# ASSESSING SPILLOVER FROM MARINE PROTECTED AREAS TO ADJACENT FISHERIES

## Baltic and North Seas, Atlantic EU Western Waters and Outermost Regions

## Final Report

European Maritime, Aquaculture and Fisheries Fund (EMFAF)


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## Final Report

Specific Contracts

CINEA/EMFAF/2021/3.1.4/Lot1/02/SC11

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| Term | Description |
|---|---|
| AC | After Control |
| ACI | After Control Impact |
| AI | After Impact |
| AIC | Akaike Information Criterion |
| AIS | Automatic Identification System |
| ANOVA | Analysis of Variance |
| BA | Buffer Area |
| BAC | Before After Control |
| BACI | Before After Control Impact |
| BUV | Baited Underwater Video |
| CFP | Common Fishery Policy |
| CINEA | European Climate, Infrastructure and Environment Executive Agency |
| CPUE | Catch Per Unit Effort |
| DG MARE | Directorate-General for Maritime Affairs and Fisheries |
| DST | Data Storage Tags |
| EEZ | Exclusive Economic Zone |
| EMFAF | European Maritime, Fisheries and Aquaculture Fund |
| EU | European Union |
| FAMD | Factorial Analysis of Mixed Data |
| FPA | Fully protected area |
| GLMs | Generalised Linear Models |
| GLMM | Generalised Linear Mixed Models |
| GAM | Generalised Additive Models |
| IUCN | The International Union for Conservation of Nature |
| MPA | Marine protected area |
| MAPAFISH | Study CINEA/EMFF/2020/3.2.6 Specific Contracts:09, Lot 1 & 10, Lot 2 |
| MLS | Minimum Landing Size |
| NGO | Non-Governmental Organisation |
| OECM | Other Effective Area-based Conservation Measures |
| OWF | Offshore Wind Farm |
| PMLS | Professor Luiz Saldanha Marine Park |
| PPA | Partially protected area |
| SAMOVA | Spatial Analysis of MOlecular Variance |
| SAC | Special Area of Conservation |
| SCI | Site of Community Interest |
| SPA | Special Protection Area |
| VMS | Vessel monitoring system |
| UK | United Kingdom |

## ABSTRACT

Marine protected areas (MPAs) are widely recognized as an important tool for biodiversity conservation and fisheries management. Despite empirical evidence that abundance and biomass of fished species increase within MPA boundaries, the potential for MPAs to provide fisheries benefits to adjacent waters remains debated. This study documents the first systematic review of empirical evidence for spillover from MPAs in the European Union and other temperate regions. Findings show that scientific evidence of ecological and fishery spillover is relatively sparse. The combination of MPA characteristics (its age, local context and whether it is part of a network) proved capable of predicting the occurrence of spillover and therefore these are key considerations for the design of MPAs. Further, this study confirms that species mobility and reproductive strategies are important traits in explaining occurrence of spillover. There is a wide range of methodological approaches (sampling design, methods, statistical analyses) used in the literature to investigate spillover. Ideally, assessment should be based on a Before After Control Impact design, with a distance gradient sampling scheme integrated over time. A combination of studies, using biological sampling and tagging, gives a more complete picture of potential spillover effects. Using the literature available and study quantitative analyses, a conceptual model tool was developed to estimate the likelihood of spillover for existing and proposed MPAs. The tool integrates the potential social, ecological and economic factors that may lead to MPA spillover. Finally, qualitative and quantitative approaches were used to evaluate ecological and/or fishery spillover effects for 15 case studies from across Europe. The case studies demonstrate that MPAs can lead to increased species spillover, but these patterns are species-specific, and spillover effects will take a relatively long time period to be relevant for fisheries. Overall, this work highlights elements that could guide strategies to enhance local fishery management using MPAs. Further research should focus on documenting the scale and magnitude of spillover, quantifying the dynamics of spillover and fisheries around MPA borders, as well as the interaction between protection time and other fishery management tools.

## RÉSUMÉ

Les aires marines protégées (AMP) sont largement reconnues comme un outil important pour la conservation de la biodiversité et la gestion de la pêche. Malgré des preuves empiriques montrant que l'abondance et la biomasse des espèces pêchées augmentent à l'intérieur des limites des AMP, le potentiel des AMP à fournir des avantages en matière de pêche aux eaux environnantes reste débattu. Cette étude fournie la première revue systématique des preuves empiriques de l'effet spillover (ou effet de débordement) à partir des AMP au sein de l'Union européenne et dans d'autres régions tempérées. Les résultats montrent que les preuves scientifiques de l'effet spillover, tant sur la composante écologique que celle liée à la pêche, sont relativement rares. La combinaison des caractéristiques de l'AMP (son âge, son contexte local et son appartenance à un réseau) s'est avérée capable de prédire l'occurrence de spillover. Par conséquent, ces éléments sont des considérations clés pour la conception des AMP. En outre, l'étude confirme que la mobilité et les stratégies de reproduction sont des traits importants de l'espèce pour expliquer l'occurrence d'un effet spillover. Les approches méthodologiques (plan d'échantillonnage, méthodes, analyses statistiques) utilisées dans la littérature pour étudier le spillover sont très diverses. Idéalement, l'évaluation devrait se fonder sur une approche expérimentale-témoin avant-après (BACI), avec un plan d'échantillonnage à gradient de distance intégré dans le temps. La combinaison d'une étude de marquage et d'une étude d'échantillonnage biologique permet d'obtenir une image plus complète des effets de spillover potentiels. À l'aide de la littérature disponible et les résultats des analyses quantitatives de notre étude, un outil interactif conceptuel a été développé afin d'estimer la probabilité du spillover dans les AMP existantes et proposées. Cet outil intègre les facteurs sociaux, écologiques et économiques potentiels susceptibles d'entraîner un effet spillover. Enfin, des approches méthodologiques qualitatives et quantitatives ont été utilisées pour évaluer les effets de spillover, sur la composante écologique et/ou sur celle de la pêche, pour 15 études de cas à travers l'Europe. Les études de cas démontrent que les AMP peuvent entraîner une augmentation du spillover des espèces, mais que les patrons sont spécifiques à chaque espèce et qu'il faut une période de temps relativement longue pour que ces effets de spillover soient pertinents pour les pêcheries. Dans l'ensemble, ce travail met en évidence des éléments qui pourraient guider les stratégies visant à améliorer la gestion locale de la pêche à l'aide des AMP. D'autres recherches devraient se focaliser sur la documentation de l'échelle et de l'ampleur de l'effet spillover, sur la quantification de la dynamique du spillover et de la pêche autour des limites des AMP, ainsi que sur l'interaction entre le temps de protection et d'autres outils de gestion des pêcheries.

## EXECUTIVE SUMMARY

The European Union (EU) biodiversity strategy sets the target that, by 2030, at least 30% of the EU's seas should be legally protected through protected areas. Understanding the effects of marine protected areas (MPAs) is therefore of particular interest to the EU. Globally, MPAs and in particular fully protected areas, have been shown to foster biological recovery over time, making them important conservation and fisheries tools. MPAs are designed to enhance biodiversity within their boundaries, and some are established to benefit fisheries through increased egg and larval production, or the 'spillover' of mobile juveniles and adults. Despite empirical evidence that abundance and biomass of fished species increase within MPA boundaries, the ability for MPAs to provide conservation or fisheries benefits to adjacent waters remains debated.

The overall goal of this study was to assemble existing information and collect new data to **provide an overview of the role that the MPAs may play for local fisheries through spillover effects** in the EU and other temperate regions. To respond to this goal, the study was designed so that it could address five specific objectives: (i) identify the presence, abundance and extent of the spillover of fish and selected invertebrates from MPAs; (ii) assess whether spillover is mediated by some MPA characteristics or species traits; (iii) review and evaluate the methodological approaches for assessing spillover; (iv) develop a conceptual model tool to estimate the likelihood of spillover for existing and proposed MPAs; and (v) assess whether there is spillover from a range of MPAs in the regional seas surrounding Europe.

To this end, the study combined a large-scale assessment collecting information on spillover from published data, and a case-study approach focusing on 15 selected case studies in which in-depth information and data for both ecological and fishery spillover have been gathered and analysed. **Ecological spillover** refers to the outward net emigration of juveniles, subadults and/or adults from the MPA into the surrounding waters. **Fishery spillover** refers to the fraction of ecological spillover that directly benefits fishery yields and revenues through fishable biomass. In this study, a comprehensive and systematic review of literature on ecological and fishery spillover was conducted. In addition, based on the systematic literature results, a meta-analysis was performed on the occurrence of spillover and its relation with species traits and MPA characteristics. A conceptual tool was developed to estimate the likelihood of spillover for a given MPA. Finally, an 'advisory protocol' was set up, describing how to research spillover and outlining essential analytical approaches and considerations for studying ecological and fishery spillover.

In order to address the **first objective**, this **study documents the first systematic review of empirical evidence for spillover from MPAs** in the EU (Baltic Sea, North Sea, Atlantic EU Western Waters including Macaronesia) and other temperate regions worldwide. The available literature is relatively sparse, with 45 relevant articles covering 127 cases (unique combination of articles, MPAs and species) where spillover was investigated. These cases provided a good starting point for investigating commonalities and trends. While **there is evidence on spillover**, given the diversity of MPA contexts and species traits, this remains a small number of observations for identifying spillover drivers.

The systematic review showed a predominance of EU and European examples, mostly found within coastal systems. In the studied literature, **ecological and/or fishery spillover was reported in 83% of the cases**, with 64% of these cases being relevant to commercial fisheries and 8.5% not being commercially relevant. Around 27% were unspecified in their relevance to commercial or non-commercial species.

There were substantial gaps found in the empirical research on spillover. There is primarily a need for a broader range of protection levels to be examined and reported. There is also a need for further emphasis on determining the level of juvenile/sub-adult spillover. Vitally, quantifying the level of this spillover from protected juvenile populations to both unprotected and protected adult populations should be prioritised.

Documenting spillover occurrence is the first step in understanding its nature and breadth. There is a **need to quantify the scale** of spillover from protected areas (i.e. the effect of distance from the MPA boundary). There are previous attempts to quantify spillover scale, but these attempts were limited by the extent of the studies' observations. Further work is also needed **to quantify the magnitude** of spillover (i.e. abundance or biomass). Work on this topic has only been reported once in the assessed literature where it relied on ecological models combined with limited empirical observations. Lastly, **quantifying the value to fisheries** (monetarily) **or conservation** (in terms of population dynamics) has not been empirically considered because it relies on documenting spillover magnitude.

Finally, there is a **need to ensure reduced reporting bias in the spillover literature**. This bias likely stems from both individual and systemic biases. Bias is likely to lead to the overestimation of spillover detection in the published literature. In this respect, individually, researchers are more likely to report case study systems where spillover is detected than where spillover is not detected. Furthermore, detecting spillover likely requires less evidence than demonstrating its absence, so positive detections are likely easier to report and publish.

The **second objective** of this study was to **assess whether various MPA characteristics and/or species traits affect the occurrence of spillover**. To investigate the similarities between MPAs and species and how these relate to spillover, a meta-analysis was conducted using a data reduction methodology. This meta-analysis revealed that five variables representing MPA characteristics are important factors in determining if spillover will occur: MPA age, MPA local context, relevant habitats, network status and protection level. The MPA local context (e.g. islands versus estuaries) contributed the most out of all variables to the outcome of spillover, while relevant habitats were the weakest in their contribution to the outcome of spillover.

The analysis did not yield results strong enough to consider the effects of any given MPA characteristic on the presence or absence of spillover independently. However, the **combination of three of these variables (MPA age, local context and whether the MPA is part of a network) proved capable of predicting spillover presence or absence**, especially in cases where spillover was an MPA objective. In this respect, the various contexts in which MPAs are situated – physically, temporally and legislatively – all contribute to variability in the presence or absence of spillover. To disentangle the effects of these drivers independently, future research should use larger datasets on the outcome of spillover studies, including negative results.

There is **evidence that traits related to species mobility and reproductive strategies are important for the ability to detect spillover**. This study confirms that species mobility (free swimming versus sessile or walking) has an impact on the occurrence of spillover. Similarly, reproductive strategies (broadcasts spawners versus brooders) also co-correlate with spillover and have an impact on its occurrence. Broadcasts spawners and free-drifting early-life stages are more co-correlated with presence of spillover than brooders and bearers of eggs.

The **third objective** of this study was to **provide an overview and evaluation of the most used sampling designs, sampling methods, data types and analyses** for assessing spillover from MPAs. Based on the reviewed scientific studies, findings show that there is a wide range of methodological approaches used to investigate spillover.

The most robust **sampling design** for detecting spillover responses in animals from MPAs involves a Before After Control Impact (BACI) design combined with sampling over a distance gradient that is integrated over time, considering changes in both time and space. However, the feasibility of this approach may be hindered by factors such as the timing of the study (e.g. MPA already established) and potential technical or financial constraints, resulting in a limited number of studies employing this methodology. Alternatively, an After Control Impact (ACI) design with a distance gradient approach could be used.

A total of 24 different **sampling methods** were identified and grouped into three main categories: commercial data, scientific sampling and tagging. Of the methods, **mark-recapture (i.e. tagging) was the most commonly used methodology for studying spillover**, applied in 33% of the identified studies: this method was able to demonstrate spillover in 89% of cases. Three other commonly applied methods for quantifying spillover are traps (i.e. scientific sampling: 24% of studies), acoustic telemetry (i.e. tagging: 20% of studies) and visual (diving) transects (i.e. scientific sampling: 20% of studies). The ideal sampling method addresses the research question being asked and is adapted to the species of interest and the site characteristics.

There are no specific **statistical analyses** that are inherently utilised in assessing spillover data. A total of 37 different data analysis methods was found through the literature review. These 37 methods can be divided into six categories: hypothesis testing, regression analysis, correlation analysis, multivariate analysis, modelling and other. The methods that we most applied to investigate spillover from MPAs were hypothesis testing methods (assessing if available evidence supports or contradicts a particular hypothesis) and regression analyses (a relationship between one or more variables). The ideal data analysis depends largely on the sampling design and sampling method, but it needs to be appropriate for the acquired data set. A statistician or modeller should be preferably involved in the design and data analysis.

Measuring different **response variables** simultaneously is to be recommended, as they can have different success rates in demonstrating spillover. The most common response variables used to investigate spillover effects are abundance, spatio-temporal range (e.g. distance moved, home range), animal length, biomass and reproductive index. Of these five, biomass was the most-used response variable for detecting a spillover effect (92% of the cases), followed by reproductive index (88%), spatio-temporal range (78%), abundance (73%) and animal length (64%).

A detailed **evaluation of the methodological approaches** showed that methods to quantify spillover were clustered into three main groups, dependent on data and logistic needs, costs and robustness.

- The first group contained sampling methods that are relatively robust, have moderate data and evidence needs, and can sample a high number of target organisms and have low needs in terms of logistics, costs, human resources and expertise. This group encompasses low technologically intensive, predominantly invasive sampling techniques (e.g. fyke, gill and trammel nets, line fishing, quadrats and passive collectors).
- The methods in the second group have much more expansive data needs, require much more intensive logistical support and may not be robust to small sample sizes. These methods include a range of boat-based invasive sampling methods

(e.g. bongo nets, long lines) and are targeted at specific groups of species (e.g. spearfishing) or are likely to have high costs (e.g. electronic data storage tags, commercial surveys, visual transects).

- The third group predominantly comprises of methods with very high costs and require high levels of logistical or human resources, which can target specific organisms. These are methods that need a large number of samples using high levels of technology (e.g. vessel monitoring systems (VMS)) or requiring high levels of boat time and human resources to utilise (e.g. acoustic telemetry, baited underwater video (BUV), mark-recapture).

Overall, a combination of approaches, using both biological sampling and tagging, gives a much more complete picture of potential spillover effects, as the disadvantages of both approaches compensate for each other.

In order to address the **fourth objective**, **a conceptual model tool (the 'SPILLEST Spillover Likelihood Tool') was developed to estimate the likelihood of spillover for existing and proposed MPAs.** The tool integrates the potential environmental, social and economic factors that might contribute to the occurrence, magnitude and detectability of spillover. The tool was build based on literature and the results of the meta-analysis. A total of 10 factors were considered to be relevant for spillover and were associated with a multiple-choice question in the tool. The factors include the location along the coast, habitat continuity outside the protected area, MPA age, MPA size compared to the species home range, network status, protection level, presence of a buffer zone, commercial value of the species, species mobility and reproductive strategy.

The SPILLEST tool allows users to explore various MPA configurations and their contribution to spillover for any relevant species. It can be applied to existing or proposed MPAs so managers can get an initial insight into whether spillover may occur within the proposed MPA area and whether certain features driving spillover need to be encapsulated into conservation objectives and MPA management plans. In this study, the SPILLEST tool was tested and validated in 11 MPA case studies and was found to largely conform with expectations of the relevant experts. Further potential improvements could come from including the relative strength of the contribution of each factor (currently all factors contribute equally) and widening the scope to accommodate a distinction between ecological and fishery spillover. However, that would require substantially more data and analysis on the contribution of the various factors to each type of spillover.

Finally, the **fifth objective** was to **assess whether there is spillover based on a range of MPA case studies** in the regional seas surrounding Europe. Both a qualitative and quantitative approach was used, with the ultimate goal of designing a methodology to better monitor and assess spillover effects in MPAs. In total, 15 case studies were selected throughout the Baltic Sea, the North Sea, and the Atlantic EU Western Waters including Macaronesia, and based on the geographical coverage and data availability. The case studies present varying MPA characteristics, species and research ongoing, resulting in complementary insights on spillover.

Our investigation shows that it was **challenging to source sufficient case studies throughout the regional seas with suitable data for the analysis of spillover effects**. The flexibility in selecting different analytical approaches based on the data availability and diverging statistical choices led to a variety of methodologies being employed across the case studies to test spillover indicators. On the one hand, there is the **qualitative approach**, which assessed perception of spillover from MPAs based on interviews of a wide range of key stakeholders, including fishers, management authorities, scientists and environmental non-government organisations. On the other hand, a **quantitative approach** allowed to apply a statistical assessment for quantifying spillover patterns. Accordingly, an **'advisory protocol'** was developed as a guide for future spillover assessments by scientists and MPA managers.

**Three of the case studies were successful in demonstrating spillover effects and five of the case studies showed the potential of spillover effects**. However, the non-uniform approach makes it challenging to attribute what shared factors lead to the presence or absence of spillover effects in the case studies. Distinguishing between methodological limitations, an inability to capture spillover and the absence of spillover are all inherently complex. Several case studies noted the necessity for the additional empirical validation of their results. Some studies concluded that the presence of spillover effects was primarily based on an increase in Catch Per Unit Effort (CPUE), regardless of whether this increase intensified over time or exhibited proximity effects to the MPA. Although increasing CPUE can be an informative indicator of spillover, this alone may not be adequate to conclusively confirm the existence of these effects. It is crucial to underscore the importance of examining these effects in relation to space and time.

Some **commonalities among the quantitative case studies were found**. For example, a no-take area is not beneficial for all species, nor does it lead to spillover for all species. Interspecific competition can take place in no-take areas, as seen in a few case studies (e.g. between lobsters and crab species in Flamanville Protected Area, Lyme Bay MPA, and Tvedestrand MPA). The higher occurrence or recurrence of top predators can affect the success of commercial fish species in no-take areas (e.g. Gotska Sandon MPA). In some cases, a significant increase in abundance was observed (sometimes temporarily), but this was less pronounced for biomass for certain species (e.g. La Graciosa MPA). The length of specimens (data were only available for crustacean species such as lobster and crabs) is mostly larger in no-take areas (e.g. Tvedestrand MPA, Flammandville protected area). Overall, the case studies that showed the greatest spillover potential were in MPAs where the measures had been in place for a while (e.g. Flammanville protected area, Lamlash Bay MPA and La Graciosa MPA), confirming that **MPA age is an important factor for the occurrence of spillover**, as also evidenced in our meta-analysis.

The **qualitative approach**, applied to case studies, shows that most stakeholders, including fishers, scientists, fisheries management authorities and environmental non-government organisations, concurred that ecological change occurs in the years after an MPA is implemented. Stakeholders agreed that they observed increases in abundance, habitat complexity and functional biodiversity, with a more diverse range of species being found inside MPAs compared to outside.

There were notable **changes in fishers' catches** after MPAs were established in several case studies. However, **the various stakeholders have different perspectives** on whether catches increase or decrease following the establishment of an MPA. The consensus among the surveyed scientists and government officials is that catches increase as a result of the MPAs. Accordingly, they state that MPAs have positive ecological results. Fishers, on the other hand, are keen to point out that MPAs reduce the size of fishing grounds and are therefore associated with negative economic consequences. Therefore, while stakeholders acknowledge MPAs' role in protecting biodiversity, **fishers express concerns about the impacts of fishing restrictions on their livelihoods**.

Nevertheless, there is **hope amongst stakeholders that MPAs can provide benefits to both biodiversity and fisheries**. For instance, stakeholders (including some fishers) felt that if the appropriate habitats that harbour exploitable stocks were protected (e.g. nursery and breeding grounds), there could be benefit to neighbouring fisheries. In contrast, stakeholders have different perspectives on the presence and absence of spillover in the case studies, even within the same stakeholder group (e.g. fishers, scientists). Spillover effects, which are often a major focus when discussing how MPAs impact local fisheries is, therefore, **still a topic of some debate amongst the stakeholders**. This is due to the perceived lack of evidence and, in most cases, appropriate data to detect spillover.

The case studies demonstrate that **MPAs can lead to increased spillover of species, but that these patterns are species specific, with such spillover effects taking a relatively long time period before they are relevant for fisheries**. The dynamics of spillover and fisheries around MPA borders and the interaction between protection time with other fishery management tools needs further investigations. The spillover process needs to be examined in more detail and in a much more diverse range of conditions than examined in the present work.

Overall, the **synthesis of all outputs shows that there is evidence for spillover from MPAs to adjacent waters**. The meta-analysis of the various factors related to MPA characteristics and species traits has shown a number of emergent patterns in relation to spillover effects. Some identified drivers for spillover include the combination of MPA characteristics (MPA age, local context and network status) and some species traits (mobility and reproductive strategies). These findings highlight under which conditions ecological spillover may be expected, allowing stakeholders to develop sound strategies when designing an MPA, where spillover is an objective. The identification of these drivers and their relative contribution should be further developed once more empirically based knowledge becomes available.

Although the scientific knowledge on the spillover effect increased substantially in this study, future research is needed. The **main recommendations for future spillover research** are:

- To better **understand the drivers of spillover**, future research should be based on larger datasets and include negative results. This demands that further field studies are both promoted and undertaken and then published in primary literature.
- More information on the **magnitude and scale of spillover** is needed. Therefore, empirical studies should start quantifying the magnitude, and the temporal frequency and spatial scale with which spillover occur.
- There is a need to investigate a **broader range of protection levels** in MPAs and other relevant areas, such as 'other effective area-based conservation measures' (OECMs).
- There is also a need for further emphasis on using data from a **diverse range of habitats and commercial species**, as well as determining the **level of juvenile and subadult spillover.**
- To improve the knowledge about **the relationship between (changes in) fishing activities and spillover**, through collection and documentation of more catch and effort data inside protected areas and outside, with varying distances to the protected areas.
- There is a need to **distinguish between ecological and fishery spillover** in future research. Being able to better predict and quantify fishery spillover would be beneficial to the dialogue among stakeholders. Fishery spillover could provide direct benefit to local fisheries and serve as an incentive for the fishing sector, potentially offsetting the impact of fishery restrictions.

- To aim for **comparable perspectives on absence or presence of spillover between stakeholders**, by improving knowledge about what spillover is through data collection in line with the above recommendations and through raising awareness on spillover effects and benefits.

- The **SPILLEST conceptual model** could be used as a tool in stakeholder dialogues when discussing features driving spillover. The tool can be updated when new knowledge becomes available.

- Specific **recommendations on methodologies** for monitoring and assessment of spillover effects are:

  - For **monitoring (data collection)**: it is recommended (i) to use a BACI design with a distance gradient sampling scheme that is integrated over time when implementing an MPA; (ii) to use a combination of traditional (biological) sampling and tagging studies, as it provides a much more complete picture of potential spillover effects; (iii) to assess different response variables simultaneously (e.g. abundance, biomass, reproductive index). Nevertheless, the ideal sampling method should address the research question being asked and be adapted to the species of interest and the MPA site characteristics.

  - For **assessing spillover (data analyses)**: the ideal data analysis method is largely dependent on the sampling design, method and data availability. Therefore, it is important to take into account spatial and temporal ranges, the number of observations, MPA characteristics (e.g. age) and species traits (exploitation history, mobility and reproductive strategies), potential population-level effects and fisheries' response to the MPA. Some more detailed guidance for future assessments is given in the 'advisory protocol'.

Finally, this work provides elements that could **guide strategies to enhance local fishery management using MPAs**. With the target of the EU biodiversity strategy of at least 30% of legal protection of the EU's seas, it is vital to better understand how MPAs may result in spillover and how this may benefit fisheries.

## RÉSUMÉ EXÉCUTIF

La stratégie de l'Union européenne (UE) en faveur de la biodiversité fixe comme objectif que, d'ici 2030, au moins 30 % des mers de l'UE devraient être légalement protégées par des aires protégées. Comprendre les effets des aires marines protégées (AMP) est donc d'un intérêt particulier pour l'UE. À l'échelle mondiale, les AMP, et en particulier les aires entièrement protégées, ont été démontrées comme favorisant la récupération biologique avec le temps, ce qui en fait des outils de conservation et de pêche importants. Les AMP sont conçues pour améliorer la biodiversité à l'intérieur de leurs limites, et certaines sont établies pour bénéficier à la pêche en augmentant la production d'œufs et de larves, ou le débordement d'organismes juvéniles et adultes en périphérie de l'aire protégée ("effet spillover"). Malgré des preuves empiriques montrant que l'abondance et la biomasse des espèces pêchées augmentent à l'intérieur des limites des AMP, la capacité des AMP à fournir des avantages en matière de conservation ou de pêche aux eaux environnantes reste sujet à débat.

