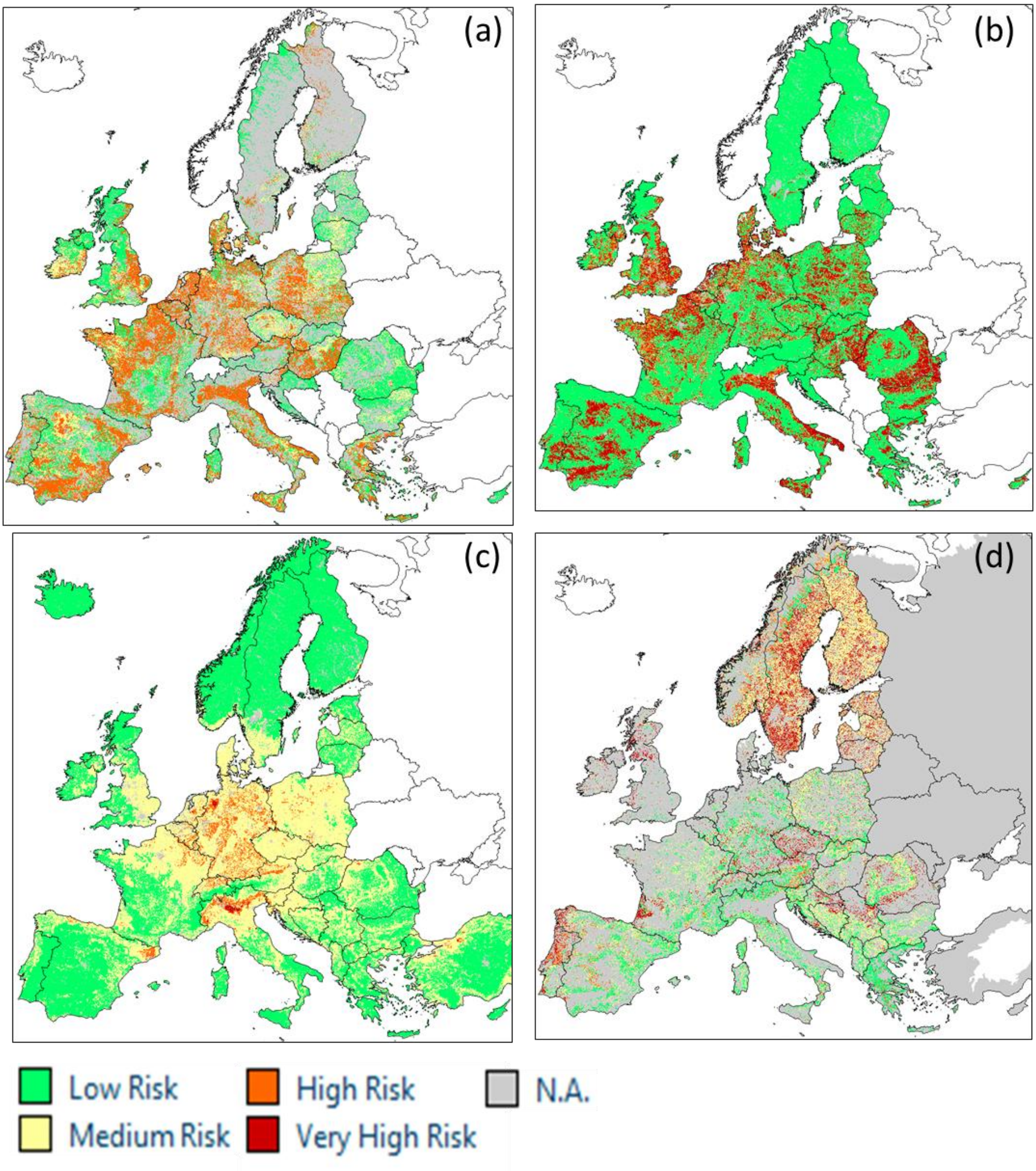


Figure 18: Maps showing the risk of a negative effect on mammals for each pressure (a) agricultural intensification; (b) habitat loss and fragmentation; (c) atmospheric nitrogen deposition; and (d) forest management intensity

4.1.5. Vascular plants

Agricultural intensification poses the most widespread and very high risk on vascular plants (Figure 20a), which concurs to findings in MAES that 83% of habitats dependent on adequate agricultural management are in inadequate conservation status (MAES et al. 2020). **Habitat loss and fragmentation** (Figure 20b) is widespread throughout Europe and, as for birds, is especially high in areas where agriculture is also practiced intensively (Figure 20a). According to the IUCN areas of high aquatic plant endemism are located in the north eastern and southern Scandinavian areas where forest management intensity is particularly high (Figure 20c) (Bilz et al. 2011).

There is a high concentration of threatened species along coasts of the south and west Iberian Peninsula, Greece, Italy, central Europe and on Mediterranean islands (Figure 19). Efforts to create natural corridors in these areas to protect vascular plant biodiversity should be increased in these areas, especially since they represent pressure refuges from **atmospheric nitrogen deposition** (Figure 19c). Pressures on vascular plants from atmospheric nitrogen deposition remain high to very high and widespread in central Europe despite the declining trend. Evidence suggests that, especially for heathlands and shrubs, active restoration will need to occur, paying careful consideration to restoring mineral nutrient balances that have been disrupted from chemical leaching processes (Bobbink et al. 2010).

Climate change threatens to change the conditions under which common varieties of agricultural crops grow optimally. It is therefore important to support and monitor alternative crop wild species. In Europe the most threatened crop wild species are in the south Iberian, and eastern Mediterranean, and the islands (Figure 19), where vascular plants also overlap with very high risk from agricultural intensification (Figure 20a). This is because alongside climate change, the greatest pressure to these wild crop species is intensive overgrazing, tourism, housing and urban development (Bilz et al. 2011).

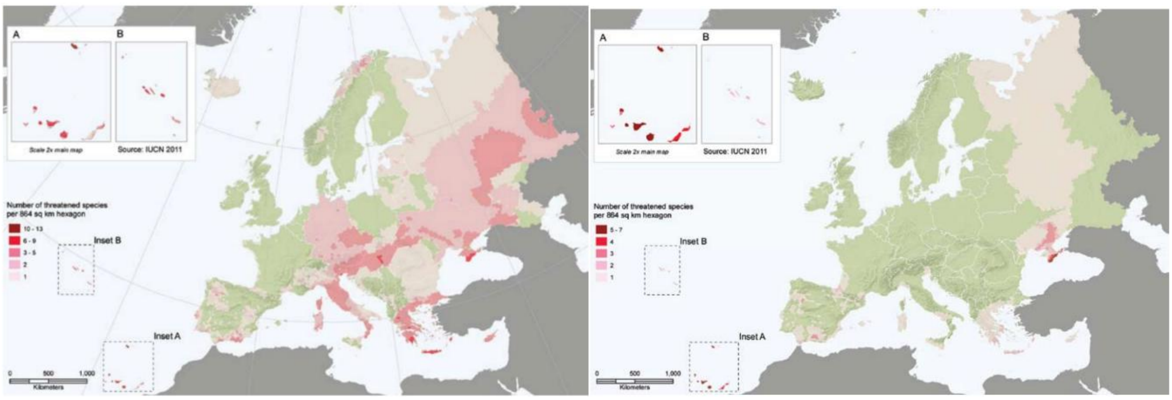


Figure 19: Maps showing the distribution of threatened policy plants in Europe (left) and threatened crop wild relatives in Europe (right). SOURCE: IUCN (Bilz et al. 2011)