L'objectif général de cette étude était de rassembler les informations existantes et de collecter de nouvelles données pour **fournir un aperçu du rôle que les AMP peuvent jouer pour les pêcheries locales grâce aux effets de spillover** dans l'UE et d'autres régions tempérées. Pour répondre à cet objectif, l'étude a été conçue de manière à pouvoir répondre à cinq objectifs spécifiques : (i) identifier la présence, l'abondance et l'étendue du spillover de poissons et d'invertébrés sélectionnés à partir des AMP ; (ii) évaluer si le spillover est médié par certaines caractéristiques des AMP ou des traits des espèces ; (iii) passer en revue et évaluer les approches méthodologiques pour évaluer le spillover ; (iv) développer un outil interactif conceptuel pour estimer la probabilité de spillover pour les AMP existantes et proposées ; et (v) évaluer s'il y a un spillover à partir d'une gamme d'AMP dans les mers régionales entourant l'Europe.

À cette fin, l'étude a combiné une évaluation à grande échelle collectant des informations sur le spillover à partir de données publiées, et une approche d'étude de cas se concentrant sur 15 études de cas sélectionnées dans lesquelles des informations approfondies et des données sur le spillover écologique et de pêche ont été recueillies et analysées. Le **spillover écologique** se réfère à l'émigration nette vers l'extérieur de juvéniles, de sub-adultes et/ou d'adultes de l'AMP vers les eaux environnantes. Le **spillover de pêche** se réfère à la fraction du spillover écologique qui bénéficie directement aux rendements et aux revenus de la pêche grâce à la biomasse pêchable. Dans cette étude, une revue exhaustive et systématique de la littérature sur le spillover écologique et de pêche a été réalisée. De plus, sur la base des résultats de la littérature systématique, une méta-analyse a été réalisée sur l'occurrence du spillover et sa relation avec les traits des espèces et les caractéristiques des AMP. Un outil conceptuel a été développé pour estimer la probabilité des effets de spillover pour une AMP donnée. Enfin, un « protocole consultatif » a été mis en place, décrivant comment réaliser une recherche sur le spillover et détaillant les approches analytiques essentielles et les considérations pour étudier le spillover écologique et de pêche.

Pour répondre au **premier objectif**, cette étude **documente la première revue systématique des preuves empiriques du spillover à partir des AMP** dans l'UE (mer Baltique, mer du Nord, eaux occidentales de l'Atlantique incluant la Macaronésie) et d'autres régions tempérées du globe. La littérature disponible est relativement peu abondante, avec 45 articles pertinents couvrant 127 cas (combinaison unique d'articles, d'AMP et d'espèces) où le spillover a été étudié. Ces cas ont fourni un bon point de départ pour étudier les similitudes et les tendances. Bien qu'**il existe des preuves de l'effet spillover**, étant donné la diversité des

contextes des AMP et des traits des espèces, il s'agit toujours d'un petit nombre d'observations pour identifier les facteurs liés au spillover.

La revue systématique a montré une prédominance d'exemples de l'UE et d'Europe, principalement trouvés dans les systèmes côtiers. Dans la littérature étudiée, **le spillover écologique et/ou de pêche a été rapporté dans 83 % des cas**, dont 64 % étaient pertinents pour les pêcheries commerciales et 8,5 % n'étaient pas pertinentes commercialement. Environ 27 % n'étaient pas spécifiés quant à leur pertinence pour les espèces commerciales ou non commerciales.

Des lacunes substantielles ont été trouvées dans la recherche empirique sur le spillover. Il est principalement nécessaire d'examiner et de rapporter une gamme plus large de niveaux de protection. Il est également nécessaire de mettre davantage l'accent sur la détermination du niveau de spillover des juvéniles/sub-adultes. Il est essentiel de quantifier le niveau de ce spillover à partir de populations juvéniles protégées vers les populations adultes non protégées et protégées.

Documenter l'occurrence de l'effet spillover est la première étape pour comprendre sa nature et son ampleur. **Il est nécessaire de quantifier l'échelle du spillover** à partir des aires protégées (c'est-à-dire l'effet de la distance par rapport à la limite de l'AMP). Des tentatives précédentes ont été faites pour quantifier l'échelle du spillover, mais ces tentatives étaient limitées par l'étendue des observations des études. Un travail supplémentaire est également nécessaire pour **quantifier l'ampleur du spillover** (c'est-à-dire l'abondance ou la biomasse). Le travail sur ce sujet n'a été rapporté qu'une seule fois dans la littérature évaluée et il s'est appuyé sur des modèles écologiques combinés à des observations empiriques limitées. Enfin, **quantifier la valeur pour les pêcheries** (monétairement) **ou la conservation** (en termes de dynamique des populations) n'a pas été considéré empiriquement car cela dépend de la documentation de l'ampleur du spillover.

Enfin, il est **nécessaire de veiller à réduire les biais de rapport dans la littérature sur le spillover**. Ce biais provient probablement à la fois de biais individuels et systémiques. Il est probable que le biais conduise à surestimer la détection du spillover dans la littérature publiée. À cet égard, individuellement, les chercheurs sont plus susceptibles de rapporter des systèmes d'étude de cas où le spillover est détecté que lorsque le spillover n'est pas détecté. De plus, détecter le spillover nécessite probablement moins de preuves que démontrer son absence, donc les détections positives sont probablement plus faciles à rapporter et à publier.

Le **deuxième objectif** de cette étude était d'**évaluer si différentes caractéristiques des AMP et/ou des traits des espèces affectent l'occurrence du spillover**. Pour étudier les similitudes entre les AMP et les espèces et leur relation avec le spillover, une méta-analyse a été réalisée en utilisant une méthodologie de réduction des données. Cette méta-analyse a révélé que cinq variables représentant les caractéristiques des AMP sont des facteurs importants pour déterminer si le spillover se produira : l'âge de l'AMP, le contexte local de l'AMP, les habitats pertinents, le statut du réseau et le niveau de protection. Le contexte local de l'AMP (par exemple, les îles par rapport aux estuaires) a contribué le plus à l'issue du spillover parmi toutes les variables, tandis que les habitats pertinents étaient les plus faibles dans leur contribution à l'issue du spillover.

L'analyse n'a pas donné des résultats suffisamment forts pour considérer les effets de toute caractéristique d'AMP donnée sur la présence ou l'absence de spillover indépendamment. Cependant, **la combinaison de trois de ces variables (âge de l'AMP, contexte local et appartenance à un réseau) s'est révélée capable de prédire la présence ou l'absence de spillover**, notamment dans les cas où le spillover était un objectif de l'AMP. À cet égard, les différents contextes dans lesquels les AMP sont situées – physiquement, temporellement et législativement – contribuent tous à la variabilité de la présence ou de l'absence de spillover. Pour démêler les effets de ces facteurs de manière indépendante, les futures recherches devraient utiliser des ensembles de données plus importants sur le résultat des études de spillover, y compris les résultats négatifs.

Il existe des **preuves que les traits liés à la mobilité des espèces et aux stratégies de reproduction sont importants pour la capacité à détecter le spillover**. Cette étude confirme que la mobilité des espèces (nage libre versus sessilité ou marche) a un impact sur l'occurrence du spillover. De même, les stratégies de reproduction (espèces à ponte libre versus espèces incubatrices) sont également corrélées avec le spillover et ont un impact sur son occurrence. Les espèces à ponte libre et les stades précoces de vie à dérive libre sont plus corrélés avec la présence de spillover que les espèces incubatrices et les porteurs d'œufs.

Le **troisième objectif** de cette étude était de **fournir un aperçu et une évaluation des plans d'échantillonnage, des méthodes d'échantillonnage, des types de données et des analyses** les plus utilisés pour évaluer le spillover à partir des AMP. Sur la base des études scientifiques examinées, les résultats montrent qu'il existe une large gamme d'approches méthodologiques utilisées pour étudier le spillover.

Le **plan d'échantillonnage** le plus robuste pour détecter les réponses de spillover chez les animaux à partir des AMP implique la conception d'une approche 'expérimentale-témoin avant-après' (BACI), combinée à un plan d'échantillonnage à gradient de distance intégré dans le temps, en tenant compte des changements à la fois dans le temps et dans l'espace. Cependant, la faisabilité de cette approche peut être entravée par des facteurs tels que le timing de l'étude (par exemple, l'AMP déjà établie) et des contraintes techniques ou financières potentielles, ce qui se traduit par un nombre limité d'études u'ilisant cette méthodologie. Alternativement, un plan 'expérimental-témoin après' (ACI) combiné à un gradient de distance pourrait être utilisée.

Un total de 24 **méthodes d'échantillonnage** différentes ont été identifiées et regroupées en trois catégories principales : données commerciales, échantillonnage scientifique et marquage. Parmi les méthodes, **l'approche marquage-recapture 'était la méthodologie la plus couramment utilisée pour étudier le spillover**, appliquée dans 33 % des études identifiées : cette méthode a pu démontrer le spillover dans 89 % des cas. Trois autres méthodes couramment appliquées pour quantifier le spillover sont les pièges (c'est-à-dire l'échantillonnage scientifique : 24 % des études), la télémétrie acoustique (c'est-à-dire le marquage : 20 % des études) et les transects visuels (plongée) (c'est-à-dire l'échantillonnage scientifique : 20 % des études). La méthode d'échantillonnage idéale répond à la question de recherche posée et est adaptée à l'espèce d'intérêt et aux caractéristiques du site.

Il n'existe pas **d'analyses statistiques** spécifiques qui sont intrinsèquement utilisées dans l'évaluation des données de spillover. Un total de 37 méthodes d'analyse des données différentes a été identifié grâce à l'examen de la littérature. Ces 37 méthodes peuvent être divisées en six catégories : tests d'hypothèses, analyses de régression, analyses de corrélation, analyses multivariées, modélisation et autres. Les méthodes les plus appliquées pour étudier le spillover des AMP étaient les méthodes de test d'hypothèses (évaluer si les preuves disponibles supportent ou contredisent une hypothèse particulière) et les analyses de régression (une relation entre une ou plusieurs variables). L'analyse des données idéale dépend largement du plan d'échantillonnage et de la méthode d'échantillonnage, mais elle doit être appropriée pour l'ensemble de données acquis. Un statisticien ou un modélisateur devrait de préférence être impliqué dans la conception et l'analyse des données.

Il est recommandé de mesurer simultanément différentes **variables de réponse**, car elles peuvent avoir des taux de réussite différents dans la mise en évidence de l'effet spillover. Les variables de réponse les plus couramment utilisées pour étudier les effets de spillover sont l'abondance, la répartition spatio-temporelle (par exemple, la distance parcourue, le domaine vital), la longueur des animaux, la biomasse et l'indice de reproduction. Parmi ces cinq variables, la biomasse était la variable de réponse la plus utilisée pour détecter un effet de spillover (92 % des cas), suivie de l'indice de reproduction (88 %), de la répartition spatio-temporelle (78 %), de l'abondance (73 %) et de la longueur des animaux (64 %).

Une **évaluation détaillée des approches méthodologiques** a montré que les méthodes pour quantifier le spillover étaient regroupées en trois groupes principaux, dépendant des besoins logistiques et des données, des coûts et de la robustesse.

- Le premier groupe contient des méthodes d'échantillonnage relativement robustes, avec des besoins de données et de preuves modérés, et peuvent échantillonner un grand nombre d'organismes cibles avec des besoins logistiques, des coûts, des ressources humaines et une expertise faible. Ce groupe englobe des techniques d'échantillonnage principalement invasives et peu technologiques (par exemple, les verveux, les filets maillants et trémails, la pêche à la ligne, les quadrats et les collecteurs passifs).
- Les méthodes du deuxième groupe ont des besoins en données beaucoup plus étendus, nécessitent un soutien logistique beaucoup plus intensif et peuvent ne pas être robustes pour de petits échantillons. Ces méthodes comprennent une gamme de méthodes d'échantillonnage invasives basées sur des bateaux (par exemple, les filets bongo, les palangres) et sont ciblées sur des groupes spécifiques d'espèces (par exemple, la pêche sous-marine) ou sont susceptibles d'avoir des coûts élevés (par exemple, les balises de stockage de données électroniques, les campagnes commerciales, les transects visuels).
- Le troisième groupe comprend principalement des méthodes avec des coûts très élevés et nécessitant des niveaux élevés de logistique ou de ressources humaines, qui peuvent cibler des organismes spécifiques. Il s'agit de méthodes nécessitant un grand nombre d'échantillons utilisant des niveaux élevés de technologie (par exemple, les systèmes de surveillance des navires par satellite (VMS)) ou nécessitant beaucoup de temps de bateau et de ressources humaines pour être utilisées (par exemple, la télémétrie acoustique, la vidéo sous-marine appâtée (BUV), le marquage-recapture).

Dans l'ensemble, une combinaison d'approches, utilisant à la fois l'échantillonnage biologique et le marquage, offre une image beaucoup plus complète des effets potentiels de spillover, car les inconvénients des deux approches se compensent mutuellement.

Pour répondre au **quatrième objectif**, **un modèle conceptuel (l'outil de probabilité de spillover SPILLEST) a été développé pour estimer la probabilité de spillover pour les AMP existantes et proposées**. L'outil intègre les facteurs environnementaux, sociaux et économiques potentiels qui pourraient contribuer à l'occurrence, à l'ampleur et à la détection du spillover. L'outil a été élaboré à partir de la littérature et des résultats de la méta-analyse. Un total de 10 facteurs ont été considérés comme pertinents pour le spillover et ont été associés à une question à choix multiples dans l'outil. Les facteurs comprennent l'emplacement le long de la côte, la continuité de l'habitat en dehors de la zone protégée, l'âge de l'AMP, la taille de l'AMP par rapport au domaine vital' de l'espèce, le statut du réseau, le niveau de protection, la présence d'une zone tampon, la valeur commerciale de l'espèce, la mobilité des espèces et la stratégie de reproduction.

L’outil SPILLEST permet aux utilisateurs d’explorer différentes configurations d’AMP et leur contribution au spillover pour toute espèce pertinente. Il peut être appliqué aux AMP existantes ou proposées afin que les gestionnaires puissent obtenir un aperçu initial de la possibilité de spillover dans la zone proposée pour l’AMP et si certains aspects qui favorisent le spillover doivent être intégrés dans les objectifs de conservation et les plans de gestion de l’AMP. Dans cette étude, l’outil SPILLEST a été testé et validé dans 11 études de cas d’AMP et s’est révélé largement conforme aux attentes des experts concernés. Des améliorations potentielles supplémentaires pourraient provenir de l’inclusion de la force relative de la contribution de chaque facteur (actuellement, tous les facteurs contribuent de manière égale) et de l’élargissement de la portée pour prendre en compte une distinction entre le spillover écologique et celui lié à la pêche. Cependant, cela nécessiterait substantiellement plus de données et d’analyses sur la contribution des différents facteurs à chaque type de spillover.

Enfin, le **cinquième objectif** était **d’évaluer s’il existe un effet spillover sur une gamme d’études de cas d’AMP** dans les mers régionales entourant l’Europe. Une approche qualitative et quantitative a été utilisée, dans le but ultime de concevoir une méthodologie pour mieux surveiller et évaluer les effets de spillover dans les AMP. Au total, 15 études de cas ont été sélectionnées dans la mer Baltique, la mer du Nord, et les eaux occidentales de l’Atlantique incluant la Macaronésie, en fonction de la couverture géographique et de la disponibilité des données. Les études de cas présentent des caractéristiques d’AMP, d’ espèces et de recherches en cours variées, ce qui donne des perspectives complémentaires sur le spillover.

Notre recherche montre qu’il était **difficile de trouver suffisamment d’études de cas dans les mers régionales avec des données appropriées pour l’analyse des effets de spillover**. La flexibilité dans le choix des différentes approches analytiques en fonction de la disponibilité des données et des choix statistiques divergents a conduit à une variété de méthodologies utilisées dans les études de cas pour tester les indicateurs de spillover. D’une part, il y a l’**approche qualitative**, qui a évalué la perception du spillover à partir des AMP sur la base d’entretiens avec un large éventail d’acteurs clés, notamment des pêcheurs, des autorités de gestion, des scientifiques et des organisations environnementales non gouvernementales. D’autre part, une **approche quantitative** a permis d’appliquer une évaluation statistique pour quantifier les patrons de spillover. En conséquence, un **« protocole consultatif »** a été élaboré comme guide pour les futures évaluations de spillover par les scientifiques et les gestionnaires d’AMP.

**Trois des études de cas ont réussi à démontrer des effets de spillover et cinq des études de cas ont montré le potentiel des effets de spillover.** Cependant, l’approche non uniforme rend difficile l’attribution des facteurs communs qui conduisent à la présence ou à l’absence d’effets de spillover dans ces études de cas. Distinguer entre les limitations méthodologiques, l’incapacité à capturer le spillover et l’absence de spillover est intrinsèquement complexe. Plusieurs études de cas ont souligné la nécessité d’une validation empirique additionnelle de leurs résultats. Certaines études ont conclu que la présence d’effets de spillover était principalement basée sur une augmentation du rendement par unité d’effort de capture (CPUE), que cette augmentation soit intensifiée au fil du temps ou présente des effets de proximité par rapport à l’AMP. Bien que l’augmentation de la CPUE puisse être un indicateur informatif du spillover, cela seul peut ne pas être suffisant pour confirmer de manière concluante l’existence de ces effets. Il est crucial de souligner l’importance d’examiner ces effets en relation avec l’espace et le temps.

Des **similitudes ont été trouvées parmi les études de cas quantitatives**. Par exemple, une zone de non-prélèvement n’est pas bénéfique pour toutes les espèces, et ne conduit pas au spillover pour toutes les espèces. La compétition interspécifique peut avoir lieu dans les zones de non-prélèvement, comme observé dans quelques études de cas (par exemple, entre les homards et les espèces de crabes dans la zone protégée de Flamanville, l'AMP de la baie de Lyme et l'AMP de Tvedestrand). La présence ou la récurrence plus élevée de prédateurs supérieurs peut affecter le succès des espèces de poissons commerciaux dans les zones de non-prélèvement (par exemple, l'AMP de Gotska Sandon). Dans certains cas, une augmentation significative de l'abondance a été observée (parfois temporairement), mais cela était moins prononcé pour la biomasse pour certaines espèces (par exemple, dans l'AMP de La Graciosa). La longueur des spécimens (les données n'étaient disponibles que pour les espèces de crustacés telles que le homard et les crabes) est généralement plus grande dans les zones de non-prélèvement (par exemple, l'AMP de Tvedestrand, la zone protégée de Flamanville). Dans l'ensemble, les études de cas qui ont montré le plus grand potentiel de spillover étaient dans les AMP où les mesures étaient en place depuis un certain temps (par exemple, la zone protégée de Flammanville, l'AMP de la baie de Lamlash et l'AMP de La Graciosa), confirmant que **l'âge de l'AMP est un facteur important pour l'occurrence du spillover**, comme également démontré dans notre méta-analyse.

L'**approche qualitative**, appliquée aux études de cas, montre que la plupart des parties prenantes, y compris les pêcheurs, les scientifiques, les autorités de gestion des pêches et les organisations environnementales non gouvernementales, sont d'accord pour dire que des changements écologiques se produisent dans les années qui suivent la mise en place d'une AMP. Les parties prenantes conviennent qu'elles ont observé des augmentations de l'abondance, de la complexité des habitats et de la biodiversité fonctionnelle, avec une gamme d'espèces plus diversifiée à l'intérieur des AMP qu'à l'extérieur.

Il y a des **changements notables dans les prises des pêcheurs** après la mise en place d'AMP dans plusieurs études de cas. Cependant, **les différentes parties prenantes ont des perspectives différentes** sur l'augmentation ou la diminution des prises suite à la mise en place d'une AMP. Le consensus parmi les scientifiques et les responsables gouvernementaux interrogés est que les prises augmentent à la suite de la création d'une AMP. En conséquence, ils déclarent que les AMP ont des résultats écologiques positifs. En revanche, les pêcheurs tiennent à souligner que les AMP réduisent la taille des zones de pêche et sont donc associées à des conséquences économiques négatives. Par conséquent, tandis que les parties prenantes reconnaissent le rôle des AMP dans la protection de la biodiversité, **les pêcheurs expriment des inquiétudes quant aux impacts des restrictions de pêche sur leurs moyens de subsistance**.

Néanmoins, il y a de **l'espoir parmi les parties prenantes que les AMP peuvent apporter des avantages tant à la biodiversité qu'à la pêche**. Par exemple, les parties prenantes (y compris certains pêcheurs) ont estimé que si les habitats appropriés abritant des stocks exploitables étaient protégés (par exemple, les zones de nurserie et de reproduction), cela pourrait bénéficier aux pêcheries voisines. En revanche, les parties prenantes ont des perspectives différentes sur la présence et l'absence de spillover dans les études de cas, même au sein du même groupe de parties prenantes (par exemple, pêcheurs, scientifiques). Les effets de spillover, qui sont souvent au centre des discussions sur l'impact des AMP sur les pêcheries locales, sont donc encore un **sujet de débat parmi les parties prenantes**. Cela est dû au manque perçu de preuves et, dans la plupart des cas, aux données appropriées pour détecter un effet spillover.

Les études de cas démontrent que les **AMP peuvent entraîner une augmentation du spillover des espèces, mais que les patrons sont spécifiques aux espèces, avec de tels effets de spillover prenant relativement longtemps avant de devenir pertinents pour les pêcheries.** Les dynamiques de spillover et de pêcheries autour des frontières des AMP et l'interaction entre le temps de protection et d'autres outils de gestion des pêches nécessitent des investigations supplémentaires. Le processus de spillover doit être examiné plus en détail et dans une gamme de conditions beaucoup plus diversifiée que celle examinée dans le présent travail.

Dans l'ensemble, **la synthèse de tous les résultats montre qu'il existe des preuves de l'effet spillover des AMP vers les zones environnantes**. La méta-analyse des différents facteurs liés aux caractéristiques des AMP et aux traits des espèces a révélé un certain nombre de patrons émergents concernant les effets de spillover. Certains des facteurs identifiés pour expliquer l'occurrence du spillover incluent la combinaison des caractéristiques des AMP (âge de l'AMP, contexte local et statut du réseau) et certains traits des espèces (mobilité et stratégies de reproduction). Ces résultats mettent en évidence les conditions dans lesquelles un spillover écologique peut être attendu, permettant ainsi aux parties prenantes de développer des stratégies efficaces lors de la conception d'une AMP, où le spillover est un objectif. L'identification de ces facteurs et de leur contribution relative devrait être développée davantage dès que des connaissances empiriques supplémentaires seront disponibles.

Bien que les connaissances scientifiques sur l'effet spillover aient considérablement augmenté dans cette étude, des recherches futures sont nécessaires. Les **principales recommandations pour les futures recherches** sur le spillover sont les suivantes :

- Pour **mieux comprendre les facteurs déterminants de l'occurrence du spillover**, les futures recherches devraient être basées sur des ensembles de données plus importants et inclure des résultats négatifs. Cela exige que d'autres études sur le terrain soient à la fois promues et entreprises, puis publiées dans la littérature primaire.
- Plus d'informations sur **l'ampleur et l'échelle du spillover** sont nécessaires. Par conséquent, des études empiriques devraient commencer à quantifier la magnitude, la fréquence temporelle et l'échelle spatiale du spillover.
- Il est nécessaire d'examiner un **éventail plus large de niveaux de protection** dans les AMP et dans d'autres zones pertinentes, telles que les 'Autres mesures de conservation efficace par zone' (AMCEZ).
- Il est également nécessaire de mettre davantage l'accent sur l'utilisation de données provenant d'une **gamme diversifiée d'habitats et d'espèces commerciales**, ainsi que de déterminer le **niveau de spillover des juvéniles et des sub-adultes**.
- Pour améliorer les connaissances sur la **relation entre les activités de pêche (et leurs changements) et le spillover**, il convient de collecter et de documenter davantage de données sur les captures et les efforts à l'intérieur des zones protégées et à l'extérieur, avec des distances variables par rapport aux zones protégées.
- Il est nécessaire de **distinguer le spillover écologique et le spillover de pêche** dans les futures recherches. Pouvoir prédire et quantifier le spillover de la pêche serait bénéfique pour le dialogue entre les parties prenantes. Le spillover de la pêche pourrait offrir des avantages directs aux pêcheries locales et servir de motivation pour le secteur, compensant potentiellement l'impact des restrictions de pêche.

- Viser des **perspectives comparables sur l'absence ou la présence de spillover entre les parties prenantes**, en améliorant les connaissances sur ce qu'est le spillover grâce à la collecte de données conforme aux recommandations ci-dessus et en sensibilisant aux effets et avantages du spillover.

- Le **modèle conceptuel 'SPILLEST'** pourrait être utilisé comme outil dans les dialogues avec les parties prenantes lors de la discussion sur les caractéristiques qui déterminent l'occurrence du spillover. L'outil peut être mis à jour lorsque de nouvelles connaissances deviennent disponibles.

- **Recommandations spécifiques sur les méthodologies** de suivi et d'évaluation des effets de spillover :

  - Pour le **suivi (collecte de données)** : il est recommandé (i) d'utiliser une approche BACI avec un plan d'échantillonnage à gradient de distance intégré dans le temps lors de la mise en œuvre d'une AMP ; (ii) d'utiliser une combinaison d'échantillonnage traditionnel (biologique) et d'études de marquage, car cela fournit une image beaucoup plus complète des effets potentiels du spillover ; (iii) d'évaluer simultanément différentes variables de réponse (par exemple, l'abondance, la biomasse, l'indice de reproduction). Néanmoins, la méthode d'échantillonnage idéale doit répondre à la question de recherche posée et être adaptée aux espèces d'intérêt et aux caractéristiques du site de l'AMP.

  - Pour l'**évaluation du spillover (analyses de données)** : la méthode d'analyse de données idéale dépend largement du plan d'échantillonnage, de la méthode et de la disponibilité des données. Par conséquent, il est important de tenir compte des gammes spatiales et temporelles, du nombre d'observations, des caractéristiques de l'AMP (par exemple, l'âge) et des traits des espèces (histoire de l'exploitation, mobilité et stratégies de reproduction), des effets potentiels au niveau de la population et de la réponse des pêcheries à l'AMP. Des conseils plus détaillés pour les évaluations futures sont présentés dans le "protocole consultatif".

Enfin, ce travail fournit des éléments qui pourraient **guider les stratégies visant à améliorer la gestion des pêches locales en utilisant les AMP**. Avec l'objectif de la stratégie de l'UE en faveur de la biodiversité de protéger légalement au moins 30 % des mers de l'UE, il est essentiel de mieux comprendre comment les AMP peuvent entraîner un effet spillover et comment cela peut bénéficier aux pêcheries.

# GENERAL INTRODUCTION

## Background

The creation of areas where human activities are restricted and habitats are protected and allowed to recover (i.e. marine protected areas (MPAs)) have been chosen around the world as a management measure to tackle habitat degradation and restore biodiversity (McConnaughey et al*.*, 2019; Ban et al*.*, 2019). Several MPAs have been created to target the benefits that come from a partially or fully protected seafloor as these may induce increased benthic habitat complexity and the return of long-lived sessile species (Sala and Giakoumi, 2017), biodiversity conservation (Edgar et al., 2014), increased sediment carbon storage, restored biogeochemical recycling properties (van de Velde et al*.*, 2018) and increased food availability to sustain food web interactions (Hiddink et al*.*, 2011).

Despite the restrictions for fishery activities within some of these areas, spatial restrictions have often proven beneficial for fisheries as habitat recovery also contributes to replenished stocks, restores resource biomass and increases the resilience of populations to other pressures. This positively affects the areas where the measures are implemented and its surroundings thanks to potential 'spillover effects' (Cullis-Suzuki and Pauly, 2010; Di Lorenzo et al., 2016; Marshall et al*.*, 2019). The long-term benefits of fully protected areas have long been argued as being more cost-effective than poorly managed and permissive MPAs. Those poorly managed and permissive MPAs come with a risk of becoming hotspots for fisheries due to their high natural value, and to serve as examples of failure (Sciberras et al*.*, 2013; Van der Reijden et al*.*, 2018; WWF, 2019).

Accordingly, MPAs have become an integral part of the approach taken by the European Union (EU) to manage and enhance marine ecosystems, fisheries and wider human activities within the marine environment. This is due to MPAs being recognised as effective tools for the conservation of biodiversity (Edgar et al., 2014; Giakoumi et al., 2017; Kriegl et al., 2021) and fisheries management (Goni et al., 2011). The EU biodiversity strategy for 2030, for example, promotes a large and well-connected EU-wide network of effectively managed MPAs as a means to protect biodiversity and to ensure more sustainable use of marine resources, which are aspects all central to the European Green Deal. Key commitments by 2030 include the legal protection and effective management of at least 30% of the EU's marine waters, one third of which (i.e. 10% of marine waters) must be under strict protection (COM(2020)380 final).

The major directives to implement these commitments are the EU Birds and Habitats Directives (2009/147/EC and 92/43/EEC respectively), the Marine Strategy Framework Directive (MSFD; 2008/56/EC), the Maritime Spatial Planning Directive (MSPD; 2014/89/EU) and the Common Fisheries Policy (CFP; Regulation 1380/2013). The Birds Directive aims to protect all naturally occurring wild bird species present in the EU. On the other hand, the Habitats Directive requires Member States to aim for the protection of over a thousand species, including mammals, reptiles, amphibians, fish, invertebrates and plants, and 230 characteristic habitat types. The Directive requires all Member States to establish a strict protection regime for species (Annex IV) both inside and outside Natura 2000 sites. Together, the Birds and Habitats Directives, have created the Natura 2000 network – which is now the largest coordinated network of protected areas in the world.

The second legal tool and framework for habitat and species protection is the MSFD. The main goal of the MSFD is to achieve and maintain a 'Good Environmental Status' across the marine environment, maintaining biodiversity and productivity, preventing adverse effects on natural habitat structures and functions, and promoting a healthy ecosystem. This requires action to achieve coordinated and sustainable management.

Appropriate management of the MPAs can be part of the MSFD measures programme to balance marine exploitation and nature conservation. Finally, there is the CFP, which is a set of rules managing European fishing fleets and conserving fish stocks. Its aim is to ensure that fishing and aquaculture activities are environmentally sustainable in the long-term and are managed in a way that is consistent with the objectives of achieving economic, social and employment benefits, and of contributing to the availability of food supplies. With their ecosystem-based approach to management, the MSFD and the CFP offer an opportunity to support MPAs deliver their full potential by taking broader ecosystem considerations – including both ecological (e.g. all species and habitats) and human dimensions – with a goal to achieving ecological and social sustainability. Under the CFP (Article 8), there is the endeavour to establish protected areas due to their biological sensitivity, including fish stock recovery areas, in order to contribute to the conservation of living aquatic resources and marine ecosystems.

Despite this comprehensive policy framework and the EU's strong commitment to deliver ambitious targets for MPAs, the fisheries benefit delivered by MPAs remain debated (Hilborn, 2016). MPAs can include fully protected areas (no-take zones) where extractive activities (e.g. fishing are prohibited) and partially protected areas (multi-use zones) where certain extractive activities are allowed, depending on the management targets (Kriegle et al., 2021). Nevertheless, those areas are expected to conserve and restore biodiversity and ecosystems within their boundaries, and to enhance biodiversity beyond their boundaries by exporting species richness and more complex biological communities (Russ & Alcala, 2011).

So far, many studies have provided evidence of the benefits produced within MPA boundaries (e.g. Edgar et al., 2014). However, overall potential benefits to local fisheries, particularly resulting from fishery spillover, are still debated. Fishery spillover refers to when the population of a particular species in an MPA becomes so abundant it 'spills over' into surrounding areas, at which point it can be targeted by fishermen. The net movement of commercial species from the MPAs to the remaining fishing grounds directly benefits fishery yields and revenues through fishable biomass. In the wider sense, ecological spillover is the outward net emigration of juveniles, subadults and/or adults of any species, hopefully contributing to the restoration of the biological communities outside the MPAs.

Although spillover may seem an interesting concept, there is limited empirical evidence and understanding for the effect. Many have suggested that the spillover benefit, if present, depends entirely on the size of the MPA and whether adjacent areas are managed as in general (Russ & Alcala, 2011; Medoff et al., 2022). Accordingly, it seems that the best conservation outcome may be achieved by good fisheries regulations inside and outside the MPAs in relation to the restoration goals within the area (Hilborn et al., 2004). For example, if a certain fishing approach threatens a habitat, such as bottom trawling, the area can be closed to that type of fishing. If a species is being threatened as a result of being caught unintentionally alongside the targeted species, the fishery may be closed, fishing may only be permitted at certain times of the year or catching techniques may be modified to reduce by-catch. Nevertheless, it is hard to determine the role that MPAs may play for local fisheries through spillover effects (e.g. Vandeperre et al., 2011; Di Lorenzo et al., 2020). Spillover depends on many factors, so a study delivering an in-depth review is needed, especially in relation to MPAs in the EU and other temperate regions, as spillover effects are more studied in tropical regions.

## Main goal and outline

The overall purpose of this study was to assemble existing information and collect new data to provide an overview of the role that the MPAs may play for local fisheries through spillover effects. This study aims to provide and improve on the scientific knowledge necessary to examine spillover in terms of ecological and fishery spillover. The initial geographic scope of the study was the EU waters of the Baltic Sea, North Sea, EU western Atlantic waters and some outermost regions (Macaronesia). Due to the low availability of spillover literature for these specific areas, the scope was enlarged to other temperate regions worldwide (EU and non-EU).

The report is divided into six main sections: the first consists of a systematic literature review of spillover from MPAs in the EU and other temperate regions to investigate the presence of spillover, its occurrence and its magnitude (**Section 1**). Based on this literature, an assessment is made of the MPA characteristics and species traits driving spillover based on a quantitative analysis of the obtained literature (**Section 2**). The literature is also used to provide an overview of the methodological approaches (sampling design, method and statistical analysis) for assessing spillover, with a semi-quantification of their strengths and limitations (**Section 3**). To guide future MPA management, a conceptual model tool is developed to estimate the likelihood of spillover. This tool can be applied to existing and proposed MPAs so that managers and other stakeholders can get an initial insight into whether spillover can be successful or whether certain features that drive spillover need to be adapted (**Section 4**). To provide examples from the field, a large set of case studies (15; from EU Member States, United Kingdom (UK) and Norway) illustrates spillover potentials in a variety of areas and MPA types (**Section 5**). Lessons learnt and recommendations derived from the previous sections are summarized in the last section (**Section 6**), while a selection of annexes offers in-depth information on key elements, including an ‘advisory protocol’ to optimally monitor and assess spillover effects.

# 1 A SYSTEMATIC REVIEW OF SPILLOVER FROM MPAs

**Key highlights**

- This section documents the first systematic review of empirical evidence regarding spillover from MPAs in the EU and other temperate regions.
- A positive detection of spillover is reported in 83% of cases (106/127 unique combinations of articles, MPAs and species) that investigated spillover.
- The diversity of MPA contexts and species demands a large number of samples so all combinations can be investigated.
- Researchers and publishers should be encouraged to report negative results where spillover is investigated but not detected to better inform future meta-analyses.
- Empirical studies should aim to document the spatial scale and magnitude (abundance, biomass) of spillover rather than only identifying its occurrence.

## 1.1 Introduction and objective

Empirical studies of spillover from MPAs are sparse, especially so for temperate waters. As more impetus has been placed on implementing MPAs, there is growing interest in documenting their effects on target and not-target species, both within the MPA borders and in surrounding areas. This has resulted in growing numbers of empirical studies quantifying spillover from MPAs. However, the resource-intensive nature of documenting and quantifying spillover means that most studies only consider one case, and they often only assess these cases over short or intermittent periods.

Gaining a better understanding of what drives spillover requires a broader overview than a small collection of case studies. Accordingly, to collate an overview of the empirical evidence for spillover and to quantify the extent of knowledge and knowledge gaps, a systematic review of evidence is necessary. Earlier reviews have provided insights into temporal developments in our understanding of MPA function, into spillover for individual and small numbers of MPAs (e.g. Götz et al., 2013; Moland et al., 2021), or they have only provided reviews of methods (e.g. Higgins et al., 2008). Previous meta-analyses have used various sizes of collections of case studies where contributors had access to raw data (e.g. Vandeperre et al., 2011; Di Lorenzo et al., 2020). There has not been a comprehensive, systematic review of evidence regarding spillover from MPAs in the regional seas surrounding Europe yet, or indeed across global temperate MPAs.

A systematic review requires that researchers specify the purpose and research questions of the review before using them to define the scope, search and exclusion criteria and the information that needs to be extracted from the selected works. These criteria are then applied to the largest possible literature sets so the resultant database does not reflect any biases of the researchers undertaking the review. This is in comparison to many reviews that use case studies that are familiar to the authors, or worse, select evidence to support a predetermined position.

The overall objective of this work was to perform a systematic review to identify and summarise the presence, abundance and extent of the spillover of fish and selected invertebrates from MPAs in the EU and other temperate regions around the world.

This work used all available evidence from primary and grey literature available from a few countries that the authors had access to.

## 1.2 Methodological set-up

The systematic literature review was initiated with **searches** undertaken in both the Web of Science and Scopus databases according to the systematic literature review protocol (Annex 1). Initially, a search was performed, focused on non-Mediterranean European studies. After deduplication (i.e. the elimination of duplicated literature), this search resulted in 300 records for screening. **Screening** was carried out in accordance with the updated search protocol. This resulted in only 19 records being retained as relevant for our review**.** Therefore, to increase the sample of literature to draw upon, we expanded the geographic scope of the review to be global (excluding tropical cases). Subsequently, the search was re-run with new search terms (see Annex 1). This resulted in 766 non-duplicate records**.** Grey literature reviews from Poland, Germany, Denmark and generic EU sources (including Ireland and France) added a further 20 potential records included before screening, resulting in **a total of 786 potential records**. Following screening (Table 1), **63 records were retained for full text analysis and data extraction**. Note that the papers that matched the geographic exclusion criteria (C, D and E) were included in the retained records after the geographic scope of the review was expanded.

The data extraction scheme that was applied to the 63 records was reviewed and updated with the partners to reduce ambiguity and to include additional relevant fields.

**Table 1. Numbers of records (peer-reviewed articles/grey literature) that were either within the original scope of the study (Short Code = Retain), were outside the original scope but included after expanding the scope (Short Code = C, D or E), or were excluded from the study at the 'screening' phase (i.e. based on Title and Abstract alone).**

| Short Code | Exclusion Criteria | Explanation | Number of Records |
|---|---|---|---|
| Retain | No exclusion criteria applied | No reason defined for excluding the article based on this level of search | 35 |
| A | Not trying to document spillover | The aims or purpose of the study are not to document spillover, in any form, from an MPA to unprotected marine areas. | 665 |
| B | Theoretical modelling study | Study does not use any empirical observations of spillover but implies spillover via theoretical dispersal models. | 18 |
| C | Outside geographic limits 1 | Study outside of the consortium scope (European waters excluding the Black Sea, Mediterranean and distant outermost regions) | 19 |
| D | Outside geographic limits 2 | Study outside of European waters | 1 |
| E | Outside geographic limits 3 | Study outside of the Atlantic / Atlantic Southern Ocean / Atlantic Arctic | 8 |
| F | Not Temperate | Study is based in tropical or polar clines. | 9 |
| G | Review | Study is a review without introducing any new observations | 29 |

| | | | |
|---|---|---|---|
| H | Not Fish | Study is not documenting spillover of fish (teleost or cartilaginous), crustaceans or molluscs (e.g. mammals, birds, or reptiles) | 2 |
| **TOTAL** | | | **786** |

Following investigation of the full-text documents, a further 18 records were excluded based on the same exclusion criteria as the screening process, **this left 45 articles in the 'ultimate fate' phase** available for data extraction and analyses (see ultimate list of articles in Annex 2). These full-text excluded records did not have enough information in their titles or abstracts to justify exclusion at the screening stage, so they were retained for full-text examination. The ultimate fate of all articles across all the stages of the review process can be illustrated with a Sankey diagram (Figure 1).

Data extraction was undertaken in two parts, according to the requirements (i) for meta-analyses of MPA characteristics and species traits associated with spillover; and (ii) to a review of methodological approaches to assess spillover.

## 1.3 Results and discussion

Of the **45 retained articles, 127 cases** (unique combinations of articles, MPAs and species) were identified. **A positive detection of spillover is reported in 83%** (106/127) **of cases that investigated spillover**. There are two potential reasons for these high levels of occurrence:

1. Spillover is a regular phenomenon that commonly occurs from within MPAs with sufficient protections.
2. The scientific literature contains a positive publication bias, whereby cases where spillover was detected are more likely to be written up as manuscripts, submitted and accepted for publication.

Some grey literature was included at the search stage to counter this bias, but it was excluded based on the predefined exclusion criteria. Both of these reasons may occur simultaneously.

The only article that attempted to quantify the amount of spillover from an MPA did so using non-empirical methods. This article was retained based on the empirical data used in some aspects of its analysis, but the reported values were based on theoretical dispersion models. Of the other 44 articles, there were 78 cases of spillover detected that did not quantify an amount of spillover. Despite not estimating a quantity of spillover, of those cases where spillover was reported (106), 64% (68) were reported (by the authors) as being relevant for commercial fisheries, while 8.5% (9) were reported as not commercially relevant, and the remaining 27% (29) were unspecified (Figure 2). Of these cases where spillover was reported, 18% (19) were reported as relevant for recreational fisheries, while 8% were explicitly not relevant for recreational fisheries. The remaining 75% did not state their importance for recreational fisheries. This highlights a knowledge gap in the study of spillover from MPAs, especially for their use in fisheries management: there is a lack of empirical, quantitative estimations of spillover, by any measure, be that number, biomass or value.

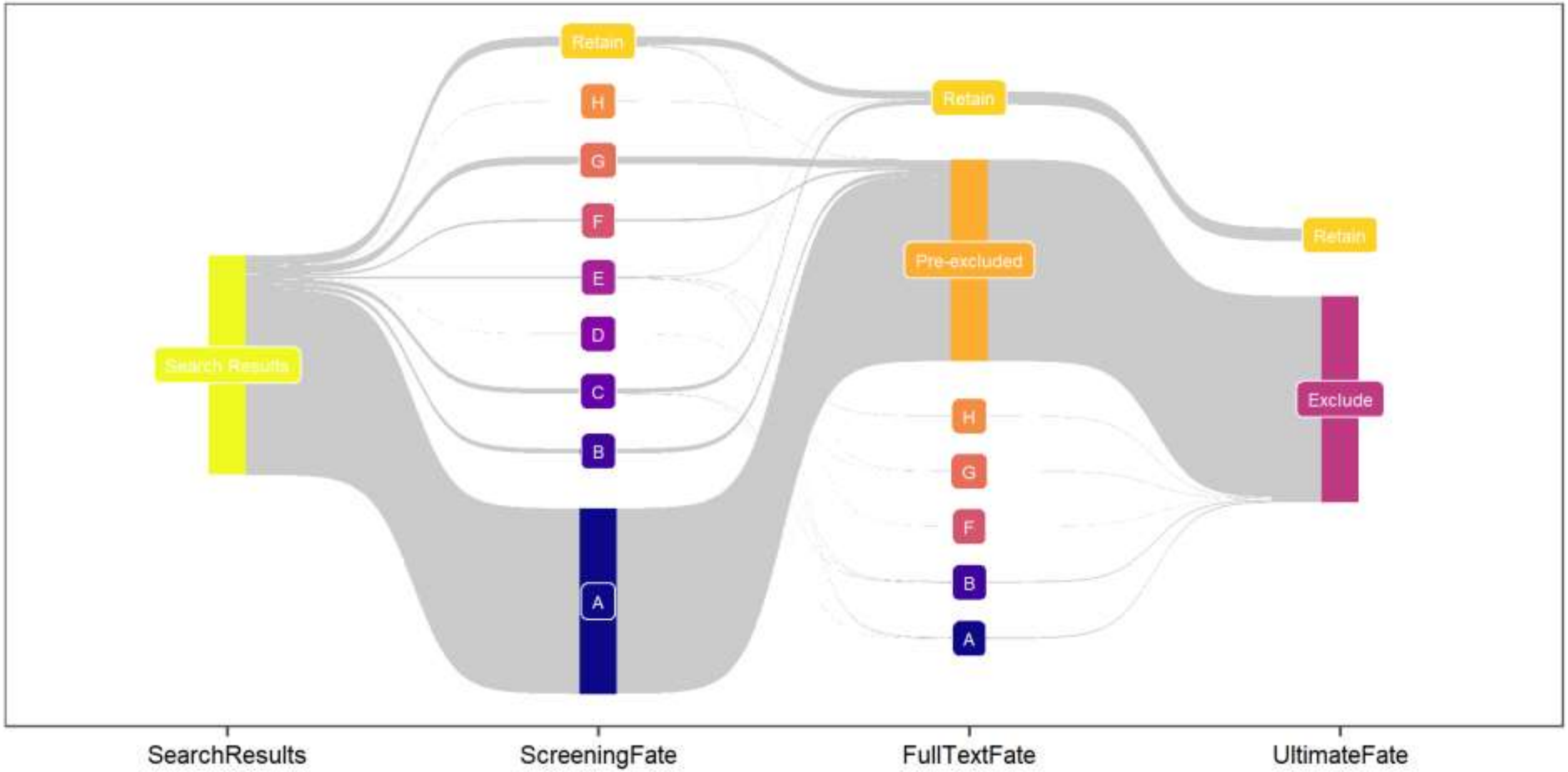


**Figure 1. Sankey diagram showing the proportions of records (relative heights of nodes and ribbons) at different fates throughout the search, screen, full-text extraction phases, as well as the ultimate fate. Letters correspond to the 'Short Code' of Table 1.**

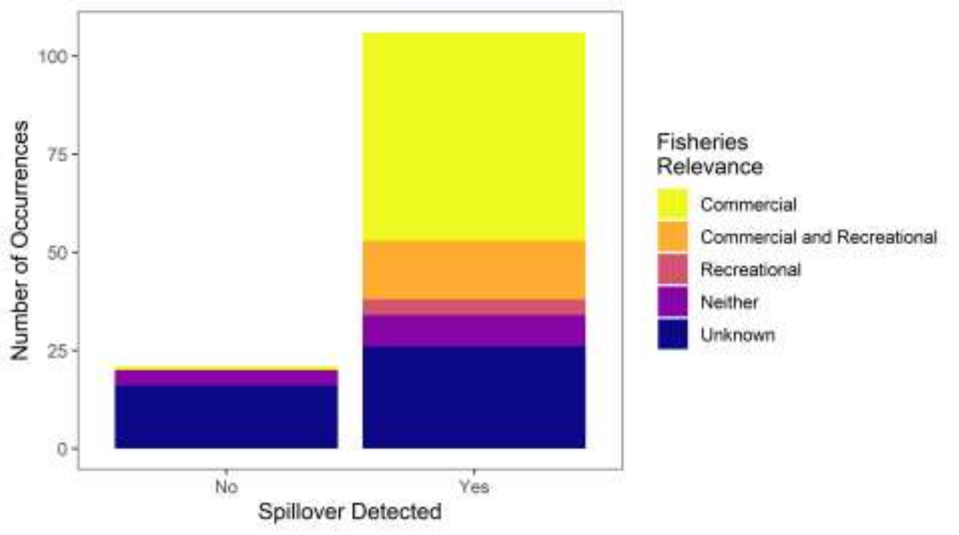


**Figure 2. Number of occurrences of spillover investigations where spillover was detected or not and the authors' stated relevance of the spillover for fisheries.**

In the remainder of this section, we provide a breakdown of the different contexts in which there is literature that addresses the topic of spillover. These visualisations are representations of the literature available on the topic, and **no direct inference can be drawn from these visualisations** from the contexts in which spillover is more or less likely to occur.

### 1.3.1 Geographic contexts

Beginning with geographic contexts, we found that most studies on spillover from temperate marine MPAs come from within the EU (Figure 3), and that the number of cases documented per article accentuated this European bias.

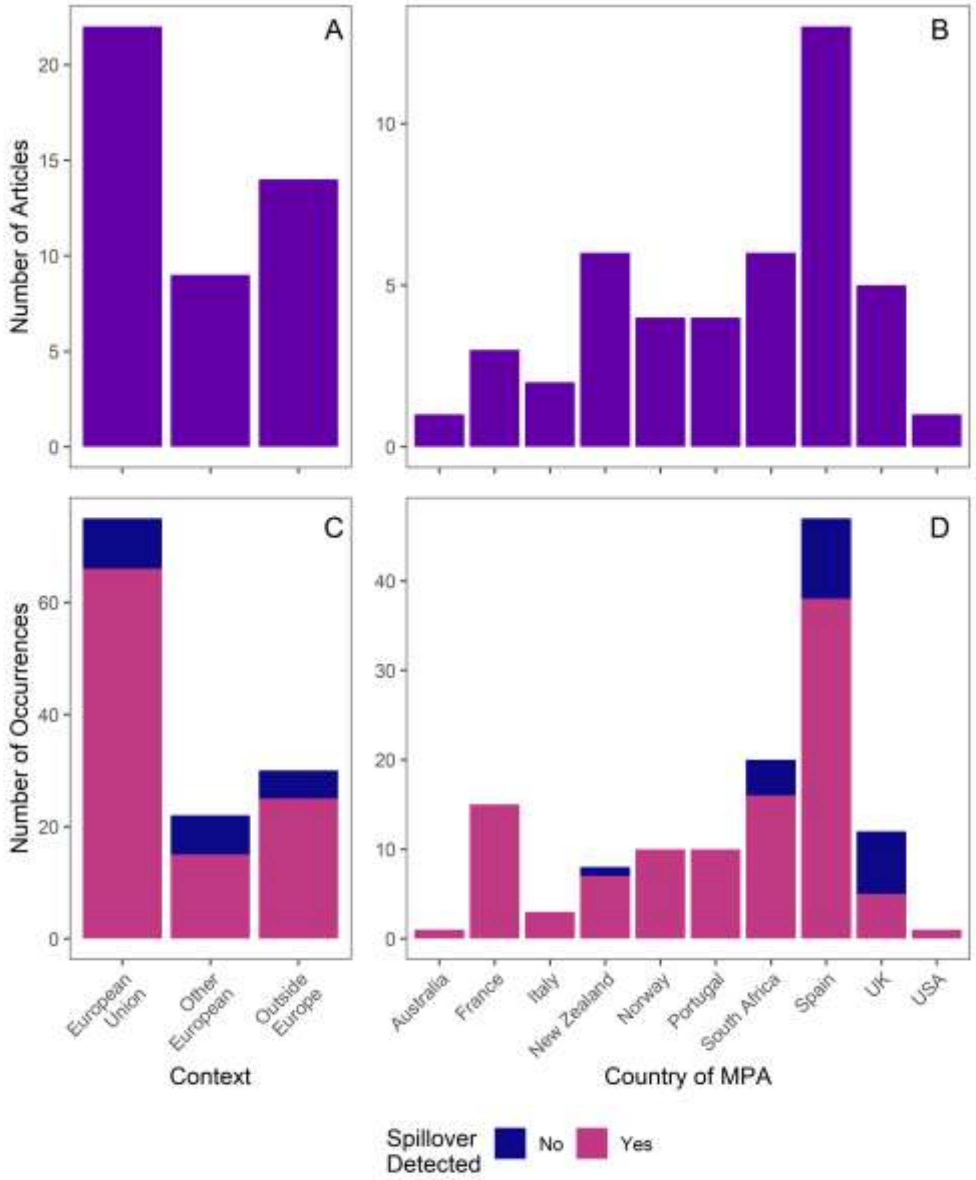


**Figure 3. Number of articles (A & B) and cases (occurrences) (C & D) that addressed spillover from marine protected areas, where spillover is documented to occur (pink) or not (blue) by European context (A & C) and country (C & D). Note that individual publications may contribute to cases multiple times by documenting multiple species or life-history stages.**

At a more local-level, relative to the MPAs in question, we found that most articles consider spillover from open coast MPAs and that there is no strong bias toward studies of networked or independent MPAs (Figure 4), where individual MPA network status was determined from either the primary article or from ad-hoc investigations into the official documentation of the MPA (e.g. governmental websites or management documents). Similarly, most cases that investigate spillover consider MPAs adjacent to open coastlines, as opposed to enclosed estuaries, islands, or open water contexts[1] (Figure 4). However, within the 'open coast' contexts, MPAs that are part of a network are better represented in the case studies in the literature. This pattern does not seem to hold across the other contexts. It may be due to what authors consider a 'Network'. In European cases, MPAs established as Natura2000 sites are often reported as belonging to a network. However, they are often designated independently and are not part of a pre-planned network that considers connectivity and refuge from anthropogenic activities.