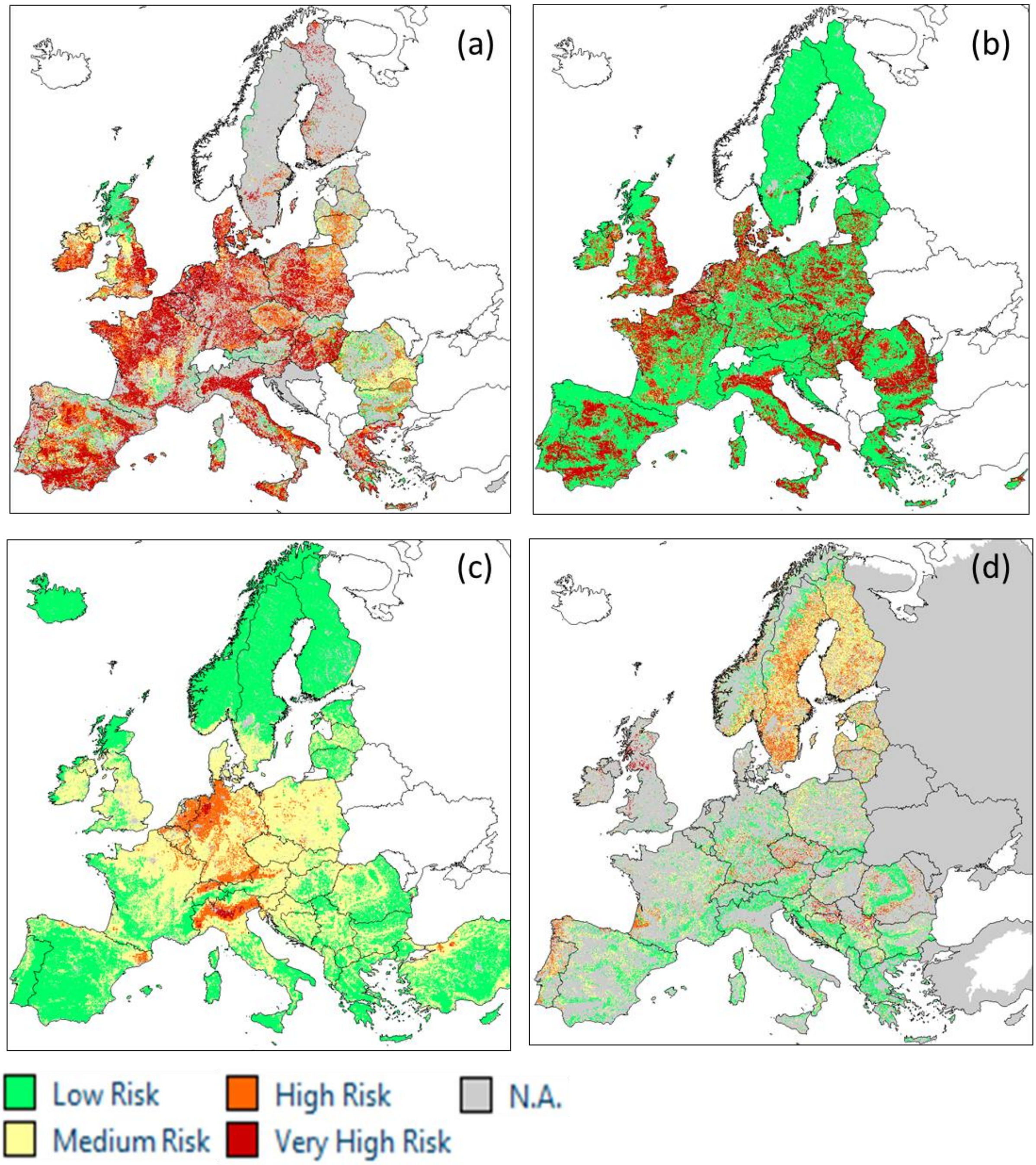


Figure 20: Maps showing the risk of a negative effect on vascular plants for each pressure (a) agricultural intensification; (b) habitat loss and fragmentation; (c) atmospheric nitrogen deposition; and (d) forest management intensity

4.1.6. Non-vascular plants and fungi

Agricultural intensification poses a major widespread and very high risk pressure to non-vascular plants and fungi across most of Europe (Figure 22a). **Atmospheric nitrogen deposition** also exerts its most acute impacts on non-vascular plants and fungi compared to other taxonomic groups (Figure 22c). Indeed, species within these taxonomic groups are often good indicators for monitoring early signs of success or failure at reducing this pressure (Bobbink et al. 2010). Lichens and mycorrhizal fungi hold potential as indicators, as they tend to be the most nitrogen sensitive and therefore the first to respond to impacts from nitrification, often both in individual population abundances and species diversity. As expected, the very high and high risk agricultural intensification of central Europe and the Po river catchment south of the Italian Alps coincide with those showing very high to high risk for atmospheric nitrogen deposition (Figure 22c). High risk areas for **habitat loss and fragmentation** also coincide with these areas (Figure 22d). These very high and high risk areas also overlap with threatened mosses, liverworts and hornworts (Figure 21). Lack of pressure mitigation in these areas will likely result in global species extinctions. The areas in northeastern coast of Scandinavia are also areas with high numbers of endemic mosses and high species richness of non-vascular plants (Figure 21). This overlaps with high risk areas for **forest management intensity** in the Alpine forests (Figure 22b).

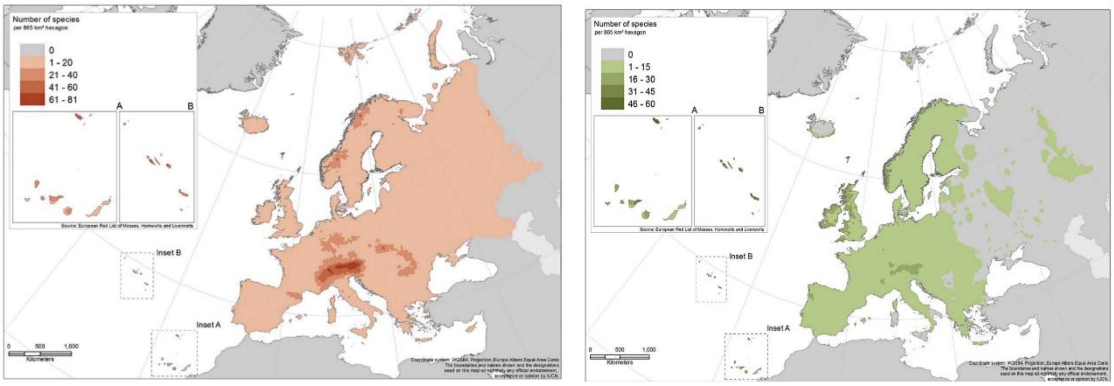


Figure 21: Distribution of a) threatened and b) endemic mosses liverworts and hornworts in Europe. ***SOURCE: Hodgetts et al. (2019)***

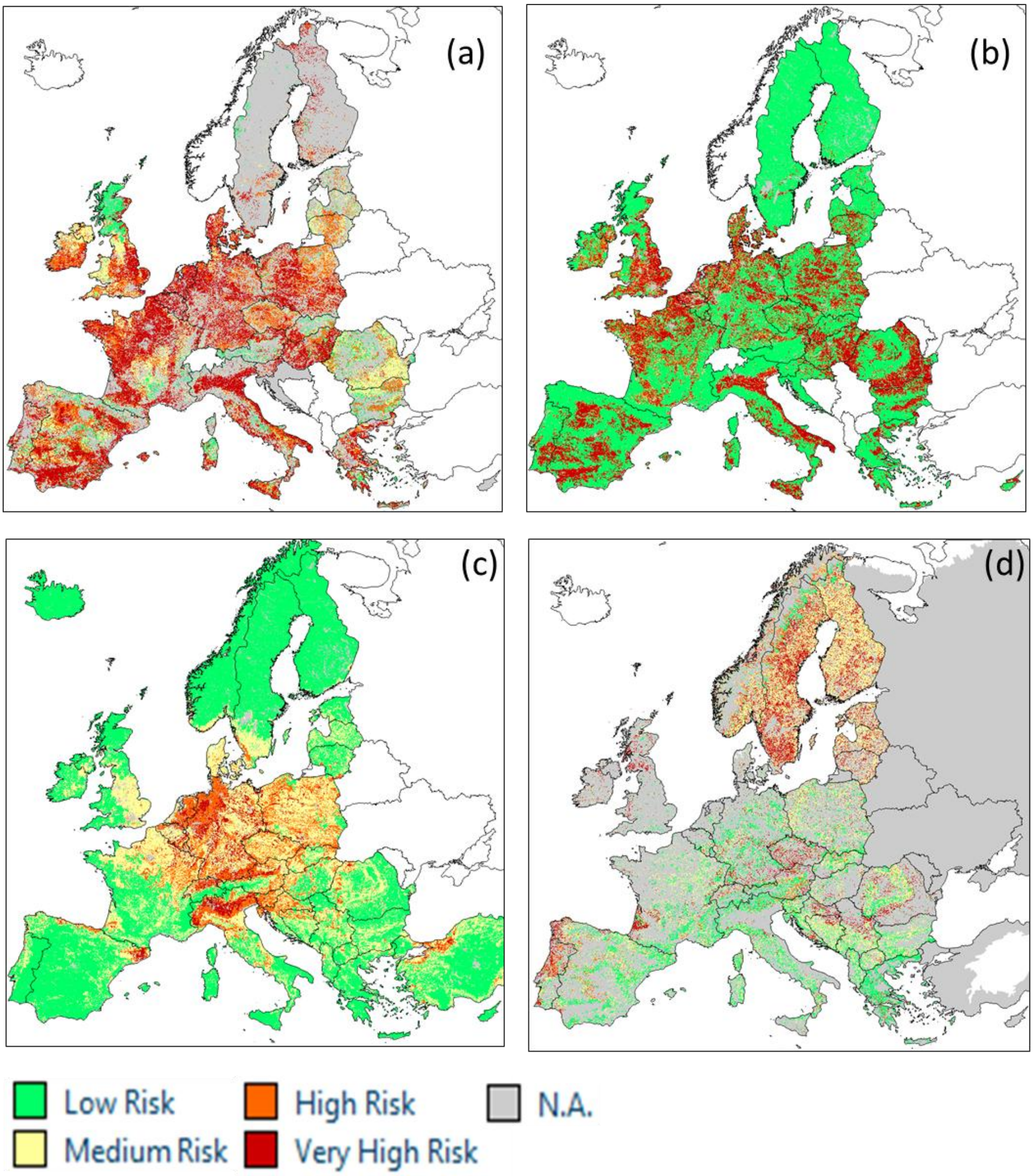


Figure 22: Maps showing the risk of a negative effect on non-vascular plants and fungi for each pressure (a) agricultural intensification; (b) habitat loss and fragmentation; (c) atmospheric nitrogen deposition; and (d) forest management intensity

4.2. Pressure effects across taxonomic groups

Pressure from **agricultural intensification** poses by far the most widespread risk (Figure 23a), with 40-65% of area for all taxonomic groups falling into a very high or high risk category (Figure 24). This proportion is highest for non-vascular plants and fungi, vascular plants, and arthropods and lowest for birds and mammals, with amphibians representing a proportion between these two extremes (Figure 24).

While loss of habitat from outright land conversion is now stable at EU level (MAES et al. 2020), the taxonomic group risk from **habitat fragmentation** remains the next most widespread and severe pressure, with 30% of area for all taxonomic groups falling into a very high or high risk category (Figure 23b and Figure 24). Restoring field margins, hedges, grass strips, lines of trees, patches of uncultivated land in agro-ecosystems, and green infrastructure to urban ecosystems is a matter of urgency as the EU embarks on its recovery programme in terms of the EU Biodiversity Strategy 2030.

Pressures posing very high or high risk from **forest management intensity** affect 20-25% of area for all taxonomic groups category (Figure 23d and Figure 24). These pressures are especially widespread and high in Boreal forests, and more dispersed high risk across the remaining forests of the EU.