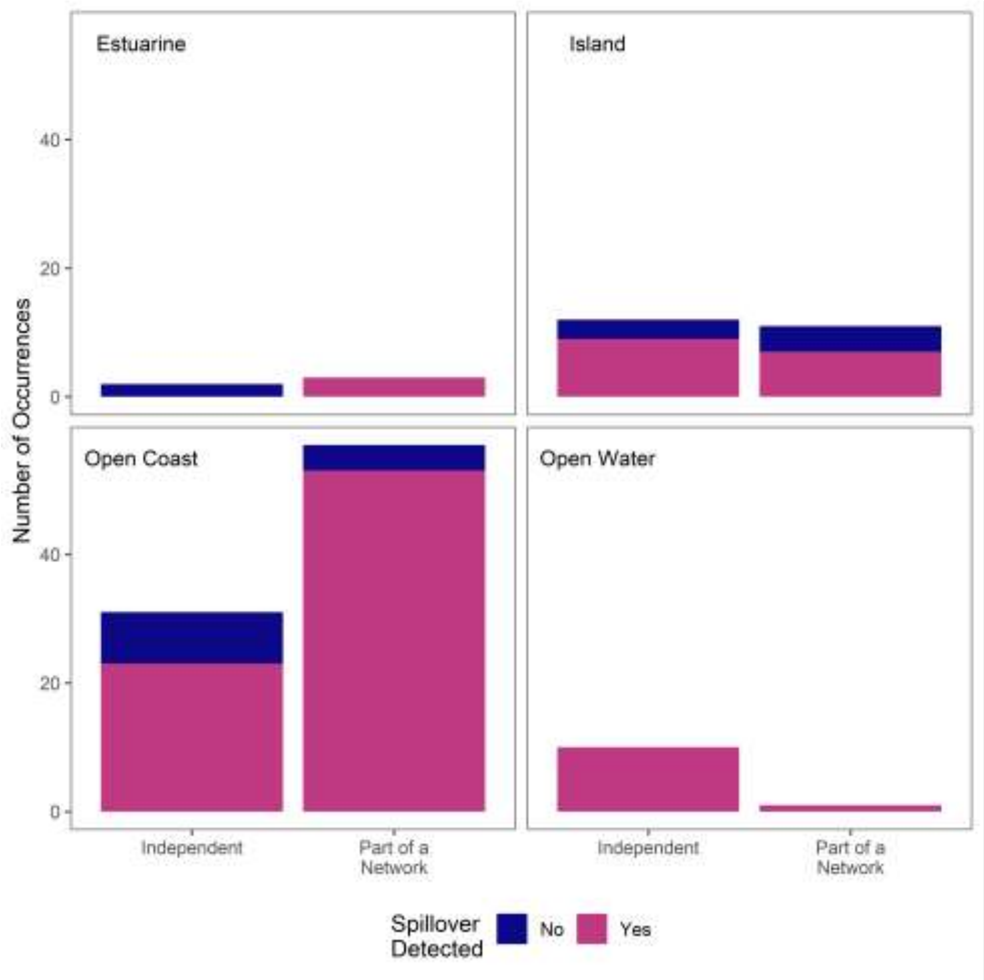


**Figure 4. Numbers of cases (occurrences) that investigated spillover in local contexts (panels) and their status as part of a network of MPAs.**

[1] 'Open coast' is one of four categories that describes MPAs' relationship to land. 'Estuarine' includes river mouths to enclosed bay systems. 'Open coast' is where an MPA has less than 180° wrap around the land. 'Island' includes cases where the MPA wraps more than 180° around the land, and 'Open water' is where the MPA is not adjacent to land.

### 1.3.2 Species characteristics

Adult regular migration is the most considered as the mechanism for spillover (Figure 5). These migrations may include daily or tidal rhythms, right up to annual or multi-annual migrations. The next most-investigated life-history stage is the routine dispersal of adults. This refers to the movement of individuals out of the MPA due to large home ranges, shifting home ranges or nomadic life-history strategies. These are often a bottleneck in population dynamics (Le Pape et al., 2020). Secondary dispersal from protected juvenile habitats[2] should, therefore, be of significant interest when examining fishery spillover.

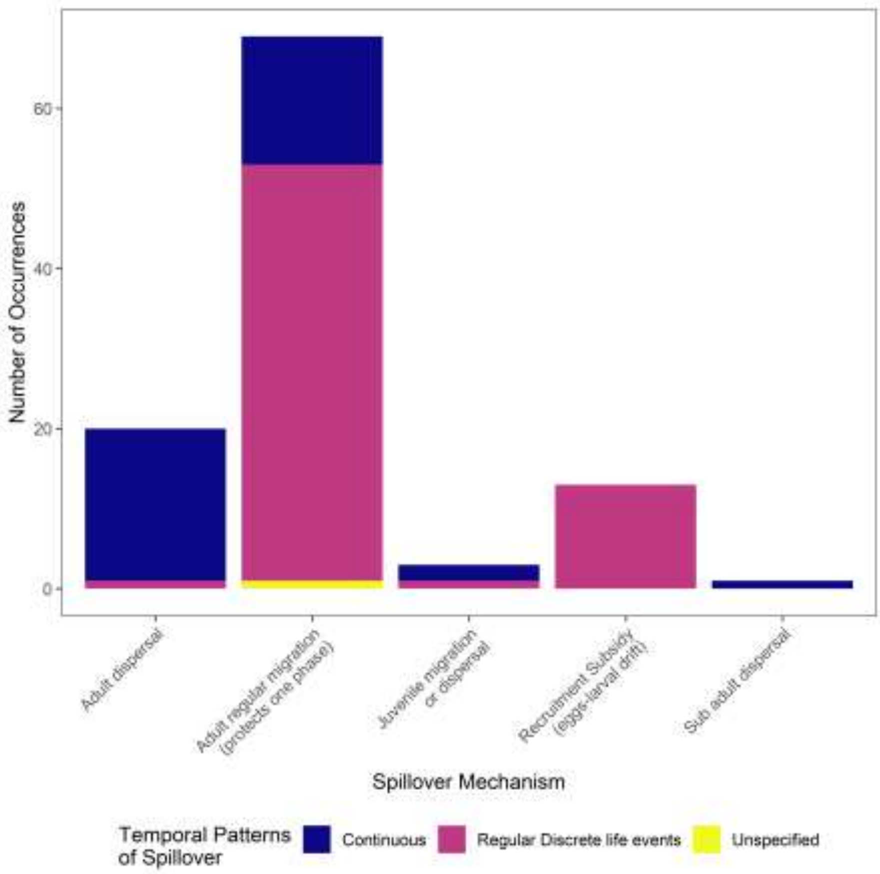


**Figure 5. Number of cases per life-history stage acting as the mechanism for spillover to occur. Colours represent the reported temporal frequency of spillover events.**

Different species and life-history stages have different potentials for spillover, as they may be more or less mobile (Ohayon et al., 2021; Kellner et al., 2007). The distances from which spillover can be detected speaks to the relevance of MPAs as a management tool for both conservation and fisheries. As such, before considering the distances at which spillover can be detected, we must consider the maximum distances at which they were investigated. In many cases, the maximum observed distance of spillover is at the limit of the studies' investigations (Figure 6), so reports of **spillover distances are likely underestimated in the literature**. Interestingly,

[2] 'Juvenile habitats' refers to all of those habitats used specifically by juvenile stages of a given species. This differs from nursery by the fact that nurseries are specifically those areas that produce a higher number of recruits per unit area but may not contribute a significant absolute number of individuals to a population. Juvenile habitats is a more general and more inclusive term.

EU and other European cases appear to investigate spillover at greater distances than it can be detected more frequently than non-European cases.

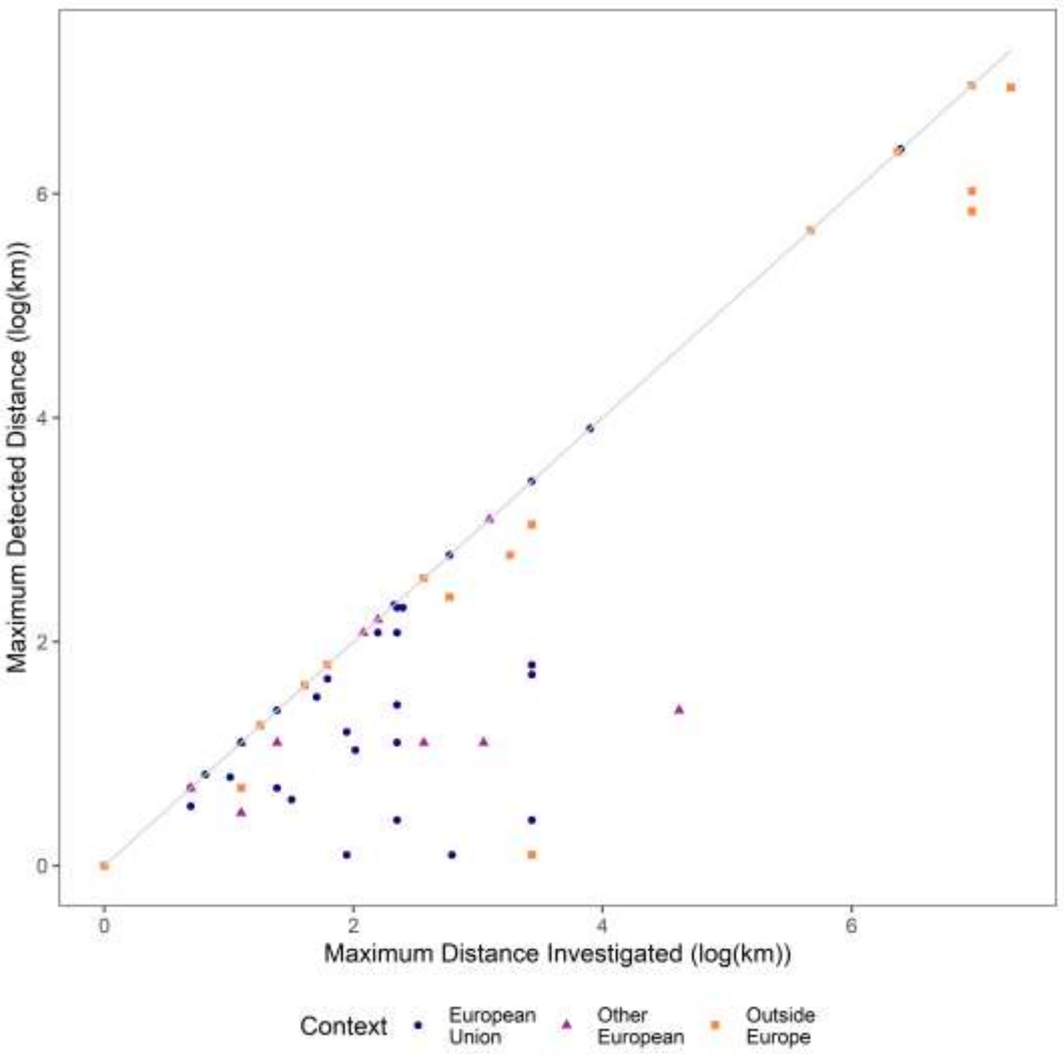


**Figure 6. Maximum distance spillover was detected over the maximum distance it was investigated, coloured by European context. Cases on the grey line represent cases where spillover was detected right up to the maximum distance investigated so maximum spillover distance is under-reported. Axes are natural log transformed to aid visualisation.**

To develop an appropriate study design for detecting spillover effects, one must possess knowledge regarding the potential extent of such effects. This potential extent is affected by various factors that encompass both species-specific traits (e.g. mobility) and MPA characteristics (e.g. MPA age). These factors must be considered when determining the distance up to which spillover effects will be assessed (Fenberg et al., 2012). These factors can either augment each other, resulting in a greater distance at which spillover effects can be detected (e.g. a highly mobile species in an established MPA) or balance each other out (e.g. a species with an expansive home range in an MPA affording minimal protection), thereby restricting the extent of the spillover effect. Due to the considerable variability in species traits, MPA characteristics, their potential interactions and the limited number of studies in the literature, this means that providing reliable estimates for the extent of spillover effects for specific species or species groups is not feasible. Nevertheless, determining the maximum sampling distance should always be founded on ecological knowledge pertaining to the species, including considerations, such as mobility and home range, in addition to an understanding the MPA's characteristics.

### 1.3.3 Types of Spillover

The investigated types of spillover appear to be defined based on the results that authors find. In all cases where spillover was detected, the significance for either fisheries or general ecology was determined, even within articles with different case studies. However, most cases that did not find spillover discuss their circumstances more generally, and they do not ascribe the contexts in which they carried out their investigations or only did so in terms of ecological implications (Figure 7).

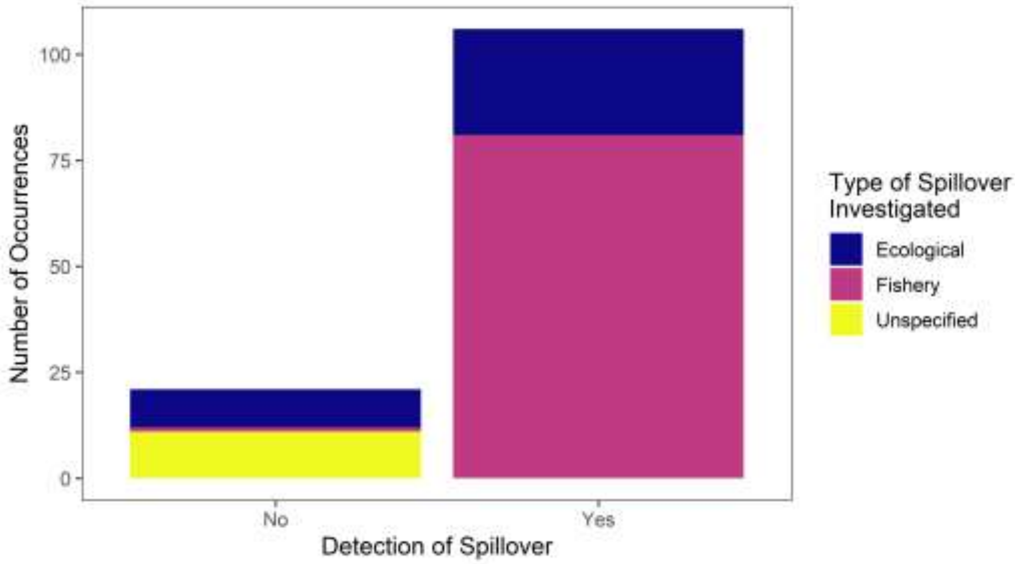


**Figure 7. Numbers of cases where different types of spillover are ascribed (colours) according to whether spillover was detected or not.**

### 1.3.4 MPA characteristics

These visualisations describe the types of MPAs where spillover has been investigated and, due to the many confounding factors and biases, comparisons between spillover and non-spillover groups should be limited to how well the literature covers them.

MPA characteristics are regularly stated as contributing to the chance, scale or magnitude of potential spillover (for a review see Di Lorenzo et al., 2020). However, these characteristics are difficult to test in empirical studies. This is because they require large-scale sampling across sets of very similar MPAs that were established at similar times in similar ecological and regulatory contexts but vary only in the characteristics of interest. This scenario is rare. Here, we can investigate how well some of these MPA characteristics are covered in our literature review. Specifically, we investigate MPA age, MPA size and relative levels of protection.

In terms of age, the literature reports on MPAs that are new, up to MPAs that are decades (maximum 40 years) old. The larger number of cases where spillover was detected also leads to a larger range of ages in MPAs than in the subset of MPAs where no spillover was detected (Figure 8). Aside from the difference in range, the distributions between these two groups look very similar, and there are some suggestions that the spillover group consists of slightly older MPAs.

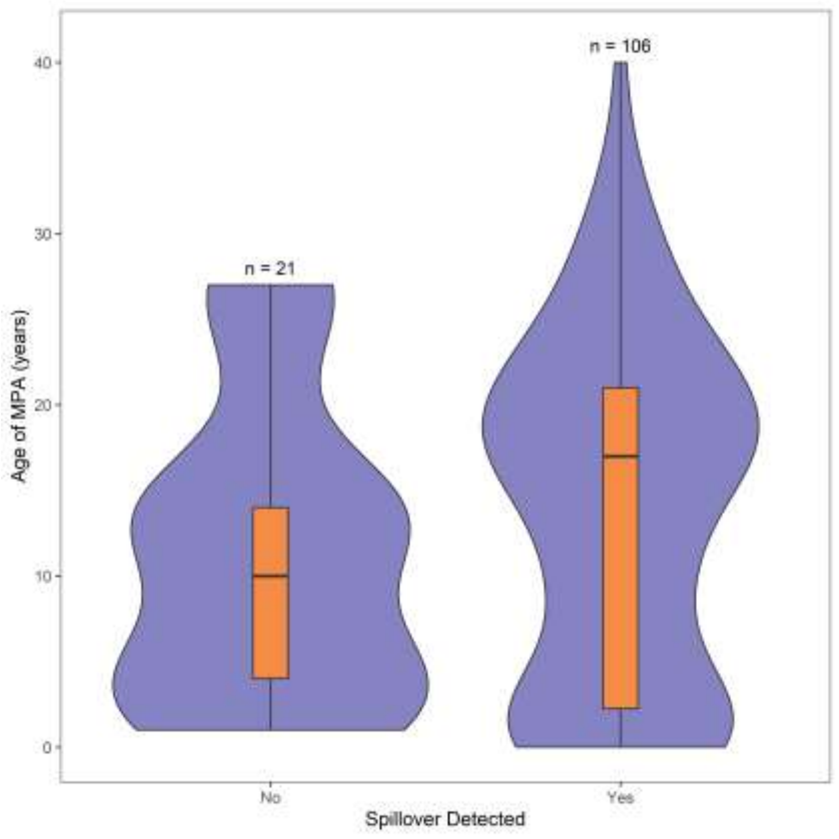


**Figure 8. Distribution of ages of MPAs from which cases of spillover are investigated. The purple 'violins' represent the density distributions of ages, while the boxplots show the median, quartiles and ranges.**

MPA size, or more specifically surface area, is also often theorised to play a role in spillover (Di Lorenzo et al., 2020). Smaller MPAs are considered more likely to have adult spillover from species with smaller home ranges. Conversely, larger MPAs are more likely to contain breeding populations for which recruitment subsides are provided to areas outside the MPA, through via egg and larval dispersal. Regardless of the theorised mechanisms, when considering the effective part of the MPA (the part where spillover was investigated from), we found cases spanning from 0.5 km² to 3,428 km². We found that the larger number of cases that found spillover had a larger range in MPA areas for the group compared to the cases where spillover was not found (Figure 9).

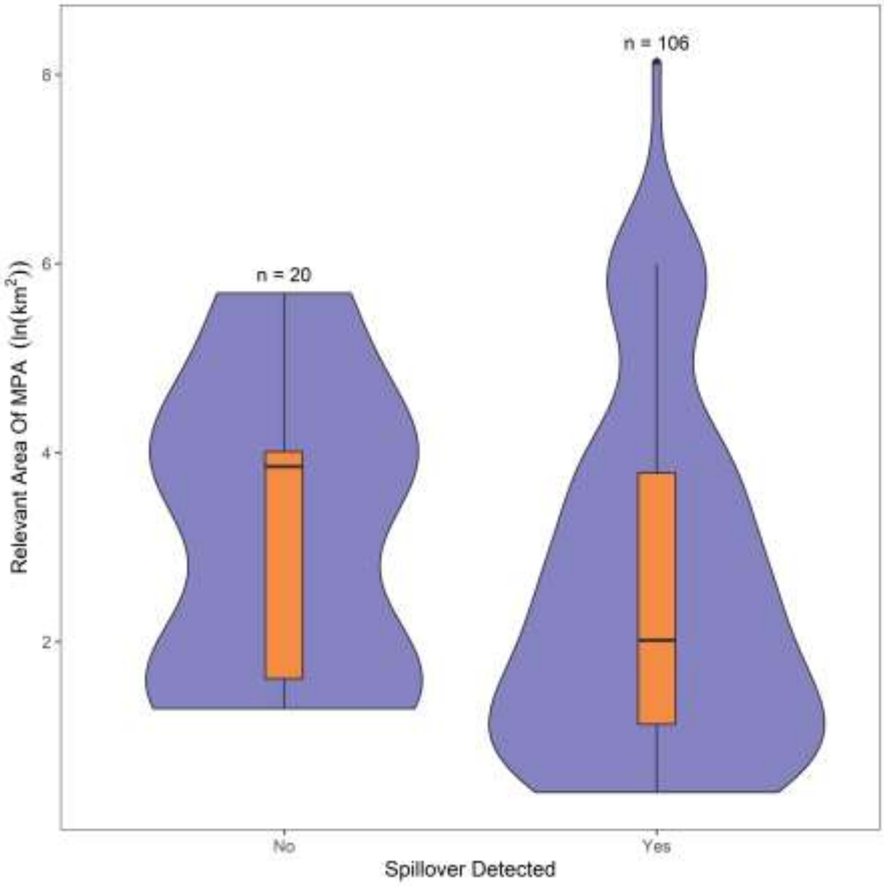


**Figure 9. The distributions of MPA areas (log(km$^2$) from literature that have investigated spillover from MPAs. The purple 'violins' represent the density distributions of ages, while the boxplots show the median, quartiles and ranges.**

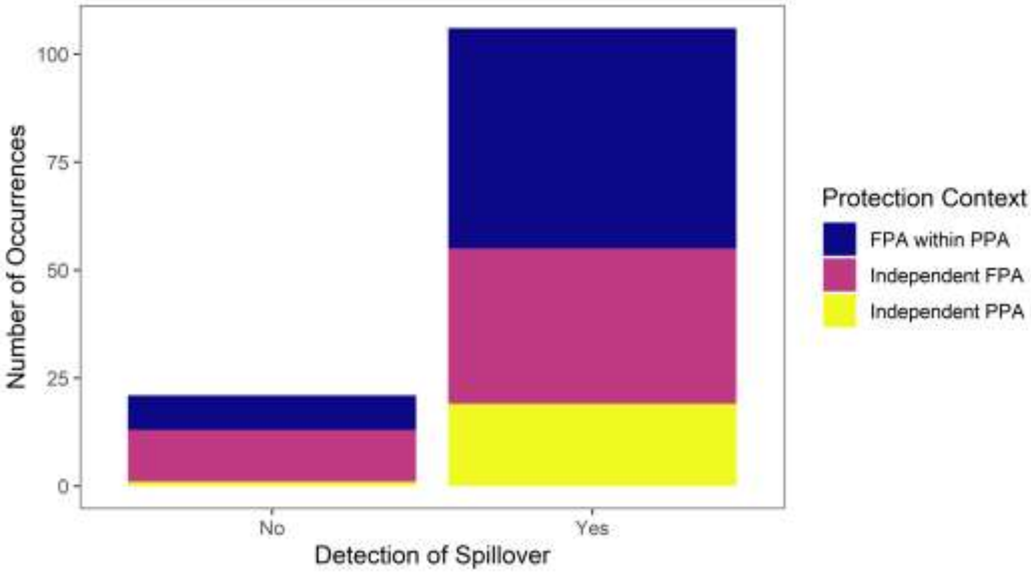


**Figure 10. Number of cases where spillover was found or not, grouped by the context of protection afforded the MPA. FPA = Fully protected area and PPA = Partially protected area (see text below for definitions).**

Intuitively, the effectiveness of an MPA should be related to the level of protection from human effects. These protections are governed by various jurisdictions, and they are put in place with various goals and caveats that are specific to local contexts. As such, we categorised levels of protection according to the stated degree of protections (not considering adherence or enforcement) into three groups. Fully protected areas (FPAs) are defined as the areas that have some degree of no-take (i.e. no fishing, harvesting or mineral exploitation), but they may still allow non-extractive activities (e.g. diving or boating). We considered partially protected areas (PPAs) as MPAs that allow some form of harvesting. This spans everything from commercial fishing bans to increased recreational bag limits or even just gear restrictions (e.g. no bottom trawls or dredges). We also consider whether these two levels of protection were implemented independently, or if the PPA was imposed as a buffer or in addition to an FPA (Figure 10). These definitions are independent of other, more rigid frameworks (e.g. those used in the sister study MAPAFISH) because they are based on authors' descriptions rather than explicit legislation or management documents.

Since PPAs are often implemented as buffers around FPAs, we should also investigate how this affects the sizes of the MPAs where spillover has been studied across different contexts. Here, we find both a reduced sample size and range of MPA areas for studies that did not detect spillover from MPAs where an FPA was established in conjunction with a PPA (Figure 11). The ranges for cases with and without spillover in the context of independent FPAs appear to be comparable, while we have no example of cases from independent PPAs where spillover was not found. This could be a result of bias in study design, where researchers want to maximise the chance of detecting spillover so focus on FPAs or PPAs around FPAs. However, some studies do report on spillover from independent PPAs. This suggests that there is also reporting bias, where only the cases where spillover is detected are ultimately written up as manuscripts and accepted for publication through peer review and editorial filters.