Pressures from **atmospheric nitrogen deposition** are decreasing in the EU, and poses very high to high risk to 5-15% of taxonomic group ranges (Figure 23c and Figure 24). Particularly notable signals of very high and high risk are evident in the Benelux regions and the Po river catchment category (Figure 23c). Nonvascular plants are most affected and attention should be given to restoring this taxonomic group, to have cascading positive effects upwards to higher trophic levels.

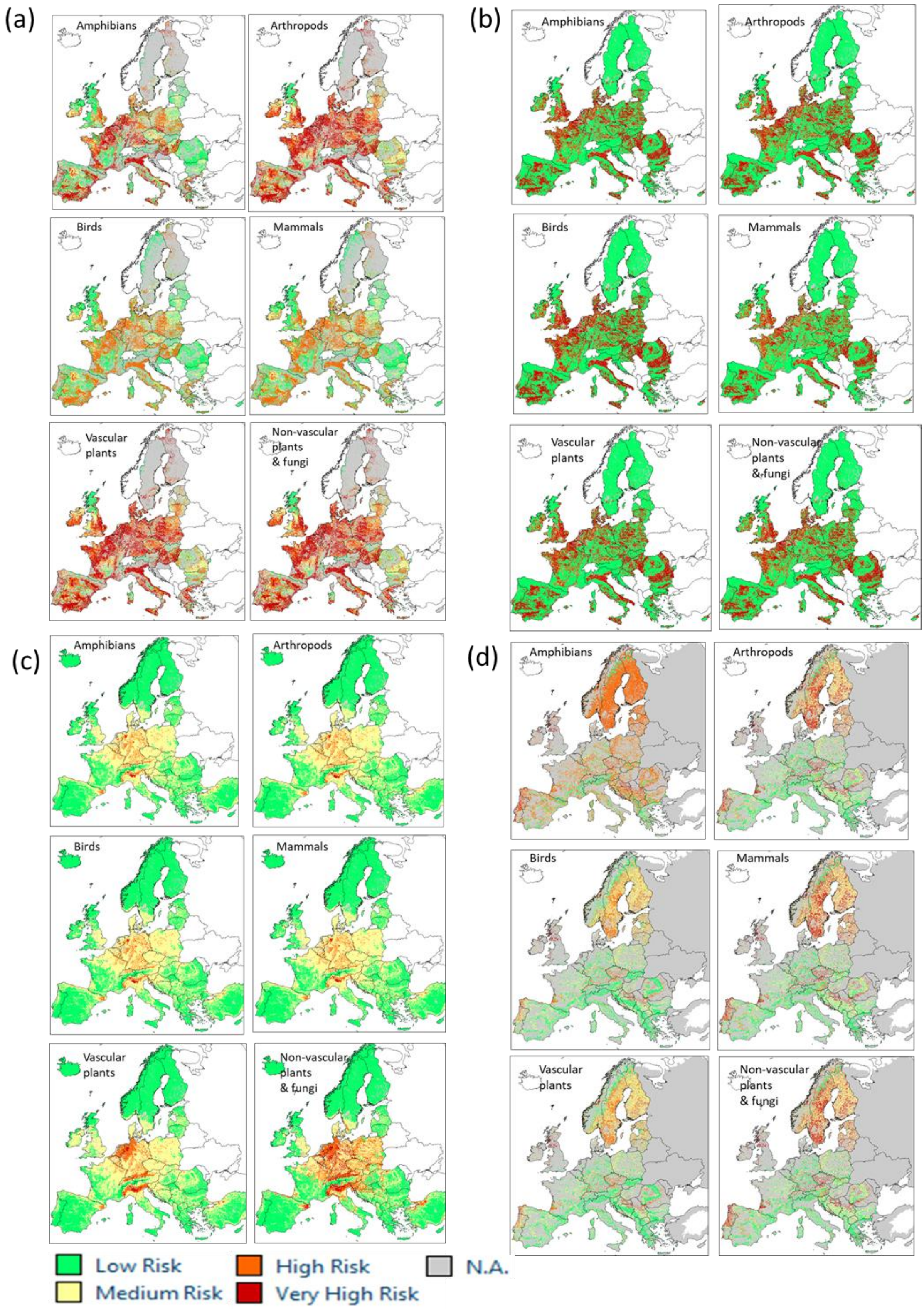


Figure 23: Differential distribution patterns of pressure risks across taxonomic groups for (a) agricultural intensification; (b) habitat loss and fragmentation; (c) atmospheric nitrogen deposition; and (d) forest management intensity

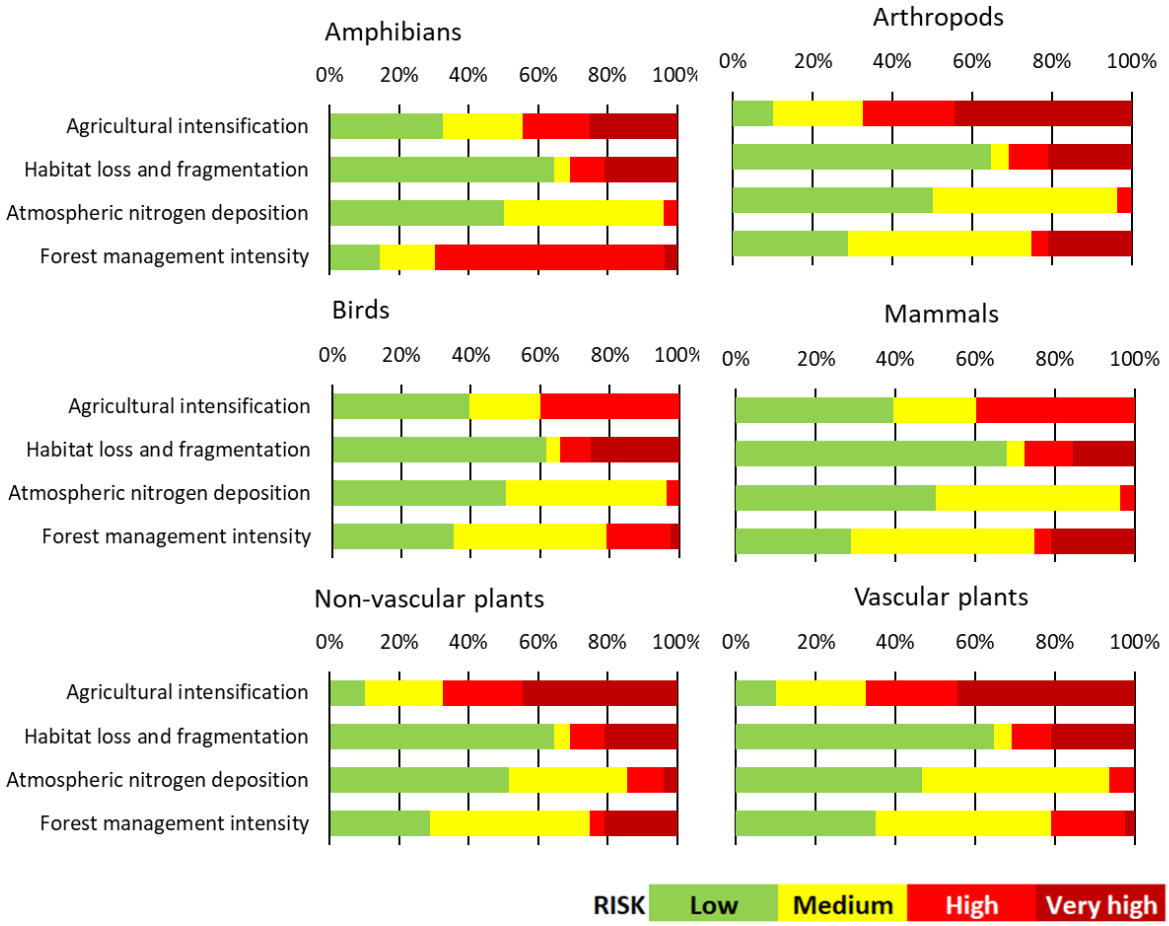


Figure 24: EU level summary for the percentage area where risk of a negative impact from each pressure is Low, Moderate, High and Very High for each taxonomic group

4.3. Pressure hotspots and coldspots in the EU

Pressure hotspots were mapped per taxonomic group, and represent areas where over half of the pressures at a location pose a very high or high risk to that taxonomic group. Similarly, pressure coldspots are areas where over half of the pressures pose a low risk to that taxonomic group. Varying very high/high and low risk categories for multiple pressures at a given location combine to produce a gradation of pressure hotspots and coldspots, as shown in the matrix of Figure 13. These combinations were mapped to provide a gradation of pressure hotspots (superhot, hot, warmer) and pressure coldspots (Supercold, cold, cooler), as shown in Figure 25.

At the EU aggregated level, the overall distribution pattern of pressure hotspots and coldspots is similar (Figure 25). However, the pressure hotspots for vascular plants, non-vascular plants and arthropods show a higher intensity with a 5-15% higher extent of pressure hotspots, including many more 'superhot' areas (Figure 26). This is driven by the higher risk of negative impact to these taxonomic groups from all pressures examined (Figure 23).

The map of pressure hotspots and coldspots visualizes opportunities that broadly inform strategic activities at EU aggregated level. These are outlined below in terms of three broad insights: pressure coldspots, pressure hotspots, and ideal areas for restoring landscape connectivity.

4.3.1. Pressure coldspots

Pressure coldspots can be viewed as refugia for species from pressures, and should be seen as focus areas for protected area expansion. Emphasizing pressure coldspots shifts policy emphasis away from the most pressurized sites, to focus on avoiding new pressure sources in currently unpolluted regions, where species loss will be more pronounced. There are good rationales to this approach. First, there is a great amount of uncertainty and disagreement in setting single (blanket) thresholds describing the limits to acceptable pressure intensity because of the variability in species responses at local levels. For many species, the evidence collated in the pressure factsheets (Nel et al. 2020) shows that by the time such single critical thresholds are reached, community assemblages and ecological functioning is already impacted in many local landscapes. Second, the restoration costs of protecting these areas is much lower. Third, the opportunity costs are likely to be lower – that pressures are lower in these areas is likely to be a good proxy that human use is low.

There are two broad regions where further protection of coldspots is particularly warranted:

- **Mediterranean pressure coldspots** are of particular importance. Although species richness may be low, the region has relatively high endemicity for all taxonomic groups compared to other parts of the EU. The implications are that global biodiversity loss in these areas is much more directly affected by pressures that threaten species in this region. In addition to the pressures that were considered in this spatial assessment, climate change and invasive species act as major amplifiers of existing pressures in the Mediterranean region.
- **Central Europe just east of the Benelux region provides an arc of pressure coldspots** interspersed with hotspot/coldspot areas. This region offers an extremely important focus area for protection via land stewardship and restoration. Biodiversity representative of this region is under severe threat from multiple pressures and immediate action is needed. Section 4.5.2 provides a storyline narrative of a landscape in southern Germany where such land stewardship is underway to bring back landscape multi-functionality and reduce pressures from agricultural and forestry management practices.

4.3.2. Ideal areas for restoring landscape connectivity

Most feasible biodiversity gains for restoration are likely to be had in the coldspot and moderate areas (as in the example in section 4.5.2). Ideally, green infrastructure and ecosystem corridors that are restored in the landscape should attempt to connect coldspot refugia through avoiding as many hotspot areas as possible. It is important to note that areas that are labelled 'hotspot/coldspot' are not free of high risk pressures (see matrix of combinations in Figure 13). Rather, species in these areas are impacted by at least one pressure hotspot. The southernmost Boreal forests of Sweden are a good illustrative example of this, in which the intensive pressures from forest management practices may pose a risk to species even though risks from other pressures are low (Figure 23d). More detailed species-specific information and management recommendations can be found in the respective pressure factsheets in Nel et al. (2020).

4.3.3. Pressure hotspots

Pressure hotspots can be viewed as land use mitigation areas, where risk from multiple pressures is very high or high, and sector-specific interventions at local and Member State level are needed to manage these areas more sustainably (e.g. sustainable agricultural and forestry management practices, sustainable cities, circularity at all scales). There are four key pressure hotspots evident at the EU aggregated level, where multiple pressures pose very high or high risk on species:

- Po river basin
- Benelux region
- southeastern United Kingdom (UK; including the East and West midlands, Eastern England and Yorkshire)
- southern tip of the Iberian peninsula

The pressure hotspots of the Po river basin and Benelux represent a meeting point of very high and high risk agricultural intensification, habitat loss and fragmentation and atmospheric nitrogen deposition. The southeastern UK and southern Iberian peninsula pressure hotspots are strongly driven by habitat fragmentation, and secondarily by agricultural intensification.

At EU aggregated level, these pressure hotspots are already well-known. However, this analysis gives a taxon-specific and ecosystem-specific spatial interpretation of how biodiversity is likely to respond to multiple pressures, and this can be regularly repeated to track how pressure hotspots and coldspots may progress as pressure gradients change.

4.4. Pressure hotspots and coldspots across ecosystem types and biogeographic regions

Pressure hotspots for taxonomic groups across ecosystem types show broadly similar results to the conservation status of habitats assessed in the MAES assessment (MAES et al. 2020), with the following ecosystems facing the highest through to lowest proportion of pressure hotspots: croplands, grasslands, forests, heathlands and shrubs (Figure 27). Across biogeographic regions, taxonomic groups facing highest through to lowest proportion of pressure hotspots include: Atlantic, Continental, Mediterranean, Pannonian, Boreal and finally Alpine (Figure 28). The threat to biodiversity posed by multiple interacting pressures is well-known in the Atlantic and Continental, and there has been concerted effort to reduce pressures in these areas, which we are seeing in pressure indicators of the MAES assessment (MAES et al. 2020). However, these reductions are still insufficient to bend the curve for most taxonomic groups that still remain with a high proportion of area in pressure hotspots. Furthermore, the pressure hotspots of the Mediterranean biogeographic region are particularly concerning. First, the region has high species endemicity thus implying high risk of global biodiversity extinctions should pressure trends continue. Second, the pressures from climate change and invasive alien species are expected to be particularly high in this biogeographic region and will act to amplify the interaction of multiple pressures in pressure hotspots.

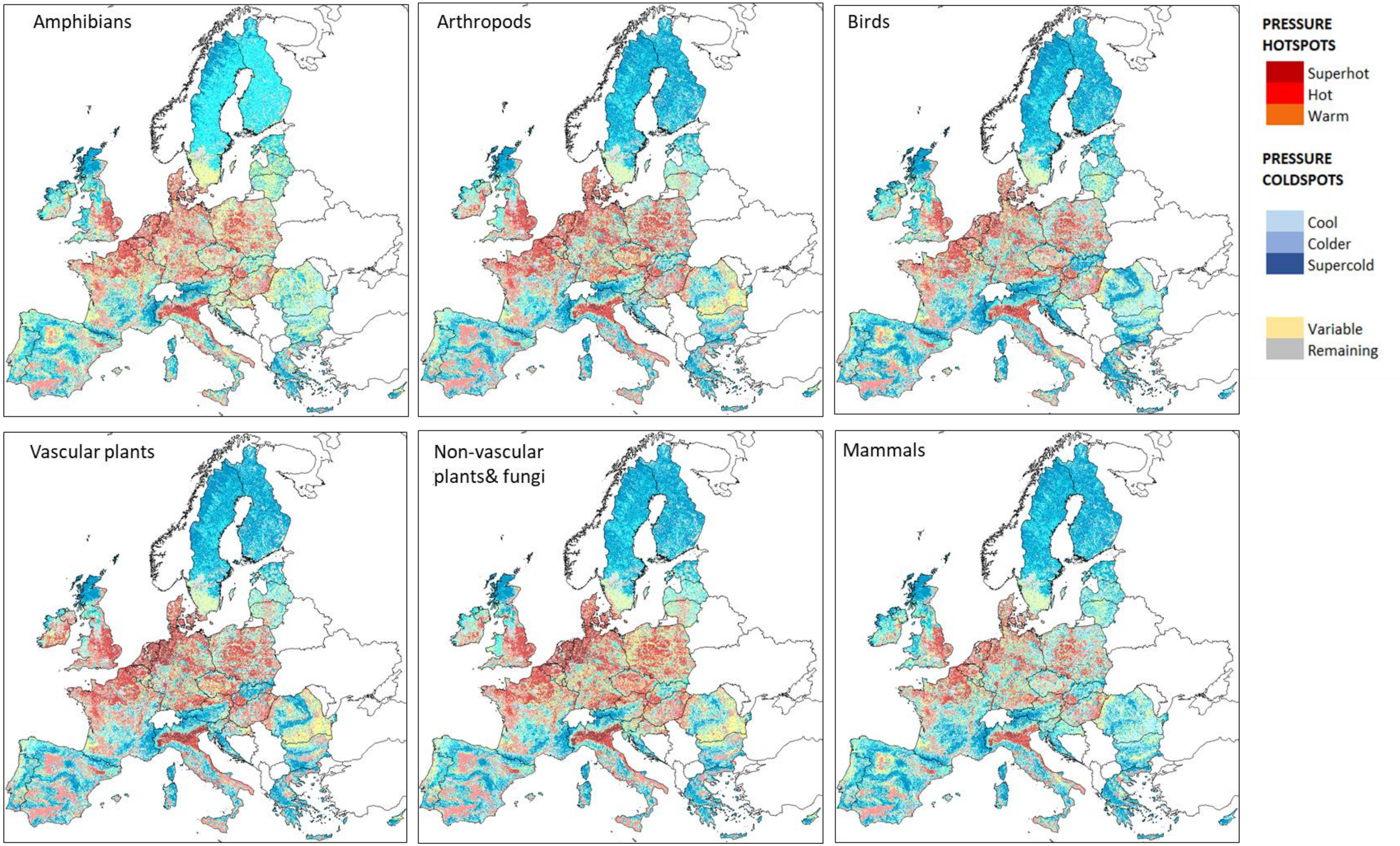


Figure 25: Maps summarizing the pressure hotspots and coldspots for each taxonomic group across the EU

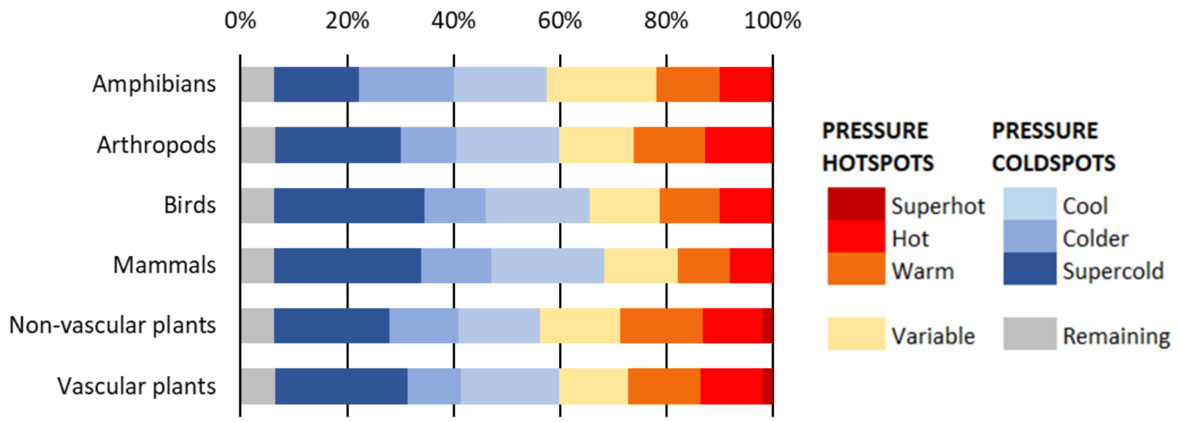


Figure 26: EU level summary of the percentage area for each hotspot-coldspot category for each taxonomic group