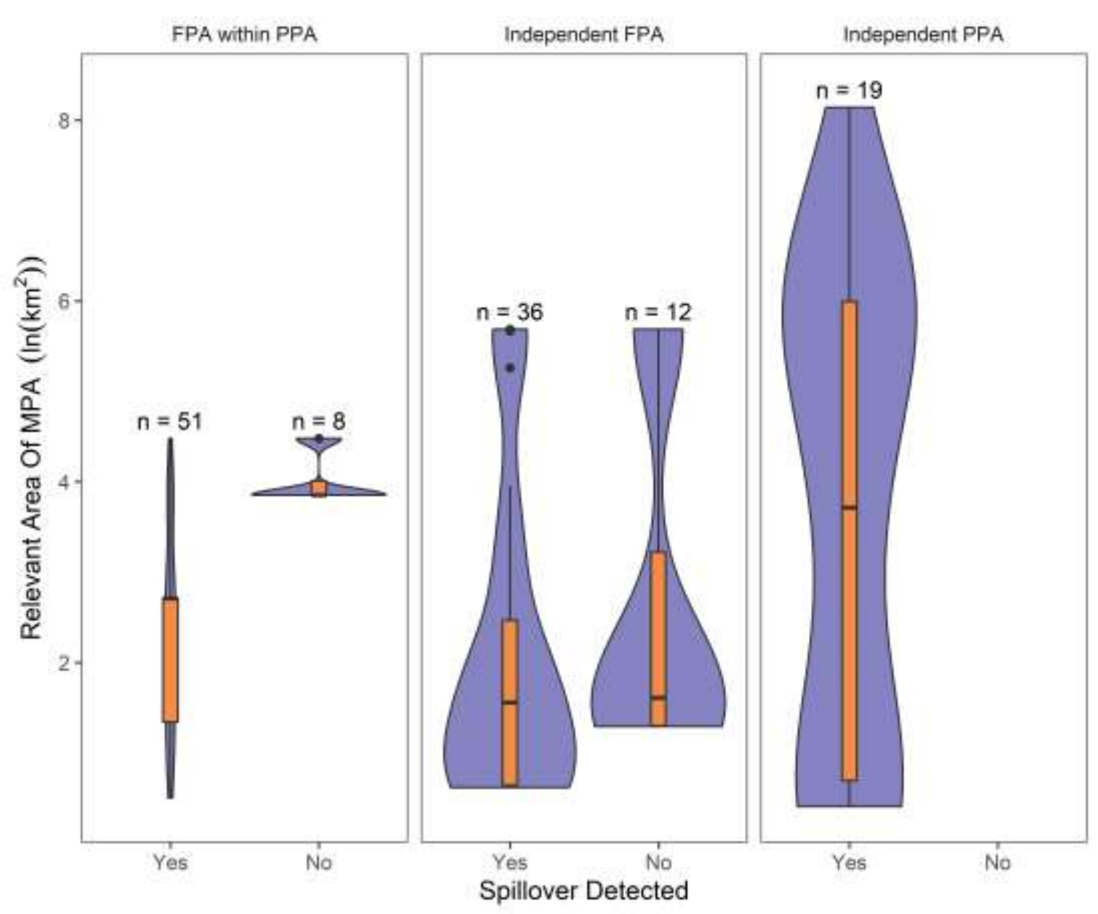


**Figure 11. MPA size distributions across different contexts of protections (panels) and whether spillover was detected or not (x-axis). The purple 'violins' represent the density distributions of MPA sizes (log scale), while the boxplots show the median, quartiles and ranges. FPA = Fully protected area and PPA = Partially protected area.**

## 1.4 Conclusions

This study provides the **first systematic review of empirical evidence for spillover from MPAs in the EU and other temperate regions**. The available literature is relatively sparse, with 45 relevant articles retained. The 127 cases identified from these articles provide a good starting point for investigating commonalities and trends. However, given the diversity of MPA contexts and species traits they represent, this is still a small number of observations to identify drivers from.

**The literature appears to contain a positive reporting bias**, which becomes more apparent when the data is broken down by MPA characteristic (e.g. protection context). Reasons for this potential bias may stem from combinations of individual and systemic biases. Individually, researchers are likely to select case study systems that they think they are more likely to detect spillover, and thus attain positive results. This positive result is more likely to motivate researchers to write manuscripts, and for editors to accept them as relevant. Furthermore, detecting spillover requires less evidence than demonstrating absence, so positive detections are easier to get through the peer review process. Independent of this bias, we are still able to document the variety of contexts in which spillover has been observed and documented.

The literature that we retained focuses on the space surrounding the EU, Europe and open coastal systems. Besides decreasing this spatial bias by addressing different contexts, our review suggests other areas that require empirical research to address gaps in the literature. First and foremost, **a broader range of protection levels need to be studied and reported** on, as our analyses are limited to very aggregated levels of protection status, based primarily on authors' choices in reporting. Additionally, **empirical investigations into the spillover of juveniles/sub-adults from protected juvenile habitats into adult habitats** (both protected and unprotected) **should be prioritised**, especially where there is a need to document fishery spillover.

Finally, simply documenting spillover occurrence is only the first step. **Quantifying scale** (i.e. distance of effect) has been attempted, but it is often limited by the spatial scale of studies' observations. **Quantifying magnitude** (i.e. numbers of individuals and/or biomass) only appears once in our dataset and, even then, it relies heavily on combined models of early life-stage development, behaviour and particle drift in large hydrodynamic models. **Quantifying the value to fisheries** (monetarily) **or conservation** (in terms of population dynamics) has not been considered empirically in the literature yet, and it relies first on documenting spillover magnitude.

# 2 META-ANALYSIS OF FACTORS ASSOCIATED WITH SPILLOVER

**Key highlights**

- A meta-analysis of various factors related to MPA characteristics and species traits has shown a number of emergent patterns in relation to spillover effects.
- A select combination of MPA characteristics (MPA age, local context and network status) proved capable of predicting the occurrence of spillover, and are therefore key considerations in the design of MPAs that have spillover as an objective.
- There is some evidence that species mobility (free swimming versus sessile or walking) and reproductive strategies (broadcast spawners versus brooders) are important factors for the occurrence of spillover.
- Empirical studies need to quantify magnitudes of spillover (export of numbers of individuals or biomass), and the temporal frequency and spatial scale with which these occur.

## 2.1 Introduction and objective

Many studies on MPAs focus on differences in species abundances and community composition within and beyond their borders (Ohayon et al., 2021). Furthermore, within the EU, MPAs' objectives are primarily focussed on biodiversity conservation, and they are assessed based on the state inside the MPA (Feary et al., 2024). Should the objectives of future MPAs include improving the abundance of organisms outside of MPA boundaries (e.g. to support broader populations and/or fisheries) then designing MPAs with characteristics that increase the chances of spillover is key to their success (Di Lorenzo et al., 2020). Furthermore, understanding whether MPA spillover is an appropriate expectation for an organism of interest is fundamental to deciding on whether to use MPAs as a management tool for that organism.

While the previous section describes the literature available on spillover from MPAs in the EU and other temperate regions, these descriptions do not provide evidence of whether any of the differences observed between rates of spillover and the various MPA characteristics are true. In this section, we attempt to look for such evidence by considering the review database as a record of the presence and absence of spillover under various conditions. First, we consider the characteristics and context of the studied MPAs. Next, we consider a set of traits of the species that were studied. The objective of this work is to investigate if various MPA characteristics or species traits affect the occurrence of spillover.

While we intended to investigate how fishing activities relate to the detection of spillover, the increased geographic scope of the literature review (Section 1) meant that data on fishing activities (Feary et al., 2024) was not available for many of our cases. Therefore, direct analysis was not possible. However, the MPA characteristic 'protection level' acts as a proxy for the effects of fishing.

## 2.2 Methodology

### 2.2.1 MPA characteristics and spillover

To investigate the similarities between MPA characteristics and how these relate to the detection of spillover, we employed a data reduction methodology called 'Factor

Analysis of Mixed Data' (FAMD). FAMD is similar to a principal components analysis, in that it positions the observations in a multidimensional space then computes new synthetic variables, called dimensions through that space that explain the most variation in the observations (Escoffier, 1979 cited in Audigier et al., 2016). These dimensions are computed iteratively so new dimensions are orthogonal to previous dimensions and maximise the discriminatory power of the sets of dimensions. However, FAMD scales and combines continuous variable coordinates and categorical dissimilarity measures so that they contribute equally and proportionally to their own variation when they are used to calculate the dimensions of maximum variability. These new dimensions are employed when visualising the relationships between these complex multivariate data sets, and in identifying and testing which variables align most with occurrences of spillover. We employed the R package *FactoMineR* (Lê et al., 2008) to implement the FAMD and *ggplot2* (Wickham, 2016) to visualise the results.

With FAMD, we included all cases (multiple cases per study), irrespective of whether spillover was detected or not. Furthermore, we utilised the variables that describe MPA characteristics as active variables, which contribute to calculating the new dimensions of the transformed data space, namely:

- Area ($km^2$) of MPA from which spillover was investigated [effectiveArea]
- Age of the MPA [MPAMinAgeAtStudy]
- Local context (e.g. island versus estuary) [MPALocalContext]
- Level of protection [ProtectionLevel]
- MPA relationship to a network of MPAs [NetworkStatus]
- Whether the relevant habitat for the target species extended from within to beyond the MPA [RelevantHabitat]

The occurrence or absence of spillover was also included as a passive, 'supplementary' variable. These 'supplementary' variables are not used during the dimension reduction phase, but they are rescaled to the same standards as the active variables. This means that their relationship to the new dimensions can be tested and visualised alongside the active dimensions.

Based on the results of the FAMD, we selected the explanatory variables for a logistic regression. First, we tested whether the values of the first three dimensions differed between the groups of cases that reported spillover or not (F-test, similar to a one-way ANOVA). We selected the variables that were significantly correlated to the given dimension (Pearson correlation coefficient) from the dimensions where there was a significant difference between spillover groups.

To perform the logistic regression, the spillover variable was transformed to a binary variable (0,1) according to the absence or presence of spillover, respectively. This was the response variable for the generalised linear mixed model (GLMM) so that, together with the select explanatory variables from FAMD, our full model was:

$$Spillover_{0/1} \sim^{Binomial}_{Logit\ link} Explanatory\ Variables + RE_{Article}$$

Where $Spillover$ is the aforementioned response variable, which is modelled by a binomial distribution with a logit link to the conditional model. The conditional model contains the $Explanatory\ Variables$ from FAMD as described above plus a random effect of study to account for the pseudo-replication we have with multiple cases for each study.

This full model was reduced to the most parsimonious combination of explanatory variables (where parsimony is the best fit of model to data without over-parameterising) using two methods. The first was to iteratively drop single fixed effects according to their contribution to the relevant FAMD dimensions. Meanwhile, the second dropped terms iteratively by selecting the next most parsimonious fit. Model parsimony was measured with the Akaike Information Criterion corrected for small sample sizes (AICc). Logistic regression models were fitted with glmmTMB (Brooks et al., 2017), and AICc comparisons were made using bbmle (Bolker et al., 2020).

The model was validated through random, repeated sub-sampling cross validation. This process led to 10% of the data being removed (test set) and the remaining 90% being used to refit the model (training set). The model refit with only 90% of the data was then used to predict the remaining 10% test set to predict datapoints that were independent of the fitting procedure. This process was repeated multiple times (999) with random partitioning of the data into test and training sets. The accuracy of the predictions was judged under the various validation conditions. The metrics we used to judge model predictive performance were bias, mean absolute error (MAE), root mean squared error (RMSE) and the squared correlation coefficient ($R^2$).

### 2.2.2 Species traits and spillover

When describing or differentiating between species, we frequently used measurements or comparisons of morphology. These morphological traits are the most immediately apparent differences between organisms. However, there are many other aspects of species' biology that differentiate them from each another, such as strategies of reproduction, methods of dispersal, types of behaviour and life-history (e.g. longevity or time spent as larva). These aspects are termed 'traits'. By using traits instead of taxonomy, we can investigate trends in biology, independent of biogeographic boundaries, and we can draw more general conclusions (Violle et al., 2007).

The data set from the systematic literature review was reduced to cases where spillover was investigated at the individual species level. The cases that were not retained only reported on spillover at the scale of higher taxonomic orders than the genus, or only reported combined measures of assemblages or communities. For cases where a genus was reported, either the stated predominant species in the article, or the 'type-species' was used to derive traits. The remaining dataset contained 98 of the original 127 cases.

Taxonomic nomenclature and spelling were checked against multiple databases (e.g. 'World Register of Marine Species', 'FishBase', and 'Integrated Taxonomic Information SystemITIS') using the R package 'taxize' (Chamberlain & Szocs, 2013). Species traits were retrieved from FishBase (www.fishbase.se) for fishes and SeaLifeBase (www.sealifebase.ca) for invertebrates, using the R interface *rfishbase* (Boettiger et al., 2012). A selection of the relevant fields was made based on the field title and the levels/values within. This selection was then reduced to include only those with sufficiently (more than 50%) complete cases for the species of this study.

The final traits available for analyses are described in Table 2. Some fields were also combined to improve completeness (e.g. L-infinity was combined with L-maximum where there were gaps in L-infinity). For the remaining gaps in trait information, an ad-hoc primary literature search was undertaken. After this process, information was still missing for seven species' maximum age, five species' spawning frequency and two species' early life stage habit. These missing values were set to the average (mean or mode for continuous or categorical variables, respectively) for the whole dataset, which is averaged across cases; not the average of the species represented.

Data reduction and variable selection for logistic regression were carried out in the same way as described for the MPA characteristics above.

**Table 2. Trait variables and their respective levels that were present in the dataset for analysing species traits and spillover from MPAs. Originally sourced from FishBase and SeaLifeBase, where possible, gaps were filled with ad-hoc primary literature searches.**

| Trait Variable | Levels |
|---|---|
| Habit | benthic, benthopelagic, demersal, reef-associated, pelagic-neritic |
| BodyShape | bivalve, fusiform / normal, decapod crab, short and/or deep, elongated, Decapod lobster, flattened, pentagonal symmetry, cephalopod |
| ReproductionMode | dioecism, protogyny, protandry, hermaphrodite |
| Fertilisation | external, internal (oviduct), internal |
| SpawningFrequency | two seasonal peaks per year, one clear seasonal peak per year, once in a lifetime, throughout the year but peaking once, biennial with one clear seasonal peak |
| ReproGuild_ELSCare | non-guarders, bearers, guarders |
| ReproGuild_ELSHabit | open water/substratum egg scatterers, external brooders, nesters, internal live bearers |
| LocomotoryMethod | jet, movements of body and/or caudal fin, legs, undulation of median or pectoral fins, sessile |
| LocomotoryMode | clam jet, subcarangiform, walking legs, anguilliform, labriform, rajiform, hydrostatic legs, affixed, siphon jet |
| LengthMax_Inf | [Numeric] (cm) |
| TrophicLevel | [Numeric] (unitless) |
| AgeMax | [Numeric] (years) |

## 2.3 Results and discussion

### 2.3.1 MPA characteristics and spillover

The FAMD procedure explained ~64% of the variation among the cases, utilising five synthetic and orthogonal variables to maximise the variation explained along each concurrent dimension (15.9%, 15.0%, 13.7%, 10.1% and 9.2% for dimensions 1–5 respectively).

The two binary levels of the supplementary variable, spillover, differ most along Dimension 1 (Figure 12). Values of dimension one can differ between cases, both with and without spillover (F-test: $R^2 = 0.031; p = 0.046$). None of the remaining four dimensions differed significantly between cases with or without spillover.

The MPAs without relevant habitats extending across borders (HabIso) were the most distant group from the centre of the dataspace in terms of Dimension 1. Estuarine MPAs were the most different group in terms of Dimension 2.

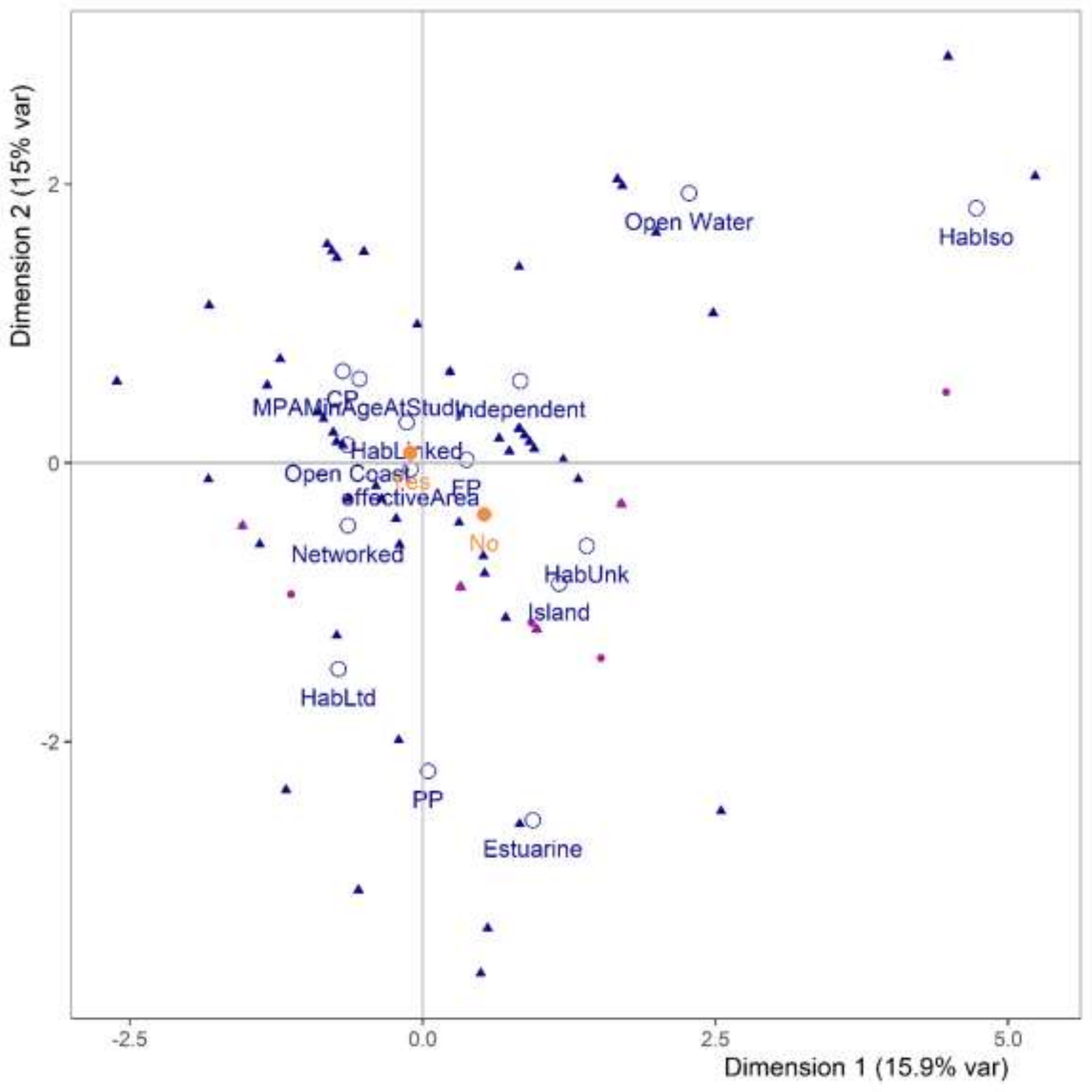


**Figure 12. Cases (small points) of investigations into spillover across the first two dimensions of a FAMD and the position of the variables and categories that contribute to generating these dimensions (hollow blue circles). Small blue triangles are cases where spillover was detected. Small purple circles represent cases where no spillover was detected (NB: where there are multiple cases per MPA with and without spillover, the overlaid figures may appear as purple triangles). The large yellow circles represent the binary categories of the supplementary variable: spillover.**

The local context of the MPA contributed the most to both Dimension 1 and Dimension 2 (Figure 13) out of all the variables. The effective area of the MPA contributed weakly to Dimensions 1, 2 and 3, but it was the strongest contributor to Dimension 4 (Figure 14). In both Figure 13 and Figure 14, the variable 'Spillover' shows weak correlation relative to the other variables. This is because the other variables are used to derive the two dimensions that they are being correlated against (a measure of their contribution to the dimension) while spillover is only plotted in this dataspace, illustrating a completely independent correlation.

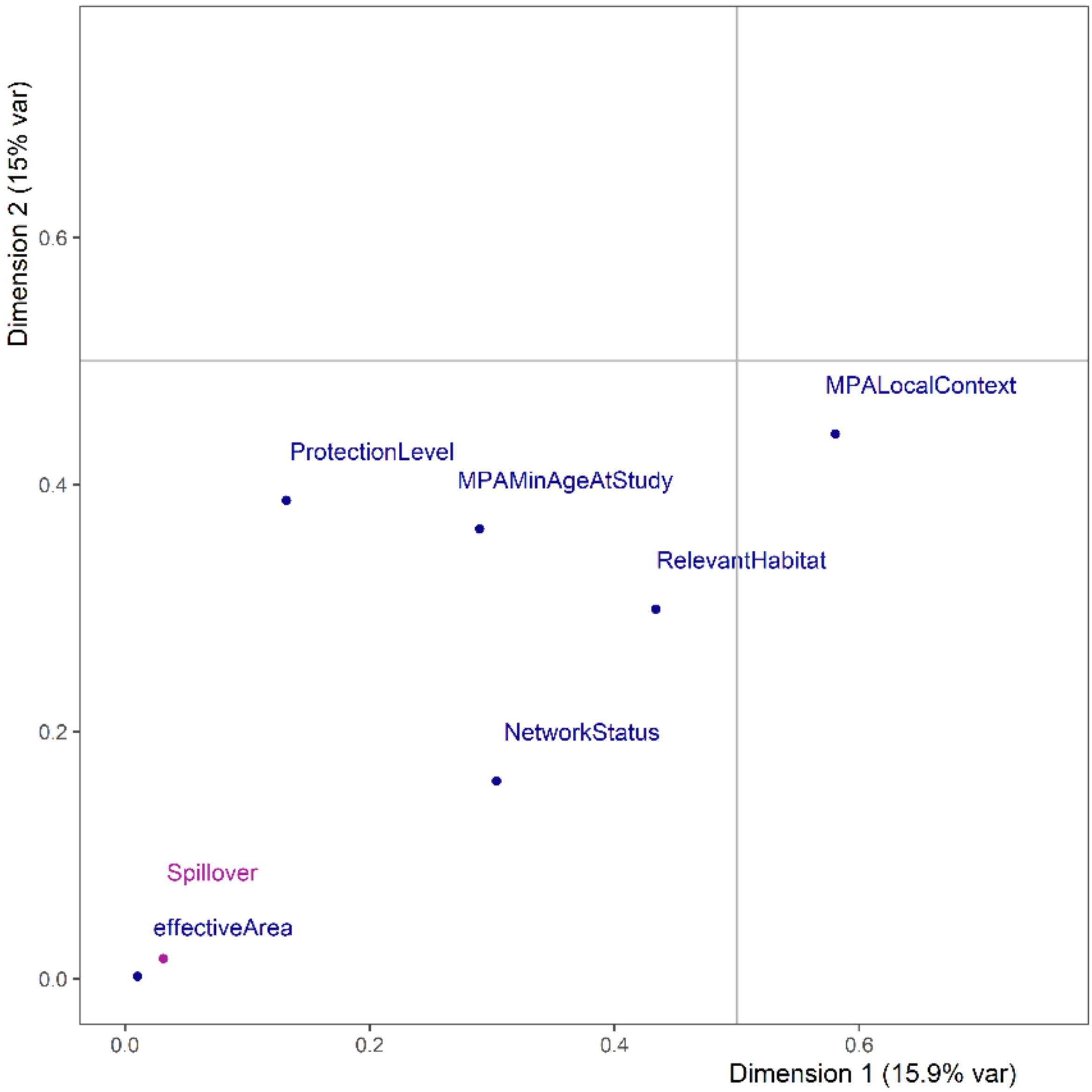


**Figure 13. Contributions of variables to the first two dimensions of the Factorial Analysis of Mixed Data for all cases in the literature where spillover was investigated from temperate MPAs. Blue variables are 'active' and contribute to the dataspace from which the dimensions are derived. The pink variable is 'supplementary', which is fitted with the same dataspace but does not contribute to the calculation of the dimensions.**

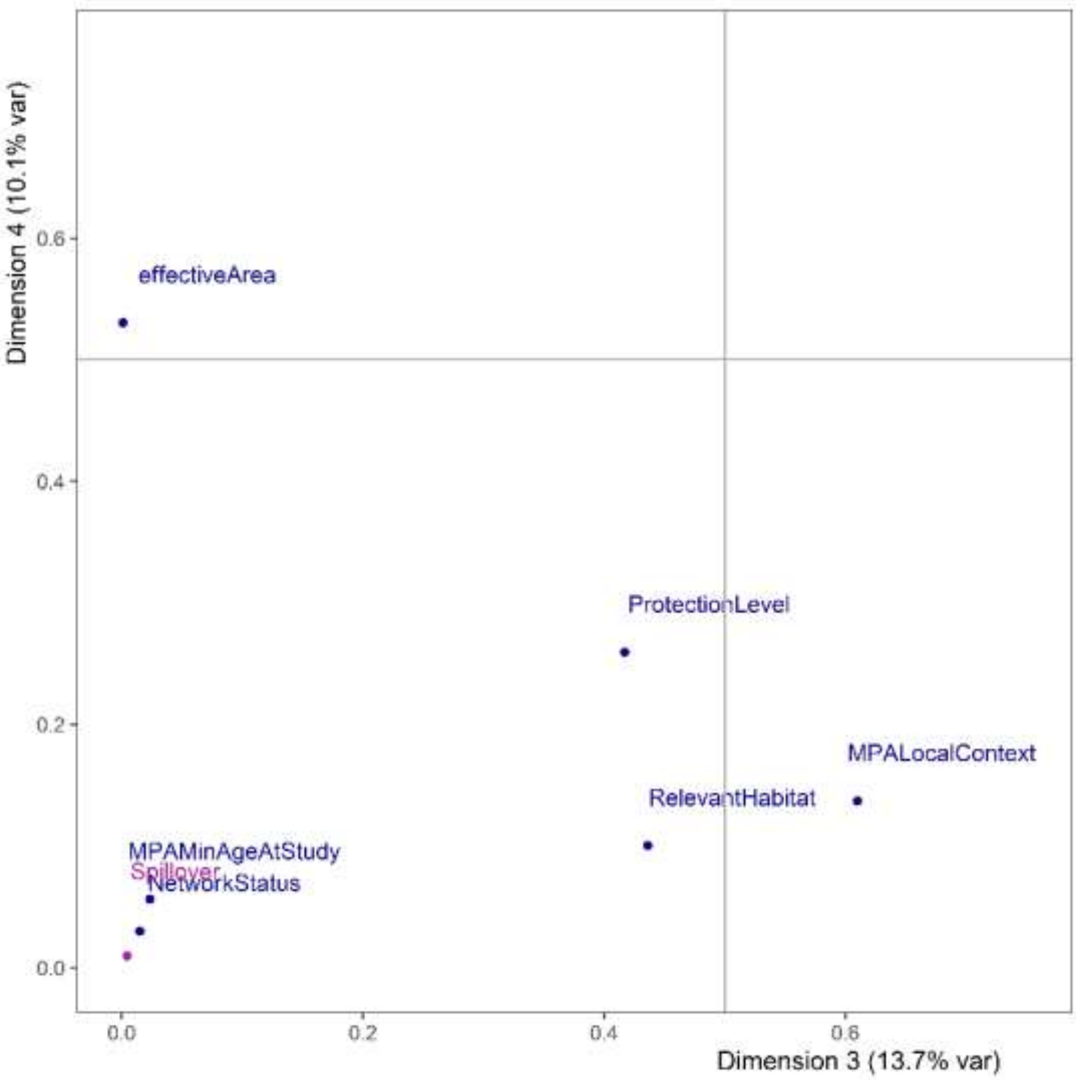


**Figure 14. Contributions of variables to dimensions three and four of the Factorial Analysis of Mixed Data for all cases in the literature where spillover was investigated in temperate MPAs. Blue variables are 'active' and contribute to the dataspace from which the dimensions are derived. The pink variable is 'supplementary', which is fit to the same dataspace but does not contribute to the calculation of the dimensions.**

When only considering the dimensions where there is a significant difference between cases with and without spillover (only Dimension 1), we find five of the six variables that represent MPA characteristics varied significantly (Table 3). These MPA characteristics were: MPA age (MPAMinAgeAtStudy), local context (MPALocalContext; e.g. island or estuary), habitat (whether it extended from within to beyond the MPA for the target species) (RelevantHabitat), the MPA's relationship to a network of MPAs (NetworkStatus) and the level of protection (ProtectionLevel).