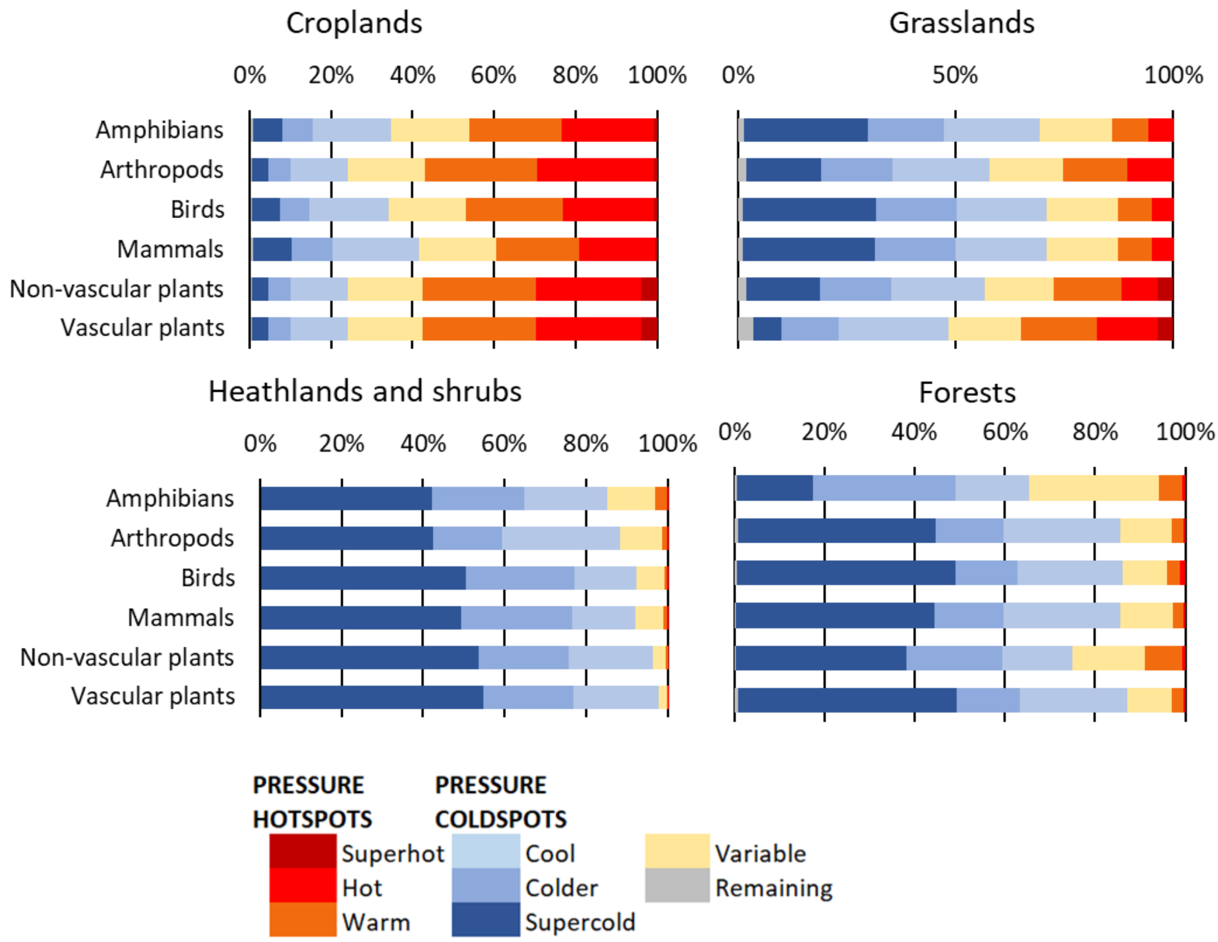


Figure 27: Summary at the level of ecosystem type of the area of hotspot-coldspot categories for each taxonomic group in terms of (a) absolute area and (b) % area

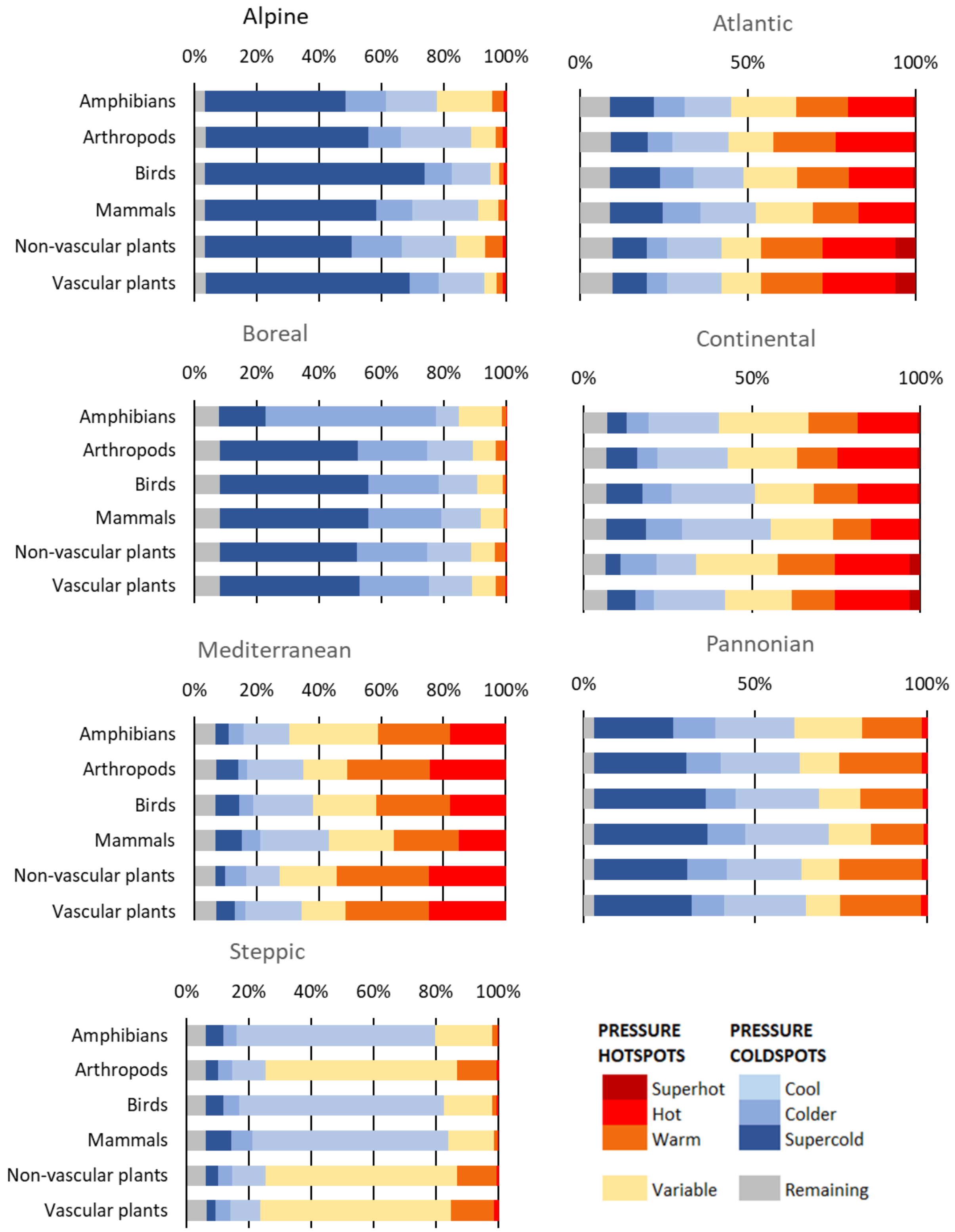


Figure 28: Summary at the level of biogeographic region of the area of pressure hotspot-coldspot categories for each taxonomic group

4.5. Illustrative integrated narratives

The integrated narratives below provide local examples of the ways in which these maps can be used as a starting point for contextualizing with local knowledge and planning conservation and restoration efforts. We have chosen four regions, with the narratives of the regions labelled 1, 2 and 3 in Figure 29 corresponding to the three broad clusters of interventions respectively associated with: mitigation in pressure hotspots, and areas for restoring landscape connectivity with pressure coldspots, and refugia of pressure coldspots. The regions labelled 4 in Figure 29 describes climate change and invasive alien pressures, which were not mapped in this spatial assessment, but are crucial to consider.