We can see that both the local context and the age of the MPA were relatively highly correlated along the same dimension that provided significant differences in spillover outcomes (Table 3). **This suggests that MPA placement relative to land (estuaries, islands, coasts, open water) and MPA age are important factors in determining if spillover will occur**. Similarly, the remaining variables in Table 3 have a lower but still significant correlation with this dimension, suggesting they also play a role in how successful an MPA is at creating spillover. However, these are only second order correlations (our 'explanatory' variable and 'response' variable are both correlated with a synthetic variable: Dimension 1 from the FAMD). In order to investigate these effects further, these variables were carried forward as explanatory variables in logistic regression.

**Table 3. Variables retained from the Factor Analysis of Mixed Data for the logistic regression and the results of the correlation tests with Dimension 1. * Indicates the passive variable, which is independent of Dimension 1**

| Explanatory Variable | Correlation with Dim1 | p-value |
|---|---|---|
| MPALocalContext | 0.580 | <0.001 |
| RelevantHabitat | 0.434 | <0.001 |
| NetworkStatus | 0.304 | <0.001 |
| ProtectionLevel | 0.132 | 0.0002 |
| MPAMinAgeAtStudy | -0.538 | <0.001 |
| Spillover * | 0.031 | 0.0460 |

Each of the drop-one procedures retained the variable MPAMinAgeAtStudy in their most parsimonious models. The method dictated by the contribution to the FAMD also retained MPALocalContext, while the pure AICc based method retained NetworkStatus. The overall difference in parsimony between these two models was negligible (difference in AICc = 2.9), and the predictive capabilities were the same, so the fuller model that used both terms and MPAMinAgeAtStudy was retained. Accordingly, our selected model considered the age of the MPA, its position relative to coastlines (estuaries, islands, open coasts, open waters) and whether the MPA was part of a designed network to explain the detection or absence of spillover.

Model residuals were deemed acceptable, as there were no unexplained deviations, dispersion or outliers and, despite some trends in residuals, overall tests for patterns in residuals were non-significant. The model itself had no significant terms (Table 4). This indicates that it is the combination of the explanatory variables in the conditional model rather than any individual variable that drives the model fit to the data. Consequently, we cannot draw any inference about changes in the probability of detecting spillover corresponding to changes individual MPA characteristics. If significant terms were found, then the 'Odds Ratio' would be the relevant column to investigate. This value represents how many times the odds of spillover occurring increase with one unit increase the corresponding continuous variable (MPA age in years) or compared to a reference condition for the categorical variables (*c.f.* estuarine MPAs for MPALocalContext and non-networked MPAs for NetworkStatus).

**Table 4. Parameters of the logistic model of spillover occurrence in relation to various MPA characteristics.**

| Variable for Parameter | Parameter Estimate (log-odds) | Std.Error | z-value | Pr(>\|z\|) | Odds Ratio |
|---|---|---|---|---|---|
| (Intercept) | 1.17E-01 | 1.17E+01 | 0.01 | 0.992 | 1.123782 |
| MPAMinAgeAtStudy | -1.54E-02 | 1.11E-01 | -0.138 | 0.89 | 0.984748 |
| MPALocalContextIsland | 5.43E+00 | 1.19E+01 | 0.458 | 0.647 | 228.3775 |
| MPALocalContextOpenCoast | 7.26E+00 | 1.19E+01 | 0.608 | 0.543 | 1416.579 |
| MPALocalContextOpenWater | 2.50E+01 | 1.55E+04 | 0.002 | 0.999 | 7.27E+10 |
| NetworkStatusNetworked | 6.57E-01 | 2.13E+00 | 0.309 | 0.758 | 1.928418 |

Despite not being able to draw inference directly from the model, model validation showed that the model was capable of predicting naïve data (cases that were not used in fitting the model) with low bias and mean absolute error. While root mean squared error was relatively high, so too were the correlation coefficients (Figure 15). When the model trained on the full dataset was allowed to predict back over the whole dataset (metrics represented with an * in Figure 15), we saw a ~93% success rate in predicting spillover or not (sensitivity = 92% & specificity = 100%). Some of the variation seen in the validation metrics is brought about by the small size of the 'test' data sets created in the iterative cross-validation procedure. With few cases to derive the metrics from, small changes in the number of the test set being close to, or far from, the model average have a larger impact on the calculated metrics.

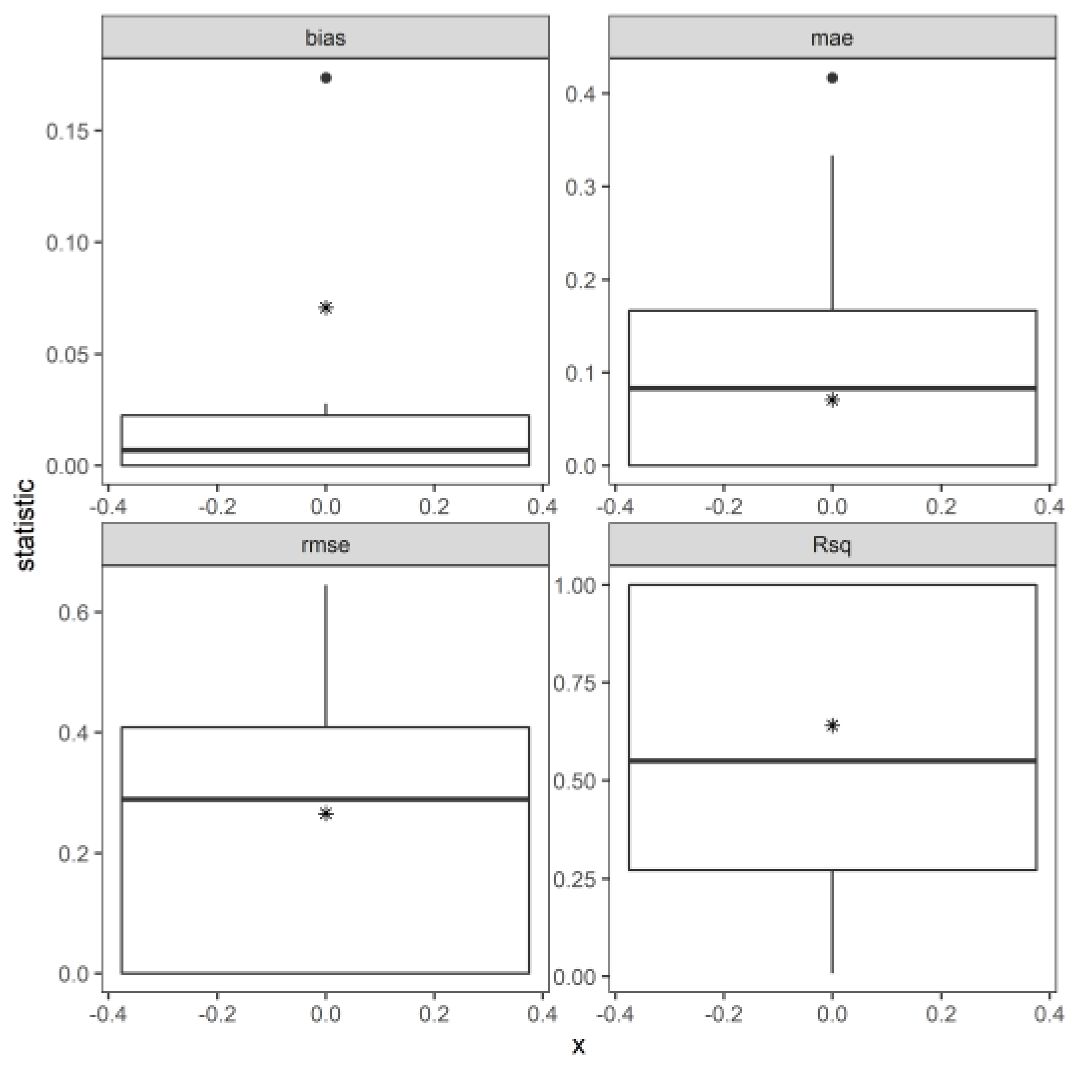


**Figure 15. The selected model of MPA characteristics capability in predicting novel data based on random sub-sampling cross validation. Validation was performed iteratively on 10% of data as test data per iteration for 1,000 iterations. Each panel shows the range, 25th and 75th quartiles and median values of the four metrics used to assess the model's performance, namely: bias, mean absolute error (mae), root mean squared error (rmse) and the correlation coefficient (Rsq) between observed and predicted values. The asterisk indicates the metric value for the model predicting over the whole dataset after being trained on the full dataset (independent of cross-validation procedure).**

### 2.3.2 Species traits and spillover

There were many more levels of differentiation between species traits than between MPA characteristics alone. There were more traits than characteristics (i.e. more variables) and more diverse levels within the trait variables than just the MPA characteristic variables. However, there were also fewer cases to capture the variation across these variables (98 versus 127) due to some studies reporting on aggregate assemblage spillover or other non-specific forms of spillover (see methods).

In applying the dimensionality reduction (FAMD) to this more diverse data set, we see how different data are clustered and differentiated by their shared and differentiating traits (Figure 16). The recombination of these different traits into the synthetic variables (Dimensions) allows us to identify what types of traits are more closely associated with differentiating spillover and which traits within these categories are associated with the detection of spillover or not. From the dimensionality reduction FAMD, we found that many of the traits associated with teleost fishes were differentiated from the traits of crabs and lobsters by Dimension 1 (Figure 16). This is exemplified by the **differentiation between locomotory types** (body-caudal fin swimmers versus walking legs and mobile versus sessile). Comparatively, Dimension 2 separated traits associated with teleosts from traits of ray type elasmobranchs and cephalopods independently. Across both of the first two dimensions, we can see reproductive traits differentiating between species clusters, with live-bearers, external brooders and egg scatterers all differentiated from one another. The **egg scatterers were more closely associated with positive cases of spillover, while external brooders were more closely aligned with the absence of spillover**. The different cases remain clustered by what appears to be taxonomic groups (although taxonomy was not explicitly included in the analysis) with little differentiation between spillover occurrence and not. Despite this apparent lack of difference, both Dimension 1 and Dimension 2 were significantly different when compared between cases of spillover and not-spillover, albeit with low levels of correlation (F tests: $R^2$ = 0.545 and 0.048, $p$-value = 0.021 and 0.03, respectively).

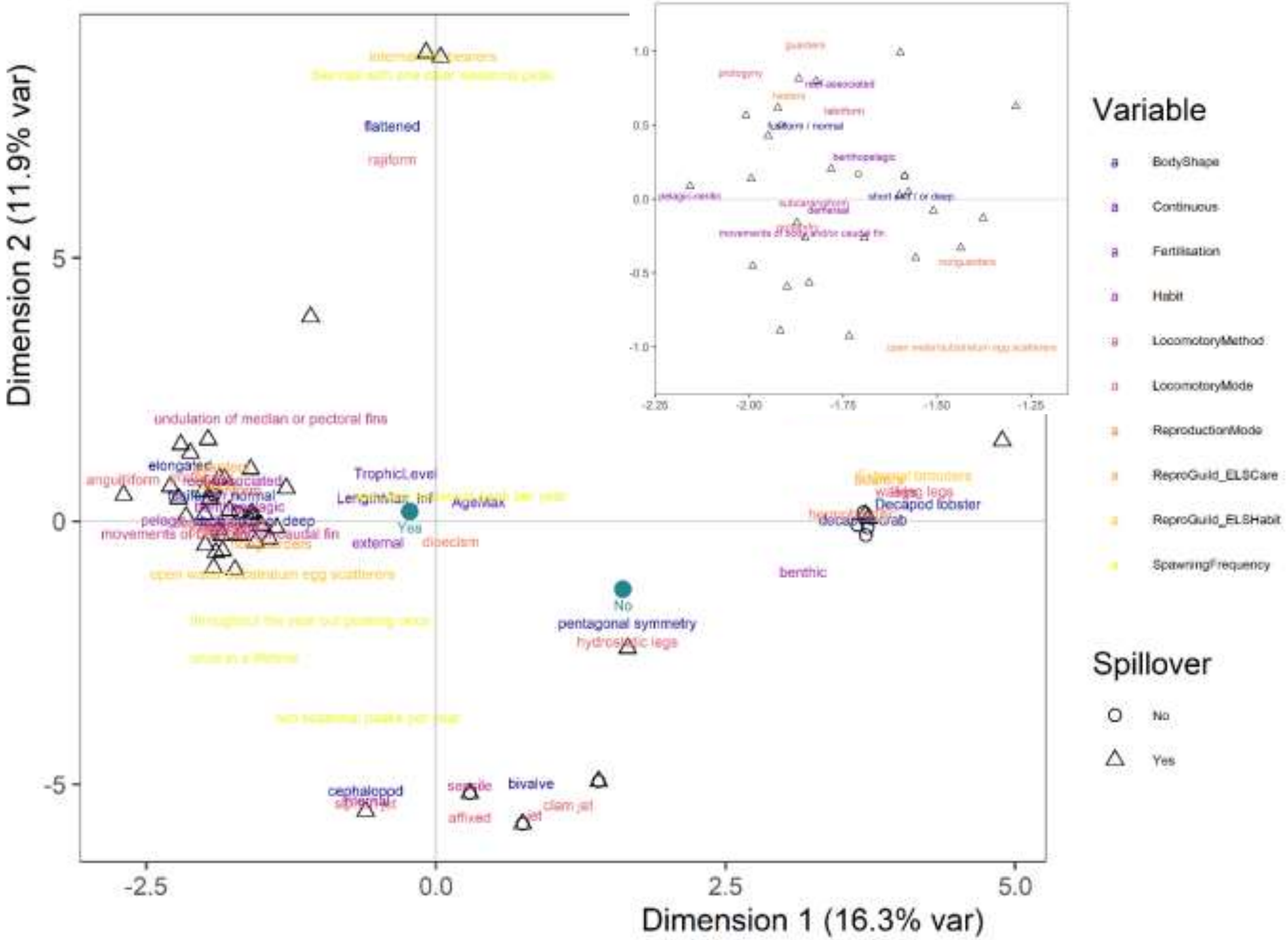


**Figure 16. Cases (hollow points) of investigations into spillover across the first two dimensions of a factorial analysis of mixed data and the position of the variables (coloured text) and categories (plotted labels) that contribute to generating these dimensions. Small triangles are the cases where spillover was detected, while small circles represent cases where no spillover was detected. The filled in green circles represent the binary categories of the supplementary variable, spillover, thus summarising the cases. Panel B (top right) zooms into the area of densest observations to enable differentiation between the points and variables, note the differences in axes values between the larger Panel A and Panel B.**

Another way of visualising the relevant contributions of the different trait categories to the synthetic variables is to plot their level of correlation to each Dimension, and to investigate these in a two-dimensional manner that is easier to interpret. In doing so, we are not looking at a two-dimensional representation of a multi-dimensional data space (e.g. Figure 16) but at measures of relatedness between trait categories and our new Dimensions (Figures 17 & 18).

In this representation, we lose visibility of the specific traits within categories and are, instead, are only interested in the effect of the trait categories themselves. In terms of the variables' contributions to the dimensions, we can see that body shape and locomotory mode are highly correlated with the first four dimensions (Figure 17 & Figure 18), while spawning frequency contributes little to Dimension 1, it correlates relatively highly with Dimensions 2, 3 and 4. Both parental care of early life stages and early life stage habits correlate closely with Dimension 1, whereas life habit stage contributes more to Dimensions 2 and 3. The supplementary variable 'species' correlates with all dimensions, as expected, because it is from this level of organisation that traits are defined. Conversely, the occurrence of spillover correlates weakly with all four dimensions. This relatively weak correlation is due to the spillover variable not being used in calculating the dimensions, so it is a truly independent variable to correlate against. With this independence comes the ability to test whether the values of the dimensions differ between the spillover and non-spillover cases, which they do along Dimensions 1 and 2. Based on there being a significant difference in spillover along Dimension 1 and 2, we retained all variables that were significantly correlated to these two dimensions for use in a logistic regression that investigated the relationship between these variables and spillover more directly (Table 5).

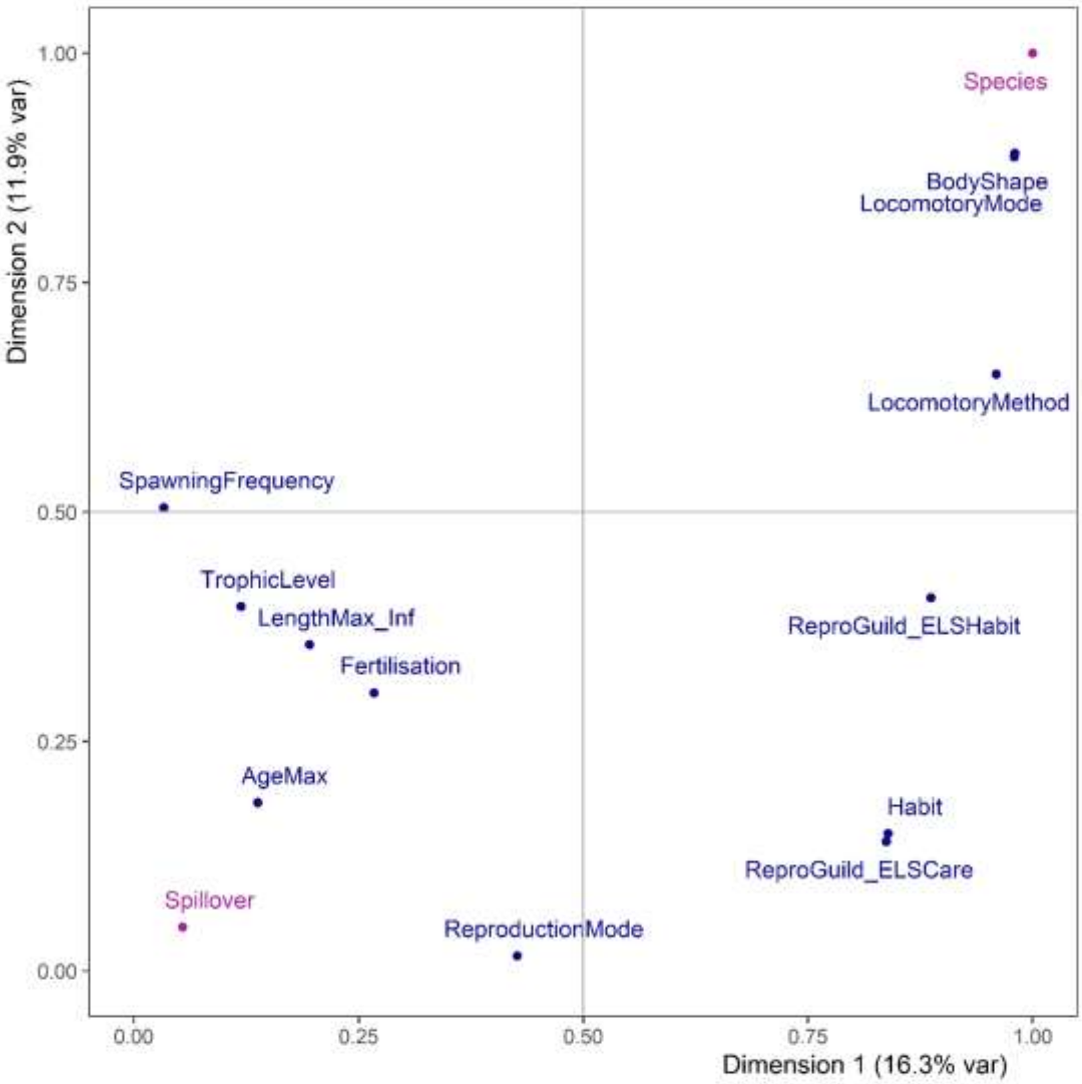


**Figure 17. Contributions of species trait variables to the first two dimensions of the Factorial Analysis of Mixed Data for all cases in the literature where spillover was investigated from temperate MPAs. Blue variables are 'active' and contribute to the dataspace from which the dimensions are derived. The pink variables are 'supplementary' and are fitted to the same dataspace but do not contribute to the calculation of the dimensions.**

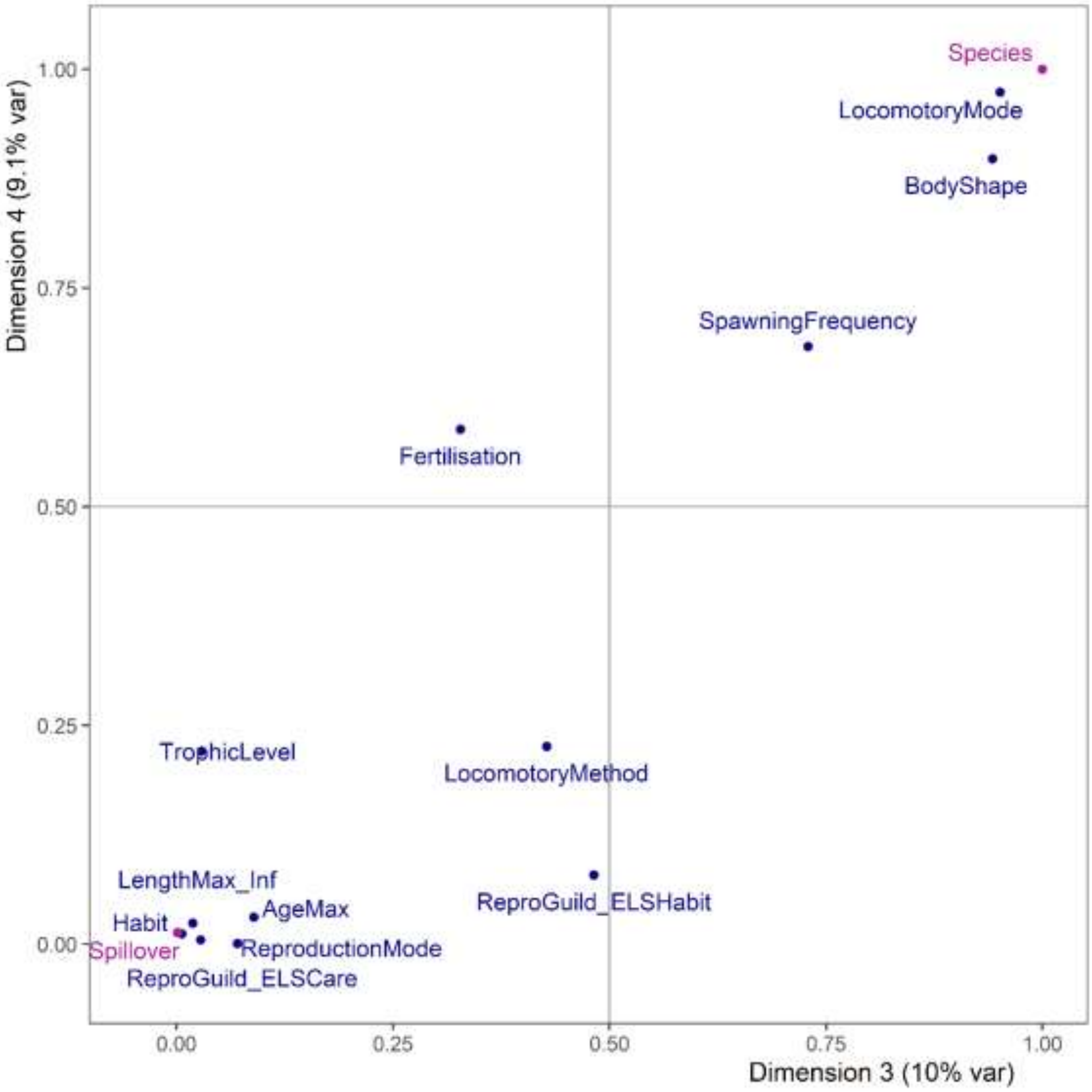


**Figure 18. Contributions of species trait variables to the third and fourth dimensions of the Factorial Analysis of Mixed Data for all cases in the literature where spillover was investigated from temperate MPAs. Blue variables are 'active' and contribute to the dataspace from which the dimensions are derived. The pink variables are 'supplementary' and are fit to the same dataspace but do not contribute to the calculation of the dimensions.**

**Table 5. Variables retained, from the Factor Analysis of Mixed Data of species traits and spillover for use in a logistic regression. Results of the correlation tests with dimensions one and two. * Indicates the passive variable, which is independent of the dimensions. NA represents variables that were not significantly correlated with a given dimension.**

| Variable | Dim1 Correlation | Dim1 p_value | Dim2 Correlation | Dim2 p_value |
|---|---|---|---|---|
| BodyShape | 0.980 | <0.001 | 0.891 | <0.001 |
| LocomotoryMode | 0.980 | <0.001 | 0.887 | <0.001 |
| LocomotoryMethod | 0.959 | <0.001 | 0.650 | <0.001 |
| ReproGuild_ELSHabit | 0.887 | <0.001 | 0.407 | <0.001 |
| LengthMax_Inf | -0.442 | <0.001 | 0.596 | <0.001 |
| Habit | 0.839 | <0.001 | 0.150 | 0.004 |
| ReproGuild_ELSCare | 0.837 | <0.001 | 0.141 | <0.001 |
| TrophicLevel | -0.346 | <0.001 | 0.630 | <0.001 |
| AgeMax | 0.371 | <0.001 | 0.428 | <0.001 |
| Fertilisation | 0.267 | <0.001 | 0.303 | <0.001 |
| SpawningFrequency | NA | NA | 0.505 | <0.001 |
| ReproductionMode | 0.427 | <0.001 | NA | NA |
| Spillover * | 0.055 | 0.021 | 0.048 | 0.030 |

All iterations of logistic regression building from both model selection procedures resulted in poorly fit models with large deviations and unexplained trends in model residuals. This indicates either that there are too few data for the variation seen across the traits or there are more important determinants of spillover that are not included in the model. Both of these situations are likely true. Our sample size from published studies is small and biased towards teleost fishes, with few cases representing the more diverse trait levels, such as for cephalopods or bivalves. Furthermore, **the first analyses show that MPA characteristics play a role in whether spillover is detected**. Accordingly, a lot of the unexplained variation in the species traits model is likely derived from the context from which the cases are drawn.