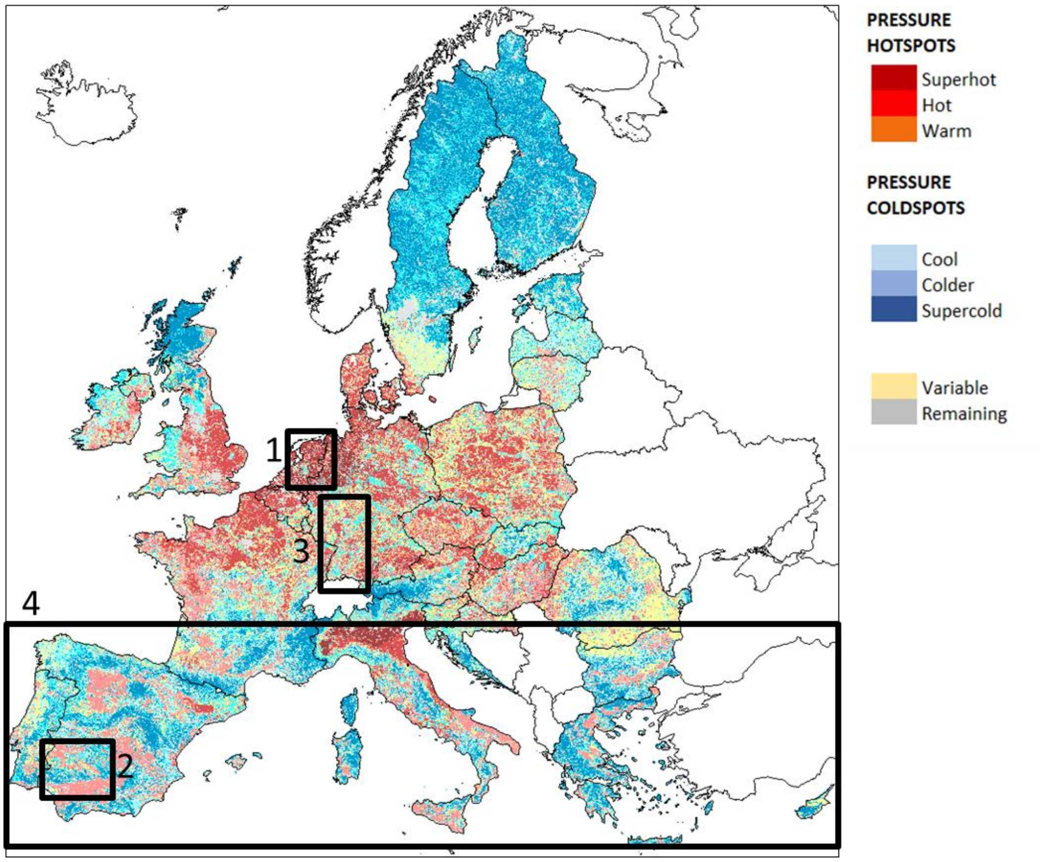


Figure 29: General locations of four integrated narratives regarding management of landscapes according to different pressure hotspot and coldspot profiles.

The hotspot-coldspot maps of non-vascular plants is used here as this represents the taxonomic group with the most widespread hotspots. Maps for other taxonomic groups are shown in Figure 25. Location numbers are discussed respectively in sections 4.5.1, 4.5.2, 4.5.3, and 4.5.4.

4.5.1. Nitrogen emission reduction and restoration of heathlands and bogs in the Netherlands

Irrespective of the taxonomic group, the Netherlands emerges as a hotspot of risk across multiple pressures. The entire Benelux and neighboring Germany are densely populated, with urban clusters alternated by intensive agricultural areas. As a result, nature in this region is highly fragmented. There is hardly any forest - only 8% of the land surface of the Netherlands consists of forest, the lowest percentage of all countries of any size in the EU27. However, the forest area is increasing: since 1990 the national government has actively stimulated the expansion of forests because there was a great need for additional recreational opportunities, for nature area and for wood as a raw material. **New forests** were created on agricultural land or in the urban area. This is expected to have positive benefits on habitat loss and fragmentation, particularly for taxonomic groups that are able to make use of improved landscape permeability, such as **arthropods, birds and mammals** (Figure 25). Although forests are expanding in the Netherlands, heathland and wetlands (in particular, raised bog areas) have been drastically reduced in extent over recent centuries to make way for agriculture. Currently, only about 50,0000 ha of heathland remain, including 6,000 ha of raised bog[8]. These nutrient-poor systems are highly sensitive to acidification from atmospheric nitrogen deposition. Precisely this region is one of the areas with the highest deposition in Europe, as a result of the large emissions from intensive agriculture in the region. Species that thrive under enriched nitrogen conditions, such as *Molinia caerulea*, threaten to eliminate specific plant species, and hence amphibians and insects that are characteristic of heathland and bog systems. The Dutch government is currently enshrining in a bill **mitigation measures for atmospheric nitrogen deposition to be greatly reduced make way for nature to become more resilient**. For agriculture, this means a transition to future-proof (circular) agriculture with as few emissions as possible. Funds will be made available for investments in **sustainable stables, less protein in cattle feed, better use of manure and other circularity measures**. With these measures, the national government is focusing on vital, robust and strong nature, which is also resilient to climate change.

Studies commissioned by the national government indicate that restoration of vulnerable nature areas is possible, but bending the curve will not take place in the short term[9]. Information collated in the pressure factsheets on atmospheric nitrogen deposition (Nel et al. 2020) show that **active restoration is need to bend the curve for biodiversity**. **Reinforcing feedbacks** occur from nitrogen deposition, such as shading, litter accumulation, production of chemicals which inhibit competitor growth, and loss of symbiotic mycorrhizal fungi. Once these processes have occurred, recovery of the original vegetation may require a very long time (Stevens et al. 2004). Grazing, mowing and sod-cutting – which remove nitrogen and excess litter – are common approaches to managing shifts in species composition in grassland, heathland and wetland ecosystems. Van der Bij et al. (2017) studied restoration on former agricultural sites under high nitrogen deposition and found **that topsoil removal reduced nitrogen but needed to be complemented with simultaneous reduction in atmospheric nitrogen**, and **attention to the soil microbial system** for enhanced vegetation development. In heathlands, restoration efforts also need to pay attention to soil microbiota and chemistry (e.g. ratios of N:P or C:N, levels of K^+, Ca^{2+}, Mg^{2+} and Al). This these nutrient-limited ecosystems, **simple removal of nitrogen enriched topsoil further exacerbates plant nutrient imbalances by removing other important minerals and thus destroying, e.g. N:P or C:N ratios** (Vogels et al. 2017). Ecological recovery may be also delayed by factors such as species' dispersal abilities and seedbank depletion (Basto et al. 2015).

[8] Compendium for the Environment; https://www.clo.nl/indicatoren/nl1590-natuurareaal?ond=20879
[9] https://www.rijksoverheid.nl/onderwerpen/aanpak-stikstof/nieuws/2020/10/13/stikstofaanpak-sterkere-natuur-perspectief-voor-de-bouw

4.5.2. Green veining in the agricultural landscape of the Upper Rhine valley

The **intensively cultivated agricultural landscape of the Rhine valley appears as pressure hotspot** with very high to high risk from multiple pressures on all taxonomic groups. It is situated between the **German Black Forest and French Vosges, which are pressure coldspots**. In this area, farming practices have historically seen increased intensification, as is the case for many other agricultural lands in Europe (Henle et al. 2008). Agricultural intensification means higher yields and less labour inputs (Clavel et al. 2011; Bukh et al. 2018), as well as higher nitrogen emissions and strong habitat fragmentation, resulting in a loss of biodiversity and ecosystem functioning (Emmerson et al. 2016).

Active restoration in this landscape however is now underway. The intensive agricultural land in the Upper Rhine valley is bordered on two sides by pressure coldspot refugia of the German Black Forest and the French Vosges. While these forest areas are partly under intensive forestry management, they also comprise **clusters of multifunctional forest (Figure 11)** which greatly benefit arthropods, plants (both vascular and non-vascular species), birds and mammals. Further **fragmentation-mitigating measures** applied in the agricultural area of the Upper Rhine valley are now benefiting these same taxonomic groups. Studies show that the creation and management of woodlots and hedgerows is increasing the permeability of the landscape for these taxonomic groups.

Woodlots serve as stepping stones, and hedgerows and flower strips along fields function as corridors for dispersion. Locally, on the German side of the valley, over 10% of the total area is now covered with flower strips, consisting of a rich mix of perennials. This leads to the local increase in pollinator abundance, which facilitates pollination services in the agricultural fields. Specifically, **biodiversity of wild bees and butterflies (even the specialists) benefitted from the network of flower strips in this area** (Bukh et al. 2018). Implementation of flower strips should include a broad diversity of flowering species, and available plant resources (even if they are dry) should be present throughout the year If these enhancement measures are made, the longer they are implemented the more specialist species are benefitted (Bukh et al. 2018). **The density of corridors are expected to have synergetic effects in climate change adaptation**: species may respond to shifting climate conditions by shifting their ranges northwards and/or mountain upwards (Lavorel 1999), which is easier in a permeable landscape (Opdam and Wascher 2004; Cormont 2011). In addition, **a landscape that is marbled with small landscape elements looks attractive**, which increases the potential for recreation in the area.

4.5.3. Cultural landscape: the Iberian peninsula

The southern parts of the Iberian peninsula are areas where agricultural intensification and atmospheric nitrogen deposition are very high (Figure 23). They are also areas where **endemic plants, bees, amphibians and birds are highly threatened** (Source: IUCN). The pressure of habitat loss and fragmentation is also a high risk in this area for almost all taxonomic groups, but **risks to endemic plants are particularly concerning**. The wild relatives of agricultural crops are also concentrated in these areas and with climate change, this genetic diversity needs to be protected in case current varieties can no longer thrive under increasing climate pressures. This is particularly important in the southern Iberian peninsula which is already one of the hardest hit regions in the EU in terms of climate change, and set to continue in this way (Maes et al. 2020).

The cultural landscape in this area (the dehesa) is an ancient human-shaped ecosystem comprising high landscape heterogeneity due to changing tree cover composition and density, mixed pastures, shrubs and the presence of livestock (Maldonado 2019). However, the landscape is becoming increasingly degraded due to overgrazing, and erosion resulting from land abandonment. Combining cultural heritage programs on farming with protected areas and land stewardship offers means of achieving joint outcomes that support integrative farming practices, preserve cultural landscapes, improve the natural area, enhance soil quality, and conserve biodiversity.

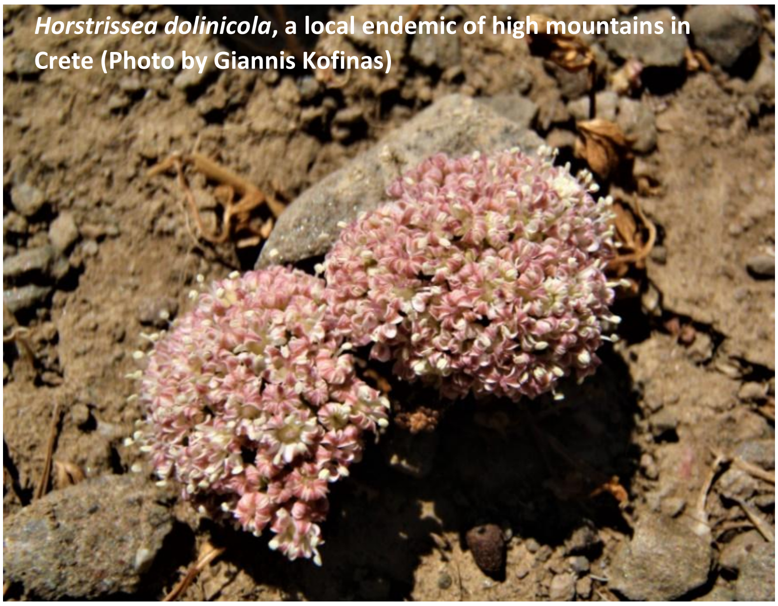
There are many co-benefits to be had from moving beyond conventional protected areas that 'lock away' resources from people in the landscape, to protection mechanisms for production landscapes that integrate indigenous and local knowledge, cultural heritage, restoration and biodiversity conservation.

The Donana area in Spain is an example where a more social-ecological approach to protection is actively seeking to reconnect people in production landscapes with nature. Historically, conventional protected areas have long been in competition with intensively managed surrounding landscapes, separating nature and people. This polarization has often resulted in social conflicts between stakeholders with different interests, with largely negative consequences for biodiversity and ecosystem services. Protection initiatives are now broadening to a more socio-ecological system perspective which emphasizes biodiversity conservation as well as a variety of ecosystem services valued by people in the landscape, including regulating and cultural ecosystem services (Oppla.eu). New ways to save and conserve this region, such as traditional farming practices and tourism, are being explored through the diverse knowledge of different stakeholders: from local residents to businesses, farmers, and tourism (Quintas-Sorian 2016). **Stimulating partnerships can help bring the ecosystem services and smarter landscape-wide practices back to this highly important ecological area for endemic and threatened biodiversity**.

4.5.4. Connecting nature to facilitate the response of species to climate change

The Mediterranean basin is a global hotspot of vulnerable species (Pacifici et al. 2015), with high levels of endemism and diversification (Médail 2017). The impact of climate change affects all of the EU and is increasing, but it is most pronounced in the Mediterranean (MAES et al. 2020), which has a projected warming for this century that far exceeds the global trend. Species respond to the impacts of climate change by moving to areas that are more favorable for their living conditions. Current climatic conditions in the Mediterranean have already forced various species, from different taxonomic groups, to migrate to higher altitudes or northern-aspect moister slopes (Médail 2017), leading to local extinctions (Thackeray et al. 2016).

While current land conversion is stable at the EU aggregated level, there is a notable increase in on the Iberian peninsula and other areas in the Mediterranean (MAES et al. 2020). If these trends continue, they will seriously jeopardize the migration potential of species belonging to all taxonomic groups. Protected areas and natural ecosystems thus need to be sufficiently connected to facilitate the movement of species between protected areas along the climatic gradients.



Horstrissea dolinicola, a local endemic of high mountains in Crete (Photo by Giannis Kofinas)

Requirements for such migration potential is exemplified by the high-altitude areas and mountaintops of Crete, and important area in terms of plant diversity and threatened endemics. These mountaintops include flagship species, such as *Horstrissea dolinicola* (see photograph). Areas along the mid- and high-altitude mountains of Crete offer plant refugia from both climate change (Kougioumoutzis et al. 2020) and invasive alien species pressures (Dimopoulos et al. 2020). Some of refugia already overlap with protected areas. Landscape connectivity between these areas can be maintained or re-established by linking pressure coldspots through the landscape, and avoiding pressure hotspots wherever feasible. Corridors that link these refugia not only provide improve biodiversity conservation, but can offer a socio-economically viable and sustainable infrastructure that provides multiple goods and services to human populations (Estreguil et al., 2019).

5. Conclusions

This spatial assessment takes an aggregated level view of how current pressures are likely to impact species in the EU. It achieves this by synthesizing and mapping taxon-specific and ecosystem-specific pressure effects on species. By so doing, we aimed to produce knowledge products readily usable for EU policy (this spatial assessment) and management (the pressure factsheets). Like the MAES assessment, these knowledge products **offer a methodology for broadening current nature reporting and monitoring to a more complete coverage of terrestrial ecosystems**. This addresses the existing legal gaps that are not filled by the current nature directives. Through its focus on species, this assessment **provides complementary knowledge to the MAES assessment,** which largely emphasizes ecosystems.

While the nature directives cover a set of critical species and habitats for legal monitoring and reporting by Member States, there are still large gaps in the legal protection of species, habitats and ecosystems not listed in the nature directives. The MAES assessment drew attention to these gaps, and made a plea for managing the condition of ecosystems using the EU Taxonomy Regulation (EU 2020/852), which defines sustainable activities to ensure that minimum criteria be met for ecosystems to reach a 'good condition'. Good condition in relation to an ecosystem means that the "*ecosystem is in good physical, chemical and biological condition or of a good physical, chemical and biological quality with self-reproduction or self-restoration capability, **in which species composition, ecosystem structure and ecological functions are not impaired***." The knowledge rules developed in this assessment were based on pressure factsheets that synthesized over 300 cases[10] of pressure effects on a variety of biodiversity metrics in the EU. These provide a valuable piece of the puzzle in defining how species composition, ecosystem structure and ecological functions are likely to respond to pressure intensity gradients. They thus offer input into setting minimum criteria at aggregated taxon-specific and ecosystem-specific level. Furthermore, the methodology developed here allows these biodiversity responses to be explicitly linked to maps of pressure intensity gradients in the EU, **enabling spatially-explicit and repeatable assessment** for regular monitoring and reporting at EU aggregated level, to monitor biodiversity effects as pressure intensity gradients change.

The sections below provide a high-level summary of overall findings, reflect on the knowledge gaps and evolving refinements that could be made, and finally conclude by outlining some next steps to leverage the potential of taking this methodology from experiment to application.

5.1. Key findings

This spatial assessment demonstrates that it is feasible to regularly evaluate the expected effects of changing pressure gradients for many taxonomic groups and pressures at EU aggregated level. The peer-reviewed literature on species responses to pressures is fraught with variation, often resulting from lack of standard metrics for measuring species response, such as different species response metrics (e.g. species richness or diversity, community composition, measures of individual fitness) and different spatiotemporal considerations (e.g. patch vs. landscape vs. regional responses; short vs. long term responses). However, when aggregated to taxon-specific and ecosystem-specific pressure effects at EU level, broad signals can be distinguished. Moreover, and changes in these

[10] Many of these were themselves reviews and meta-analyses collectively on hundreds of cases

signals over time – as pressure gradients change – can help to track successes and failures at reducing pressures on biodiversity. The pressure factsheets capture the key species-specific variability at local context, information that is crucial for informing restoration efforts at local to Member State level. By contrast, the spatial assessment also shows that by aggregating this local-level information to taxonomic groups and ecosystem types, we can gain a 'helicopter view' of what is happening by the EU aggregated level.

A key conclusion of this report is that spatially-explicit assessment of pressure effects on taxonomic groups is crucial. Differential responses of taxonomic groups to pressures in different ecosystem types produce divergent spatial patterns of biodiversity risk across the EU. The differential responses combine with spatial pressure intensity gradients across the EU to produce **different risk profiles for each taxonomic group**. For example, the proportional area in the EU under risk of a very high to high negative effect from agricultural intensification for vascular plants, non-vascular plant, fungi, and arthropods is estimated to be 1.5 times that of other taxonomic groups. Likewise, under the current atmospheric nitrogen deposition on non-vascular plants is about 3 times higher than that of vascular plants under the current pressure intensity gradients.

Taxonomic risk maps emphasize the need to focus restoration efforts on lower trophic levels first (i.e., non-vascular plants and fungi, vascular plants and arthropods). Taxonomic groups at lower trophic levels display consistently higher and more widespread risk responses to pressures compared to those of higher vertebrate groups. This indicates that it will be insufficient to recover biodiversity at lower trophic levels by targeting large, charismatic species at higher trophic levels. This conclusion is supported by local level management findings and recommendations in all pressure factsheets (Nel et al. 2020) which show early alterations to lower trophic levels cascade to higher taxonomic groups through biophysical alterations to predator-prey relations, micro-climates and nutrient cycling etc. Changes to lower trophic levels have early and long-lasting impacts that need to be restored to bend the curve for biodiversity of higher taxonomic groups. Understanding these cascading impacts is crucial for restoration interventions at site level and they are generally poorly studied in the literature.

Broad signals of pressure hotspots and coldspots group interventions in the landscape into three broad opportunities for action. **Pressure coldspots** can be viewed as refugia for species from pressures, and should be seen as focus areas for protected area expansion – either through conventional protected areas or through land stewardship agreements. **Pressure hotspots** can be viewed as land use mitigation areas, where risk from multiple pressures is very high or high, and sector-specific interventions at local and Member State level are needed to manage these areas more sustainably (e.g. sustainable agricultural and forestry management practices, sustainable cities, circularity at all scales). The most feasible biodiversity gains for restoration are likely to be had in the **pressure coldspot and moderate risk areas** and these areas offer ideal opportunities for establishing ecological corridors or stepping stones that improve the connectivity of landscape and coherence of the EU nature network. Importantly the pressure hotspot-coldspot maps do not yet include pressures from climate change and invasive alien species. These pressures are increasing and are viewed as major amplifiers to co-occurring pressures. It is imperative that refugia from pressures of climate change and invasive alien species are thus included in future iterations of pressure hotspot-coldspot maps.

5.2. Reflection on knowledge gaps

The synthesis of peer-reviewed evidence of species responses to pressures was foundational to this assessment. The pressure factsheets thus produced provide a range of local effects of different species responses and management considerations from regional to local scales. Each pressure factsheet concludes with an aggregated response matrix summarizing the taxon-specific and ecosystem-specific responses to various pressures and assigning confidence limits based on the literature. Below we reflect on knowledge gaps evident in both the aggregated matrices (section 2) as well as the limitations of the spatial assessment (sections 0 and 4).