**Analyses combining both species traits and MPA characteristics should be investigated in the future.** However, they will require much larger sample sizes and thus more empirical evidence. This requirement is two-fold: it demands that field studies are both undertaken and published in the primary literature. It should be noted that Di Lorenzo et al. (2020) modelled both MPA and species characteristics together, and they used a smaller sample size than this current study. However, their models considered a smaller number of MPA characteristics and only two species characteristics, one of which was not biologically relevant. Furthermore, their dataset was more selective, and only utilised measures of abundance within and around MPAs. This provided them with quantitative response variables, but the 'relative abundance' response variables only provided indirect evidence of spillover. This study only considers a binary response 'spillover or not', but includes studies with indirect evidence (e.g. relative abundance in Di Lorenzo et al. (2020)) as well as a range of more direct evidence (e.g. mark-recapture, active tags).

## 2.4 Conclusions

A meta-analysis of the various factors related to MPA characteristics and species traits has shown a number of emergent patterns in relation to spillover effects. These should be further developed once more empirically based knowledge has become available. The main pattern observed was the significant correlation of the observations of spillover with the primary dimension (synthetic variable) of the FAMD on MPA characteristics. The subsequent logistic regression did not yield results strong enough to consider the effects of any MPA characteristics independently. However, **the combination of retained effects (MPA age, local context and whether the MPA is part of a network) proved capable of predicting the occurrence of spillover and are thus important considerations for the design of MPAs**, especially in cases where spillover is an objective.

There is evidence that **traits related to species mobility are important for the ability to detect spillover**, where different modes of swimming are co-correlated with the presence of spillover along the first two dimensions of our FAMD and contrasted to walking and sessile organisms, especially along the primary dimension. Similarly, **reproductive strategies also co-correlate with spillover** where brooders and bearers of eggs are more co-correlated with the absence of spillover than broadcasts spawners and free-drifting early-life stages.

The various contexts in which MPAs are situated – physically, temporally and legislatively – all contribute to variability in the presence or absence of spillover. Furthermore, the mobility of adults and dispersal potential of early life-history stages (among other traits) also appear to influence an organism's contribution to spillover. Disentangling the effects of these diverse drivers and how they interact in different contexts will require a larger dataset of targeted empirical studies. To understand how these MPA characteristics and species traits affect the magnitude of spillover from MPAs, **empirical studies need to start measuring or estimating the export of numbers of individuals or biomass and the temporal frequency and spatial scale with which these occur**. Reporting these findings is important regardless of whether spillover is detected or not and the publication of 'negative results' should be encouraged. The most appropriate design, methods and analyses to detect and quantify spillover are addressed in the following section.

# 3 METHODOLOGICAL APPROACHES TO ASSESS SPILLOVER

**Key highlights**

- There are a wide range of methodological approaches (sampling designs, sampling methods, statistical analyses) used to investigate spillover effects.
- To assess spillover, a Before After Control Impact (BACI) design should be favoured with a distance gradient sampling scheme that is integrated over time.
- The ideal sampling method addresses the research question being asked and is adapted to the species of interest and the site characteristics.
- The ideal data analysis is largely dependent on the sampling design and sampling method, but it needs to be appropriate for the acquired data set. A statistician or modeller should be preferably involved in the design and data analysis.
- A combination of approaches, using both biological sampling and tagging, gives a much more complete picture of potential spillover effects.

## 3.1 Introduction and objective

The current literature on spillover effects from MPAs uses a wide variety of study designs, data collection and data analysis methods. However, information is often lacking in terms of the reasoning behind certain method choices or the advantages or disadvantages of the used methods. Furthermore, evaluations of spillover effects are frequently omitted from the conservation goals and management strategies of MPAs (e.g., only in one of the 15 case studies, namely the Formigas MPA; Section 5). This omission often results in the adoption of suboptimal study designs when assessing spillover *a posteriori*. Therefore, a review was carried out on the methodological approaches used and under development for assessing ecological and fishery spillover from MPAs to adjacent fisheries.

The main objective of this work was to give an overview of the most used sampling designs, sampling methods, data types and analyses within the reviewed scientific studies together with a discussion on their advantages and disadvantages. As such, this overview can be used as a tool for MPA managers, scientists and other stakeholders who are looking to develop a monitoring plan or design a study that aims to assess spillover effects.

## 3.2 Methodology

The review of the methods used to assess spillover from MPAs was carried out for all 45 studies retained from the systematic literature review (Section 1). The fields that were used to extract the relevant data from the literature can be found in the data extraction scheme (Annex 1). Each paper or report was scanned thoroughly for any relevant information on the sampling method and design, as well as the data analysis methods. Information was only extracted for sampling methods and analyses that involved trying to demonstrate spillover, as some studies had multiple aims. Some fields were added (e.g. number of tagged animals, sampling design code) during the extraction phase to ensure that all relevant information was captured and to make subsequent analysis more straightforward.

To make the interpretation of the extraction easier, the nomenclature was standardised over all the studies, and similar methods, designs and techniques were grouped. Sampling designs were grouped based on whether data were collected before (B) and/or after (A) the establishment of the MPA and whether samples were taken inside (I) and/or in control (C) areas outside the MPA. This resulted in five different sampling designs: BACI, BAC, AI, ACI and AC (Figure 19). Field sampling methods were grouped based on the similarity of the sampling tools and techniques (e.g. net type) or the origin of collection methods and analyses to facilitate the visualisation of the data. Descriptions of the sampling methods can be found in Table 6. Response variables were grouped based on similarities on the type of information (e.g. abundance versus fish length).

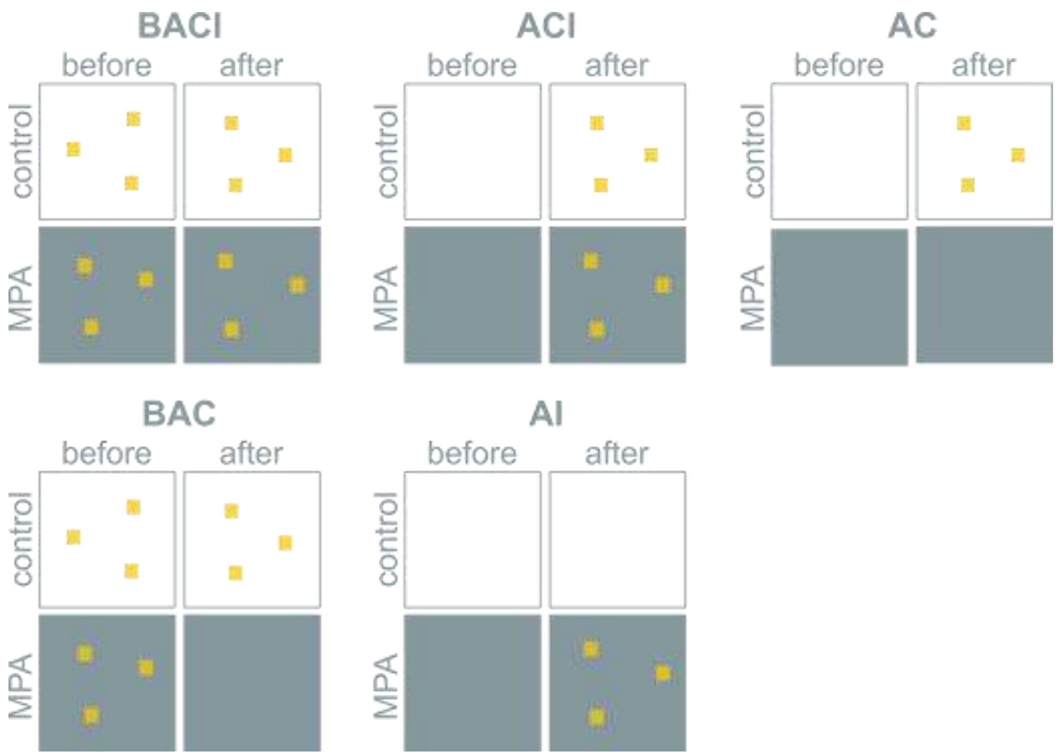


**Figure 19. Conceptual overview of the five different study designs identified in the literature review. The yellow squares indicate sampling stations.**

**Table 6. Descriptions of sampling methods used in the literature.**

| Sampling method | Description | Response variables relevant for spillover |
|---|---|---|
| Acoustic telemetry | Acoustic telemetry involves implanting or attaching small acoustic transmitters into or on fish, crustaceans and molluscs, which emit unique sound signals. These signals are then detected by underwater receivers, enabling researchers to monitor animal movements, behaviour, and migration patterns in the marine environment. | Presence/absence, 2D/3D position of animals |
| Boat-based counts | The number of static fishing gears (e.g. lobster pots) within the study area as a proxy of fishing effort. | Fishing effort |
| Bongo nets | Plankton sampling device consisting of two cylindrical nets with collection containers at the end, mounted side by side on a frame. The nets are usually towed over a fixed distance by a | Abundance, density, biomass, diversity |

| Sampling method | Description | Response variables relevant for spillover |
|---|---|---|
| | research vessel and can collect fish eggs, fish larvae and zooplankton. | |
| BUV | BUV or 'baited (remote) underwater video' consists of an underwater camera system that is equipped with some type of bait in order to attract animals towards the camera. It is left on the bottom for a certain time period in multiple locations. | Relative abundance, estimated length, diversity |
| Commercial landings | Commercial landing data encompasses the total catch (usually in kg or tonnes) from commercial vessels that is brought ashore to port facilities. | Biomass |
| Commercial surveys | A commercial survey involves the measuring, counting or collection of individuals by scientists on board of commercial fishing vessels. | Biomass, abundance, length, density, fishing effort, diversity, animal collection |
| Dredge surveys | A dredge is a towed device used for collecting sediment, rocks, organisms, or other materials from the bottom. It is often used for the collection of scallops or other bivalves. | Abundance, density, length, biomass, diversity, animal collection |
| Data storage tagging | Data storage tags (DST) are attached to or implanted in fish, crustaceans or molluscs and have sensors that record parameters such as depth, temperature and light levels, and store these data internally. After the tag is recovered from the animal (either by recapturing the animal or through mechanisms that release the tag), the stored data can be downloaded and analysed. Geolocation modelling based on the sensor data allows for the estimation of the swimming track of the animal and, as such, gives information on the movement ecology of a species. | Depth profile, temperature profile, presence/absence, geographic position |
| Fixed plankton nets | Plankton sampling device existing of a cylindrical net with a collection container at the end and is fixed to a buoy and left in the water column for a certain period of time. It is used to collect fish eggs, fish larvae and zooplankton. | Abundance, density, biomass, diversity |
| Gill nets | Gill nets are a type of fishing gear that consists of a netting material suspended vertically in the water column to capture fish by entangling them in their gills. Gill nets are designed with mesh sizes that allow the head of the fish to pass through, but as the fish tries to retreat, its gills become caught in the mesh, preventing it from escaping. The mesh size and the position of the gill net in the water column is chosen based on the species of interest. | Abundance, density, biomass, diversity |
| Hand catching | Hand catching involves the catching of animals by hand. | Animal collection |

| Sampling method | Description | Response variables relevant for spillover |
|---|---|---|
| Light traps | Sampling device that attracts different kinds of larvae or animals (including crustacean and molluscs) using a neon lamp for attraction. The lamp is attached to a plexiglass container with slits and a collection container on the bottom side. This device is then fixed in the water column for a certain period of time. | Abundance, density, biomass, diversity, animal collection |
| Long line | A type of fishing gear consisting of a main fishing line, suspended horizontally in the water column using floats and weights. Along this main line, smaller lines are attached at intervals, each with a baited hook. | Abundance, density, biomass, diversity |
| Line fishing | A fishing method that involves using a single fishing line with a hook or hooks attached to catch fish. | Animal collection, abundance, density, biomass, diversity |
| Mark recapture | A mark recapture method involves the capturing and marking of a subset of individuals (predominantly fishes, but have also been used on large mammals), and releasing them back into their habitat. By subsequently recapturing individuals and noting whether they are marked or unmarked, researchers can track the movement patterns and distances travelled by marine species. | Distance travelled, position of recapture |
| Passive collectors | An artificial substrate used for the collection or settlement of larvae. | Animal collection, abundance, density, biomass, diversity |
| Photographic surveys | A camera system that captures digital images of the seabed, using a fixed camera setup and lighting. It can be deployed from a research vessel using a winch system. | Abundance, density, diversity |
| Quadrats | A quadrat is a square or rectangular frame used to define a standardized area for visual sampling of organisms or features on a certain substrate, such as the seabed. | Percentage cover, abundance, density, diversity |
| Quadrat samples | The collection of organisms or organic material on a substrate within a standardized surface area (quadrat). | Animal collection, abundance, density, diversity, biomass |
| Spear fishing | A method of fishing where a person uses a specialized underwater weapon, called a spear gun, to hunt and capture fish or other aquatic organisms. | Animal collection (e.g. for tissue samples) |
| Trammel nets | Fishing nets with three layers of netting that capture fish by entangling them through their gills as they swim. The inner layer prevents fish from escaping, making trammel nets more selective than standard gill nets. | Abundance, density, biomass, diversity |
| Traps /pots | A trap or pot is a specialized fishing device consisting of a netted cage that is baited to attract animals. It has entrances that allow animals to enter but make it difficult for them to escape. | Animal collection, abundance, density, biomass, diversity |

| Sampling method | Description | Response variables relevant for spillover |
|---|---|---|
| Visual transects | Visual transects are carried out by divers who swim a standardized transect and visually assess presence, percentage cover, abundance or length of animals observed along the transect. | Abundance, density, diversity, biomass |
| VMS data | Vessel monitoring system (VMS) data refers to information collected from satellite-based tracking systems installed on fishing vessels. These systems transmit real-time location and operational data. | Position, time, vessel name |

Building on this understanding of the range of methods used in the spillover literature, we provide a critical evaluation to elucidate the limitations, weaknesses and strengths of each method utilised to examine ecological or fishery spillover. To undertake this work, we clustered the sampling methodologies into three 'common types' of methods: (i) scientific sampling (invasive sampling or non-invasive sampling); (ii) tagging; and (iii) commercial data. Scientific sampling involved the collection of data in the field, whereby individuals were caught or extracted from the environment (invasive sampling) or visually assessed (non-invasive sampling). Then, for each of the methods, we evaluate their methodological robustness, evidence type, data requirements, application scale, target organism, logistics, human resources, costs, skills and expertise required using a three-point assessment scale (Table 7).

**Table 7. Three-point scale assessment scheme to assess spillover methodology.**

| Method | Description | Semi-Quantitative scale of assessment |
|---|---|---|
| Methodological robustness | Does the method have the capacity to remain unaffected by small variations (i.e. reliability of the method) | 1 = Method has low robustness (highly impacted by small data variation)<br>2 = Method has medium robustness (likely impacted by small data variation)<br>3 = Method is highly robust (not impacted by small data variation) |
| Evidence type | Can the method collect a range of different data types or is it specific to only one type of data | 1 = Method is highly specific to collecting one data type (no variation in data type collected)<br>2 = Method is able to collect between 2 and 4 data types<br>3 = Method is able to collect > 5 data types |
| Amount of data requirements | Is the method only suitable when using a high number of data points, or is it also suitable when only a small number of data points are able to be collected? | 1 = Method requires a high number of data points collected (>100)<br>2 = Method requires a relatively low number of data points collected (>50)<br>3 = Method requires a low number of data points collected (<50) |
| Application scale | Can the method be utilised across a wide spatial scale (e.g. a range of different habitats, different ocean basins) or is it only applicable to a specific spatial scale | 1 = Method is only applicable to a specific spatial scale<br>2 = Method is applicable at several spatial scales<br>3 = Method is applicable at any spatial scale |

| Method | Description | Semi-Quantitative scale of assessment |
|---|---|---|
| Target organisms | Is the method only targeted to a specific organism or can it encompass a range of organisms | 1 = Method is only applicable to a single target organism (e.g. population)<br>2 = Method is applicable to several target organisms (e.g. several related populations)<br>3 = Method is applicable to any number of target organisms (e.g. community, assemblage) |
| Logistics | Does the method require a high level of logistical support (i.e. high technological needs) or low logistic support (i.e. low technological needs) | 1 = Method requires high technological support (i.e. can only be undertaken using specific technology)<br>2 = Method requires low technological support (i.e. has several steps that need technological support)<br>3 = Method does not require technological support |
| Human resources | Does the method require high levels of human resources and capacity or is able to be undertaken with little human resources and little capacity | 1 = Method requires high levels of human resources (e.g. requires high number of people or range of people with high expertise)<br>2 = Method requires medium levels of human resources (e.g. requires several people with relatively low expertise)<br>3 = Method can be utilised with low human resources (e.g. requires low number of individuals with low technical capacity) |
| Costs | Is the cost of undertaking the method high per sample data point collected or is it cost effective? | 1 = Method is very costly per sample collected (>100 EUR per sample collected)<br>2 = Method is relatively costly per sample collected (between 50 and 100 EUR per sample collected)<br>3 = Method has little to no cost per sample collected (0 – 50 EUR per sample collected) |
| Skills and expertise required | Does the method require a high level of skills and expertise that need to be attained over a long time period or can it be undertaken by someone with low skills or expertise? | 1 = Method is only able to be undertaken by someone with >20 years' experience<br>2 = Method is able to be undertaken by someone with 5 – 10 years' experience<br>3 = Method is able to be undertaken by some with <5 years' experience |

## 3.3 Results

### 3.3.1 Sampling designs

The sampling designs of the reviewed literature were divided into five categories: BACI, BAC, AI, ACI and AC (Figure 19, Figure 20). Most of the studies (71%) used an ACI-design with sampling occurring only after the MPAs were established. In these designs, samples collected within MPAs were compared with samples taken outside of the MPAs. In 79% of cases, this design successfully identified the presence of a spillover effect. The AI design, in which data is only collected within MPAs after they are established, is the second most common sampling design (13%). It was able to provide evidence for spillover in 70% of cases. Apart from one field experiment carried out within the borders of the MPA, all studies that implemented this design used acoustic or conventional tagging methods to investigate the presence or movement of the tagged animals. In 8% of studies, an AC design was used, in which sampling was conducted or commercial data was used from outside the MPA only after its establishment. The distance from the MPA was used as an explanatory variable to test for a spillover effect in every study but one. Only two studies used a BAC design (4%). This design includes data from before and after the establishment of the MPA, but not from within. Both studies used commercial data, which is not available within the MPA as no fishing activities were allowed within its borders. A full BACI design, where data is collected both within and outside the MPA and before and after its establishment was only used in one study (2%). All three studies that used a BAC or BACI design were able to demonstrate a spillover effect.

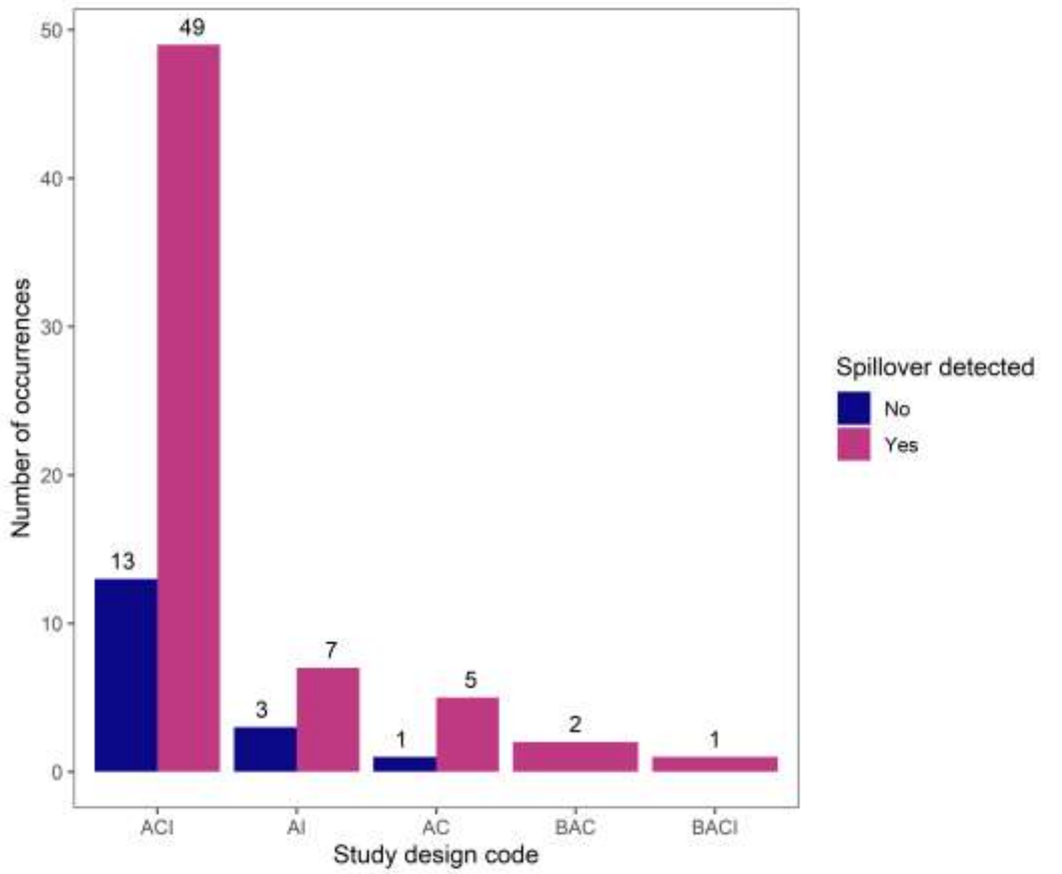


**Figure 20. Number of occurrences of a certain sampling design (BACI, BAC, AI, ACI and AC; B=before, A=after, C=control, I=impact) and whether or not a spillover effect was detected. The number of occurrences corresponds to the number of cases (n = 81) and is not equal to the number of studies, as some studies used the same design to detect spillover in different areas for different species and for different spillover mechanisms.**

### 3.3.2 Sampling methods

After grouping, a total of 24 different sampling methods were identified that were used to assess spillover (Figure 21). These methods could be divided into three large categories: commercial data, scientific sampling and tagging. The collation of studies that utilise commercial data was gleaned from studies on fishing activities or commercial landings in relation to MPAs. Scientific sampling involved the collection of data in the field, whereby individuals were caught or extracted from the environment (invasive sampling) or visually assessed (non-invasive sampling). These samples were largely taken within and outside the MPA to compare differences in samples or test for gradients in sample variables according to distances to the MPA. The last category contains studies where animals (usually fish) were tagged using traditional or electronic tags to follow their movement patterns in relation to MPAs. **Mark-recapture was the most commonly used methodology for studying spillover, and it was used in 33% of the studies. This method was able to demonstrate spillover in 89% of cases** (Figure 22). The second most-used method (24% of studies) involved using traps to catch animals, often in combination with a mark-recapture approach. In 58% of cases, the presence of a spillover effect was shown using this method. Acoustic telemetry and visual (diving) transects were each used in 20% of the studies. These demonstrated spillover in 88% and 75% of the cases, respectively. The rest of the methods were used in fewer than 20% of the studies.