5.2.1. Pressure factsheets synthesizing peer-reviewed evidence

A plea for global meta-analyses to include more regional disaggregation. Meta-analyses provide a statistical procedure for combining data from multiple studies to identify common (or variable) effects. With the explosion of knowledge and data being published, meta-analyses are increasingly being encouraged as a way to systematically review evidence in the literature. It was beyond the scope of this assessment to undertake its own meta-analyses, but we actively searched for existing meta-analyses and upweighted the findings of these compared to single case studies through the use of confidence levels (section 2.1). However, the use of meta-analyses was confounded by the issue that many target a global audience – partly a result of high impact, global journals favouring a global perspective. Despite including many European cases, the vast majority of global meta-analyses only report effects at global level, requiring a return to the raw data to tease apart regional signals. This must change if we are to support regionally-contextualised strategies for bending the curve for biodiversity. It is not a big step to assemble these regional results when collating the results of a global meta-analysis. There are many global platforms that undertake regional assessments that could benefit from this regional disaggregation. Reporting according to globally-defined ecosystem types would also bring additional benefit. Initiatives aimed at developing globally-defined ecosystem types, such as those within the IUCN Red List of Ecosystems or Natural Capital Accounting processes[11], would greatly facilitate ecosystem disaggregation of global meta-analyses.

The collation of evidence made explicit which taxonomic groups and ecosystem types have severe knowledge and data limitations (grey cells in Figure 1). In general, vascular and non-vascular plants, fungi and arthropods were relatively well-studied across the different pressures compared to higher taxonomic groups. The evidence base is particularly lacking for molluscs and reptiles; thus we had to exclude these taxonomic groups from further spatial assessment. The pressures effects on species in sparsely vegetated habitats and wetlands are also under-studied relative to other ecosystem types. This is particularly concerning, as it is precisely these ecosystem types that face increasing pressure from coastal development and climate change, and – for wetlands – agricultural intensification. More peer-reviewed work targeting these ecosystem types is needed. In the interim, these **gaps can be addressed through the ample local knowledge that exists within Member States**, which can be mobilised through networks such as the emerging communities of practice emerging associated with the MAES assessment and IPBES Regional assessment (see next steps, section 5.3).

[11] https://seea.un.org/content/iucn-global-ecosystem-typology-v101-descriptive-profiles-biomes-and-ecosystem-functional

Species effects are more variable for habitat loss and fragmentation and forest management intensity. Although the overall pressure effect is negative for these pressures, the confidence levels show a much higher prevalence of Inconclusive or Unresolved signals (Figure 1). This is in part related to variation in species response metrics used and spatial and temporal scales over which the effects were studied (see next point).

Although we were able to ascertain broad pressure effect signals for taxonomic groups, important knowledge gaps still exist on the pressure effects to species across broader spatial scales and longer time scales. As a consequence, a lot is known about structure, composition and functioning at patch scale, but much less is known about the importance of these across broader scales, how they may be moderated by surrounding landscapes, and how they may be outweighed by other broad-scale processes such as increased spreading of risk and increased regional habitat diversity. There is also a lot of evidence to support the existence of time lags in species responses to pressures, but relatively few long term experiments have been set up to examine these.

Key knowledge gaps per pressure: **Agricultural management intensity** effects are biased towards vascular plants, birds, butterflies and mammals. Fewer studies are conducted on bryophytes, amphibians and small mammals, yet the effects from the few studies that do exist seem broadly similar to well-studied organisms like insects, birds and vascular plants. Biogeography seems to have a considerable effect on responses of the larger mobile taxonomic groups, yet pressure effects across biogeographic regions are poorly studied. **Forest management intensity** effects are particularly poorly studied in Mediterranean forest types, which are a naturally rare ecosystem type. There is also a lack of evidence of the effect of forest management intensity on amphibians, reptiles and molluscs. In this spatial assessment, effects of amphibians were assumed to be negative based on the expert opinion in the IPBES regional assessment (IPBES 2018), and thresholds were set according to the forest type sensitivity. **Habitat loss and fragmentation** effects are biased towards forests and grasslands, with only 28% cases accounting for species of heathlands and shrubs and wetlands. There is no evidence documenting the effects on sparsely vegetated habitats. Arthropods are by far the most-studied taxonomic group, focusing largely on butterflies. Vascular and non-vascular plants and mammals are also fairly well documented. The evidence base for fragmentation effects on amphibians is extremely limited, and there were no recent cases (>2010) focusing specifically on the fragmentation effects on reptiles or molluscs. **Atmospheric nitrogen deposition** effects on animal taxa are poorly studied and focus mainly on single species population. Animal community-level changes cannot yet be quantified. Impacts on animal taxa accounted for only 25% of the cases collated and there were no cases exploring the effects on mammals or reptiles. In this spatial assessment, effects of mammals were assumed to be negative based on the expert opinion in the IPBES regional assessment (IPBES 2018), and thresholds were set according to the ecosystem type sensitivity. The cases reporting on arthropod and amphibian impacts all focused on effects occurring on single species populations. Only the bird cases reported more broadly on the cascading impacts between arthropods and birds. There were no cases reporting on changes in animal species richness or diversity. There are no agreed critical exceedance loads for fauna. **Invasive alien species** effects on wetland ecosystems was less studied that the other ecosystem types. The effects of alien invasive species on all animal taxa studied was overall negative, but there is a lack of information for many taxonomic groups – notably reptiles and amphibians. Riparian habitat is particularly susceptible to invasion but it is not yet possible to make this explicit using MAES ecosystem types.

5.2.2. Risk matrices, pressure intensity gradients and spatial products

In addition to the knowledge gaps on taxonomic groups and ecosystem types described above, important data gaps on pressure intensity constrained the spatial assessment. While it was feasible to assess the four pressures we considered, different aggregated approaches to exploring other pressures may be needed. For example, **pressures from invasive alien species and climate change** may require a less aggregated assessment, as these pressures require consideration of strong local context specificity (e.g. micro-climate and species interactions for climate change, recipient community interactions with invasive species, social-economic contexts). Integration of these effects into the pressures hotspot-coldspot maps is especially important because pressures from **climate change and invasive alien species are both increasing and act as major risk amplifiers when interacting with other pressures**. The use of the QuickScan tool allows for flexibility to include new information, should data become available through peer-reviewed literature or expert consensus (see next steps, section 5.3).

Limitations to spatial maps of pressure intensity. Pressure intensity gradients were mapped using different spatial layers of ecosystem types, which caused some spatial mismatches. The data layers of **agricultural intensification and forest management intensity** did not include explicitly include wetlands ecosystems, which meant we were unable to assess wetlands in this spatial assessment. The **Landscape Mosaic**, used as one layer to depict habitat loss and fragmentation, does not include small woody linear features which are becoming increasingly important in restoring agro-ecosystem landscapes. In addition, there may be a need to consider variable widths of the surrounding landscape in calculating **a Landscape Mosaic for different taxonomic groups (e.g. sessile vs wide-ranging biota).**

Communicating underpinning uncertainty in maps. We established many relationships to determine the taxon-specific and ecosystem-specific risk category of each pressure effect (section 3.1). The original peer-reviewed evidence places **different confidence levels on these relationships**: Well established, Established but incomplete, Inconclusive, Unresolved (section 2.1; Figure 1). Depicting how these differing confidence levels combine in the taxonomic risk maps and pressure hotspot-coldspot maps is challenging and has not been attempted in this experimental version. Testing the **sensitivity of the pressure intensity thresholds** used should also be carried out.

5.3. Next steps

This work began as an experimental project to develop and test a methodology for an aggregated spatial assessment of pressure effects on taxonomic groups at EU level. We have shown that it is feasible to do this for at least four pressures and six taxonomic groups. Moreover, the assessment can be repeated at regular intervals to track the changes to taxonomic groups as pressure intensity gradients change. This experimental work provides a good foundation on which to build, and is now ready for a more iterative expert deliberation to make refinements, fill knowledge gaps and develop consensus on the pressure intensity thresholds used to denote the taxon-specific and ecosystem-specific responses to pressures.

We recommend that an iterative review process be adopted with various EU stakeholders to leverage the potential of taking this methodology from experiment to application. There are many application opportunities, which include:

- **Enhancing the species dimension of the MAES assessment framework** by including the taxon-specific risk per ecosystem type. Both assessments provide the possibility for monitoring and reporting on EUs progress towards bending the curve for biodiversity.
- **Testing the application of this approach in biodiversity accounting** in terms of the United Nation's System of Environmental Economic Accounting (SEEA).
- **Input into the EU Taxonomy Regulation (EU 2020/852)** in terms defining minimum criteria at aggregated taxon-specific and ecosystem-specific level that ensure that species composition, ecosystem structure and ecological functions are not impaired.
- **Informing the EU nature restoration plan in terms of its new 2030 Biodiversity Strategy**. Two specific applications are possible. First maps of pressure hotspots and coldspots can inform the building of a coherent Trans-European Nature Network through connecting pressure coldspots (refugia) by avoiding pressure hotspots where possible. The narrative storylines in section 4.5 provide local examples of the ways in which these maps can be used as a starting point for contextualizing with local knowledge. Second, it can facilitate repeated assessment to track how the EU progresses in its pressure reductions on taxonomic groups.

Targeting stakeholders involved in these applications would be a good point of departure. These stakeholders can be mobilised through the emerging communities of practice associated with the MAES assessment, the EU networks involved in the IPBES Regional Assessment, and the EU networks involved in the global process of experimental ecosystem accounting (SEEA-EEA). Importantly, the approach to the spatial assessment used a participatory GIS tool (QuickScan) to set up the knowledge rules and generate the maps outlined in this report. This tool can be used in collaborative workshops with experts and local stakeholders to incorporate the rich local knowledge at Member State level.

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