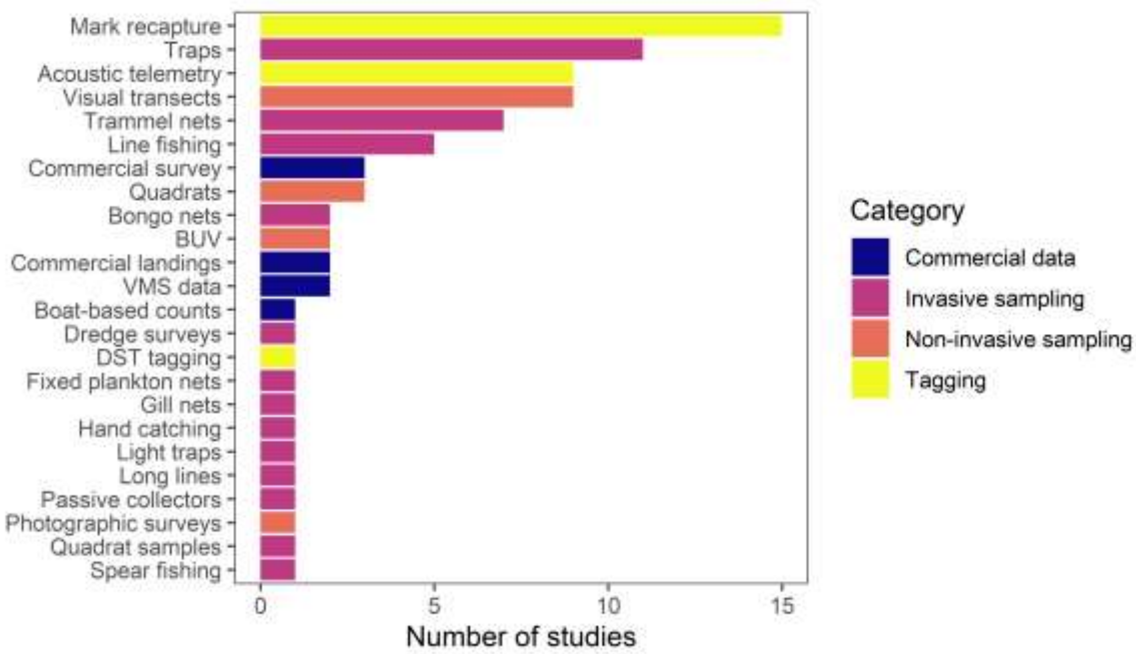


**Figure 21. Number of studies using a certain sampling method for studying spillover effects. Most studies used multiple methods for data collection.**

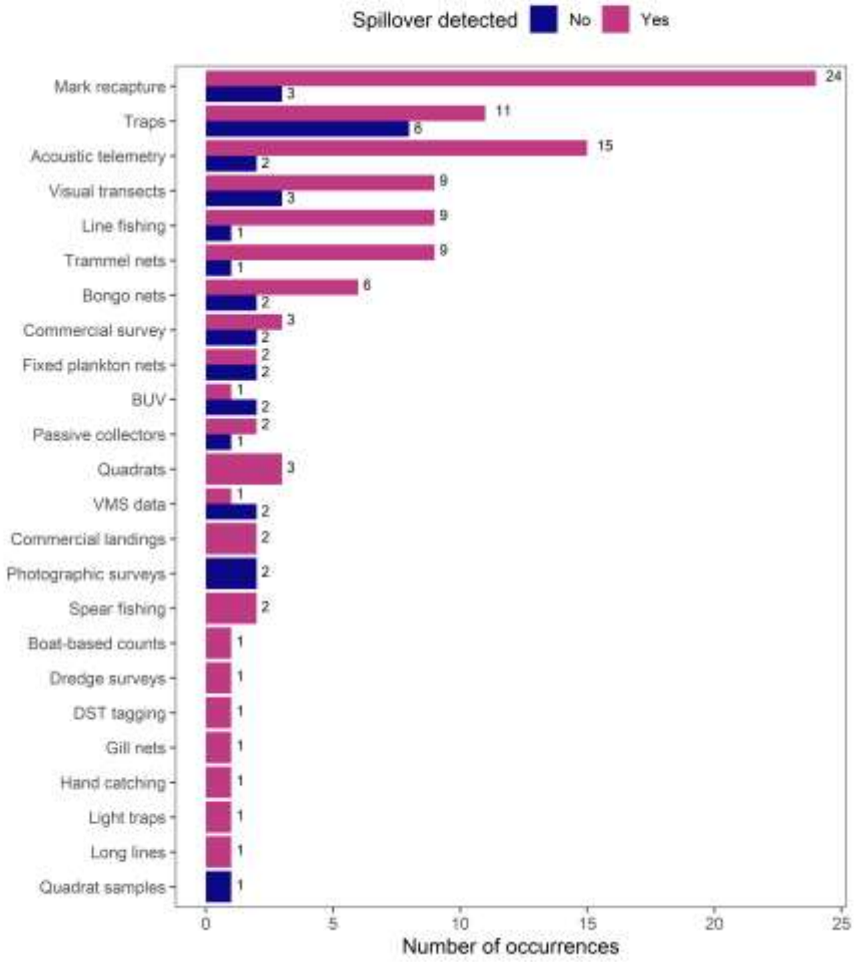


**Figure 22. Number of occurrences of sampling methods for studying spillover effects. The number of occurrences (n = 138) is not equal to the number of studies, as some studies used multiple methods or the same methods to detect spillover in different areas, for different species and for different spillover mechanisms.**

### 3.3.3 Data analysis and measured variables

A total of 37 different data analysis methods were found during the literature review (Figure 23). These methods were divided into six different categories: hypothesis testing, regression analysis, correlation analysis, multivariate analysis, modelling and others. Hypothesis testing methods and regression analyses were the most commonly used methods for investigating spillover from MPAs. Hypothesis testing methods (e.g. statistical tests ANOVA, T-test and Kruskal Wallis) were used to assess whether the available evidence supports or contradicts a certain hypothesis, while regression analyses methods were used to model the relationship between independent variables and dependent variables. Correlation analysis, on the other hand, was used to measure the strength and direction of a linear relationship between two or more continuous variables. Different multivariate analysis techniques were used to assess relationships between multiple variables simultaneously. In most cases, it was used to study the effects of the presence of an MPA on the community composition of organisms. 'Modelling' refers to methods where a model was developed based on collected data in the field that tries to describe the movement of animals. Other methods that did not fit in any of the forementioned categories were grouped in the category 'Others'. It includes spatial analyses methods (Kriging), catch curve and growth curve analyses and SAMOVA (Spatial Analysis of Molecular

Variance), which is a clustering method that identifies genetically differentiated groups of animals.

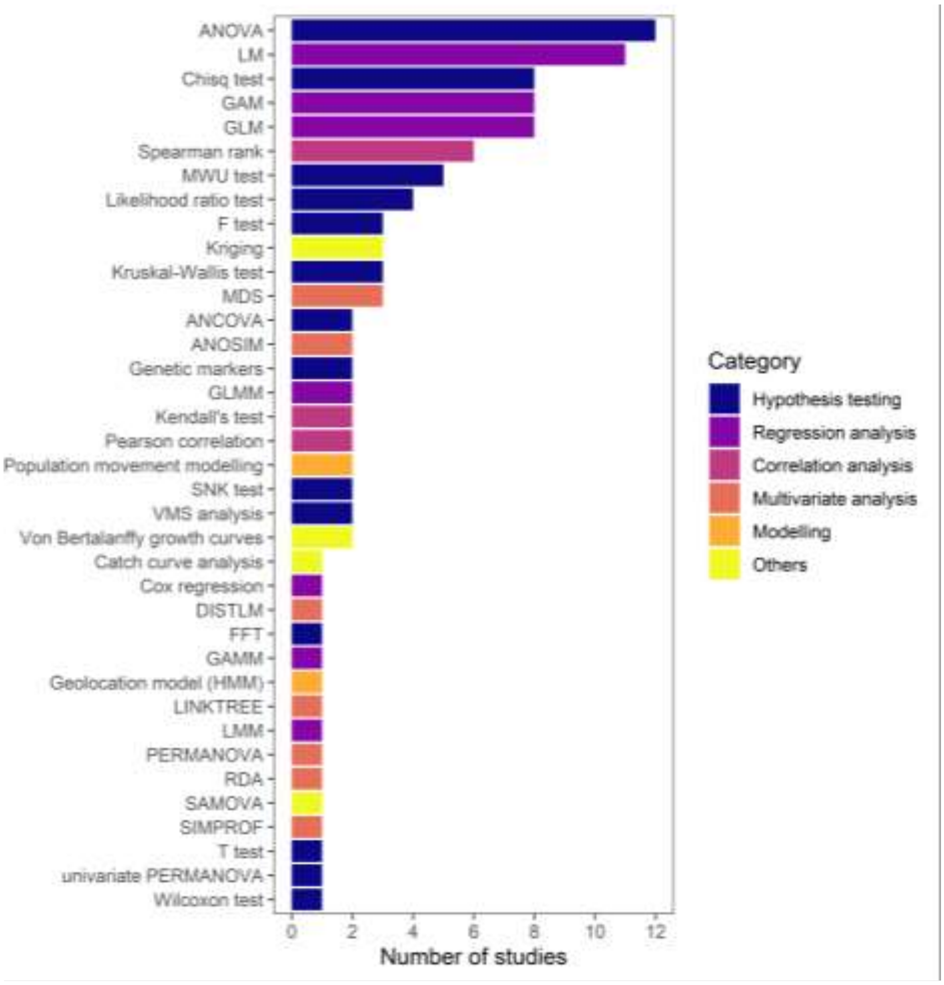


**Figure 23. Data analysis methods used in the studies to assess spillover effects from MPAs. Most studies used multiple methods for data analysis.**

The most common response variables used to investigate spillover effects are abundance, variables related to the spatio-temporal use of the area (e.g. distance moved, home range, presence index), animal length, biomass and reproductive index (Figure 24). Of these five, biomass was the most-used response variable for detecting a spillover effect (92%), followed by reproductive index (88%), spatiotemporal use (78%), abundance (73%) and animal length (64%). For the explanatory variables specifically linked to spillover, protection (within versus outside MPA) and distance to MPA were by far the most commonly used, with a detection success of 73% and 75%, respectively (Figure 25).

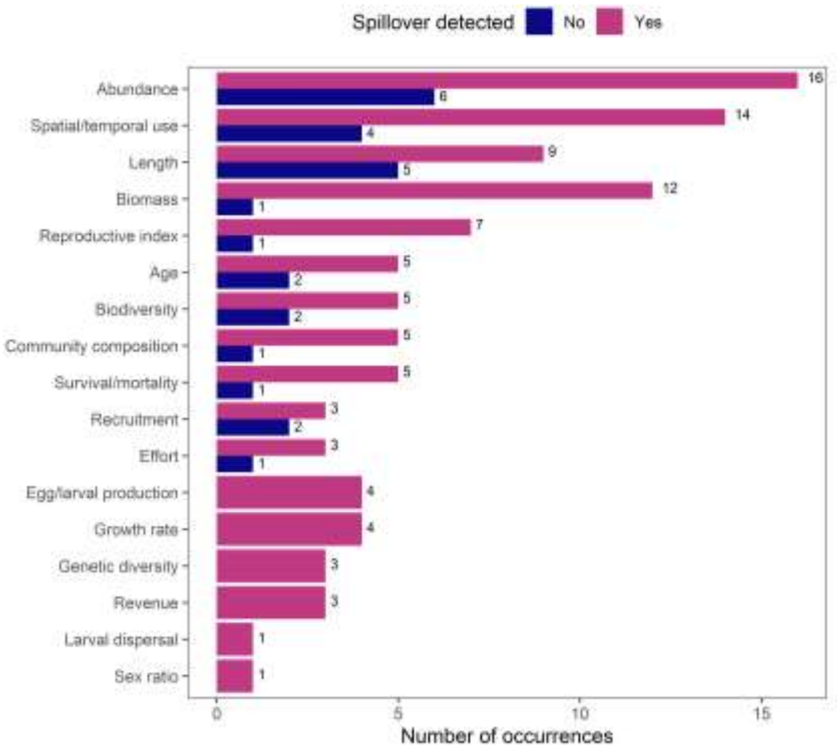


**Figure 24. Number of occurrences of a certain response variable (grouped) and whether or not a spillover effect was detected. The number of occurrences (n = 124) is not equal to the number of studies as some studies used multiple explanatory variables.**

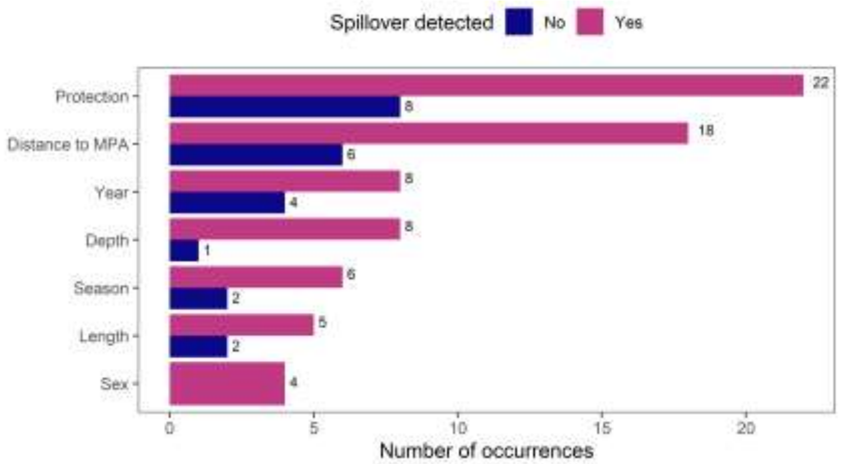


**Figure 25. Most used response variables occurring in >3 studies and whether or not they were able to demonstrate spillover effect. The number of occurrences is not equal to the number of studies, as some studies used multiple explanatory variables.**

### 3.3.4 Evaluation of the methodological approaches

This analysis showed a relatively specific grouping of sampling methods into three main clusters (Table 8). The first (labelled green) are sampling methods that are relatively robust, have moderate data and evidence needs. They are able to sample a high number of target organisms and have low logistics, costs, human resource and expertise needs. This first group predominantly encompasses low technology invasive sampling techniques, including a range of net types (fyke, gill, trammel), line fishing and methods that predominantly sample whole benthic communities (quadrats and passive collectors).

The second clustering of methods (labelled orange) involve methods that have much more extensive data needs, require much more intensive logistic support or may also be relatively less robust to small sample sizes. These methods include a range of boat-based invasive sampling methods (e.g. bongo nets, long line), as well as methods that are targeted at specific groups of species (e.g. spearfishing), are likely to involve high costs (e.g. DST tagging, commercial surveys) or are visual censuses.

The final clustering of methods (i.e. labelled red) comprises methods with predominantly very high costs and high levels of logistical or human resources, while also being specific to target organisms. These are predominantly methods that need high numbers of samples with data collected using high levels of technology (e.g. VMS) or that need high levels of boat time and human resources (e.g. acoustic telemetry, BUV, mark recapture).

**Table 8. Results of the three-point scale assessment of spillover sampling methodologies.**

| Sampling method | Type of sampling | Robustness | Evidence type | Data needs | Application scale | Target organisms | Logistics | Human resources | Costs | Skills/ Expertise | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Fyke nets | Invasive | 2 | 2 | 2 | 1 | 3 | 3 | 3 | 3 | 3 | 22 |
| Gill nets | Invasive | 2 | 2 | 2 | 1 | 3 | 3 | 3 | 3 | 3 | 22 |
| Trammel nets | Invasive | 2 | 2 | 2 | 1 | 3 | 3 | 3 | 3 | 3 | 22 |
| Line fishing | Invasive | 2 | 3 | 2 | 2 | 2 | 2 | 3 | 2 | 3 | 21 |
| Quadrats | Non-invasive | 2 | 2 | 2 | 2 | 3 | 2 | 3 | 3 | 2 | 21 |
| Passive collectors | Invasive | 3 | 3 | 2 | 2 | 3 | 2 | 2 | 1 | 2 | 20 |
| Boat-based counts | Invasive | 1 | 1 | 1 | 2 | 3 | 3 | 3 | 2 | 3 | 19 |
| Hand catching | Invasive | 1 | 1 | 2 | 1 | 2 | 3 | 3 | 3 | 3 | 19 |
| Photographic surveys | Non-invasive | 2 | 2 | 2 | 2 | 3 | 2 | 2 | 2 | 2 | 19 |

| Sampling method | Type of sampling | Robustness | Evidence type | Data needs | Application scale | Target organisms | Logistics | Human resources | Costs | Skills/ Expertise | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Spear fishing | Invasive | 1 | 1 | 1 | 2 | 2 | 3 | 3 | 3 | 3 | 19 |
| Traps | Invasive | 1 | 2 | 2 | 1 | 1 | 3 | 3 | 3 | 3 | 19 |
| Commercial surveys | Commercial | 2 | 3 | 1 | 3 | 3 | 2 | 1 | 1 | 2 | 18 |
| Dredge surveys | Invasive | 2 | 3 | 2 | 1 | 3 | 2 | 2 | 1 | 2 | 18 |
| DST tagging | Tagging | 1 | 2 | 2 | 2 | 3 | 2 | 2 | 2 | 2 | 18 |
| Bongo nets | Invasive | 2 | 2 | 2 | 1 | 3 | 2 | 2 | 1 | 2 | 17 |
| Fixed plankton nets | Invasive | 2 | 2 | 2 | 1 | 3 | 2 | 2 | 1 | 2 | 17 |
| Long line | Invasive | 2 | 2 | 2 | 1 | 3 | 2 | 2 | 1 | 2 | 17 |
| Quadrat samples | Invasive | 2 | 2 | 2 | 1 | 3 | 2 | 1 | 2 | 2 | 17 |
| Visual transects/ census | Non-invasive | 1 | 2 | 2 | 1 | 3 | 2 | 2 | 2 | 2 | 17 |
| VMS data | Commercial | 2 | 2 | 1 | 2 | 3 | 1 | 1 | 2 | 2 | 16 |
| Acoustic telemetry | Tagging | 2 | 2 | 1 | 1 | 3 | 1 | 1 | 2 | 2 | 15 |
| BUV | Non-invasive | 1 | 2 | 1 | 2 | 2 | 1 | 2 | 1 | 2 | 14 |
| Commercial landings | Commercial | 3 | 1 | 1 | 2 | 3 | 1 | 1 | 1 | 1 | 14 |
| Light traps | Invasive | 1 | 2 | 1 | 1 | 2 | 2 | 2 | 1 | 2 | 14 |
| Mark recapture | Tagging | 1 | 2 | 1 | 2 | 1 | 2 | 2 | 1 | 2 | 14 |

## 3.4 Discussion

Sampling designs in which data is collected both before and after the establishment of an MPA and within its borders and in adjacent control areas (i.e. a BACI design) are deemed the most robust for detecting spillover responses in animals. However, only one study employed this type of design. The reason for this is likely because this design is often not feasible. Usually, MPAs are established when studies focusing on their potential effects are conducted. This is because dedicated long-term monitoring plan are often not in place from the start. The advantage of sampling before an MPA is established is that it captures the spatial variation between the area of the MPA and the control areas outside its borders. As such, any differences found can be attributed to the presence of the MPA and not to variation within the environment with greater certainty. Although ACI-designs miss the 'before' component, they can still be valuable when assessing spillover from MPAs. This is especially true when they are combined with a distance gradient approach (Methratta, 2020). In this approach, samples are taken along a distance gradient starting from the centre of the MPA up to a distance from the edge of the MPA. As such, differences between samples within and outside the MPA can be observed, but gradient responses can be investigated as well. The relationship between a response variable (e.g. animal abundance) and distance to the MPA centre may be linear, but the relationship may also be sigmoid, with abundances declining very fast from the border of an MPA towards adjacent areas. This information is vital for management purposes as it provides data on the spatial extent of spillover effects and their relationship with distance.

The **most ideal approach when considering traditional sampling combines a BACI-design with sampling over a distance gradient** so changes in time and space are considered. It is important that sampling takes place multiple years before and after the establishment of the MPA. Otherwise, only information on two points in time (before versus after) is included, which can result in a misrepresentation of the actual situation (Fenberg et al., 2012). Communities in newly established MPAs are not fixed and are constantly evolving, while variation in the environment can mask certain signals. Sampling at only one point in time can therefore over or underestimate certain effects that increase or decrease over time. A time-integrated approach is therefore recommended.

**An alternative approach involves the use of tagging methods** (acoustic, mark-recapture, DST), which often results in high resolution data on the spatial behaviour of animals. However, only information for a limited number of individuals is obtained, especially for electronic tags. Therefore, caution should be taken when conclusions are drawn based on data for only a few individuals. Ideally, **tagging studies should be combined with sampling data collection that occurs at a broader level** (spatial and temporal) but includes much higher numbers of individuals. As such, the disadvantages of both methodologies are balanced out and present a much broader understanding of animal movement patterns and whether they can translate to ecological or fishery spillover. For acoustic tagging studies, deploying receivers within, at or outside the borders of the MPA is recommended. As such, animals can be observed as they leave or enter the MPA.

A lot of different data analysis methods were used to assess the presence of spillover from an MPA. Although some analysis methods are more robust than others, a method's suitability is mainly dependent on the research question, the type of data collected (tagging versus biomass data) and sampling design (BACI versus ACI). Therefore, **it is not relevant to recommend a single ideal data analysis method for the assessment of spillover effects**. Nevertheless, a method should always be suitable for the data that needs to be analysed, and there are often multiple options available that offer similar outcomes. Ideally, **statisticians or modellers should be consulted before any sampling is carried out** so that designs or methods can be adapted to suit the data analysis method. This is salient as some analyses have very specific data needs or assumptions that need to be met. Moreover, it is also a good idea to **measure different response variables simultaneously, as they show different success rates in demonstrating spillover**. Abundance could therefore be assessed alongside biomass and reproductive index. As such, the changes of detecting a spillover effect will increase.

Due to the limited number of studies within this review (n = 45), care should be taken when the results are interpreted with regard to the ability of sampling designs and methods for demonstrating spillover. Although some designs and methods indicate a 100% success rate in demonstrating spillover, this is not as meaningful when there are only a couple of studies that have implemented that design or method. Moreover, there is a publication bias that needs to be considered when interpreting the effectiveness of methods for showing spillover effects (Section 1). This is based on the fact that studies that do not show any effects are less likely to be published. As such, based on the current published literature, there is a risk that the ability of a method to demonstrate spillover can be overestimated.

## 3.5 Conclusions and recommendations

In conclusion, the **most robust sampling design for detecting spillover responses in animals from MPAs involves a BACI design combined with sampling over a distance gradient**, considering changes in both time and space. However, the feasibility of this approach may be hindered by factors like the timing of the study (e.g. MPA already established) and potential technical or financial constraints, resulting in a limited number of studies employing this methodology. Selecting an optimal sampling method within a study design depends on factors such as the research question, the species under consideration, and the characteristics of the study site. Ideally, **simultaneous measurement of various response variables is recommended** to enhance the identification of potential spillover effects. Alternative methods, such as tagging studies, offer high-resolution spatial data but should be cautiously interpreted due to limited sample sizes. Additionally, the choice of data analysis methods should align with the research question, type of data collected, and sampling design.

Based on the reviewed scientific studies, we have the following recommendations for sampling designs, sampling methods and statistical analyses for investigating ecological or fishery spillover.

- Use a BACI design with a distance gradient sampling scheme that is integrated over time. Otherwise, it is recommended to opt for an ACI design with a distance gradient approach.
- If sampling within the MPA is impossible, use a distance gradient approach starting from the border of the MPA.
- If only commercial data are available, use a distance gradient approach and include data from before and after the establishment of the MPA.
- Use as much randomisation as possible in the sampling design (e.g. select sampling locations randomly over the study area instead of using fixed sampling stations).
- The ideal sampling method should address the research question and be adapted to the species of interest and site characteristics.
- For a more realistic assessment of fishery spillover effects, it is best to use sampling methods consistent with those employed by local fisheries or to incorporate commercial data for analysis. Fishery spillover effects also need to be studied on a relevant spatial scale for fisheries management.
- The best data analysis method is largely dependent on the sampling design and method. However, it needs to fit the acquired data set. A statistician or modeller should be involved in the design and the data analysis to ensure the methods are applicable.

- Assess different response variables at the same time (e.g. abundance, biomass and reproductive index), as they show different success rates in demonstrating spillover.
- A combination of a tagging study and traditional (biological) sampling study provides a much more complete picture on potential spillover effects as the disadvantages of both approaches compensate for each other.

# 4 CONCEPTUAL MODEL FOR MPA SPILLOVER

**Key highlights**

- A conceptual model tool was developed (SPILLEST) to estimate the likelihood of spillover for existing and proposed marine protected areas (MPAs).
- The tool integrates the potential environmental, social and economic factors that contribute to the occurrence, magnitude and detectability of spillover.
- Based on literature and a meta-analysis, SPILLEST can be applied for any relevant species and allows users to explore various MPA configurations and their contribution to spillover.
- SPILLEST was tested and validated in several MPA case studies and was found to largely conform with expectations of the relevant experts.

## 4.1 Introduction and objective

A number of governments around the world, including Member States of the European Union, have committed to protecting at least 30% of their ocean by the year 2030. The EU biodiversity strategy for 2030, for example, promotes a large and well-connected EU-wide network of effectively managed MPAs. Key commitments by 2030 include the legal protection and effective management of at least 30% of the EU's marine waters, 10% of which must be under strict protection (COM(2020)380 final).

Achieving this goal will require the creation of new MPAs and other spatial protection measures. Should the objectives of existing and future MPAs include improving the abundance and biomass of organisms outside of MPA boundaries (e.g. to support broader populations and/or fisheries) then developing a tool that helps government authorities, fishers, managers and other stakeholders to have an indication of the likelihood of spillover for MPAs is key. To this end, a conceptual model was developed in this study, the 'Spillover Likelihood Tool' (SPILLEST). The tool was developed to enable users to estimate the likelihood of spillover for existing and proposed MPAs.

In the SPILLEST tool, user input needs to be in the form of answers to a set of questions related to the occurrence of mechanisms promoting or preventing spillover. These mechanisms operate across the environmental, social and economic aspects of MPAs. The conceptual model tool can be used as a resource in the early stages of MPA planning to generate expectations about spillover potential, as well as to explore the effects of implementation variants (e.g. total or partial closure) on that potential.

In the tool the word 'MPA' defines any marine geographical area where the fishing regulations are more restrictive than in the area around it. The questions in the tool can be used to provide answers for a wider area made up of a complex number of zones and for zoned areas within larger networks (e.g. Natura 2000 sites).

## 4.2 Factors and mechanisms that can contribute to spillover

The factors demonstrated to be associated with the occurrence of spillover in the meta-analysis (see Section 2.3) form the first source of input for the SPILLEST tool.

These factors were:

- **Local context**: Is the MPA estuarine, surrounding an island or open water? Estuarine has the strongest and open water the weakest association with the detection of spillover.
- **Relevant habitat**: Does the relevant habitat for the species being studied extend beyond the borders of the MPA, or does the MPA fully enclose the habitat? Extended habitat outside the MPA is more strongly associated with the occurrence of spillover.
- **Network status**: Is the MPA part of a network of MPAs, or is it isolated in terms of protection? A network of MPAs is more strongly associated with the occurrence of spillover.
- **Protection level**: Is the habitat fully or only partially closed? Full protection is more strongly associated with the occurrence of spillover.
- **MPA age** (at the time of the study): Older MPAs are over-represented among those where spillover occurs.
- **Species mobility:** Sessile species are unlikely to move across MPA boundaries.
- **Reproductive strategy:** Spillover is less likely for brooders and bearers of eggs than species with broadcast spawning or free-drifting early-life stages.

Although the meta-analysis in Section 2 indicates that the individual linear contributions of these factors to the occurrence of spillover cannot be determined, and their effect is most likely context-dependent, they are valid as a starting point for the conceptual model.

In addition to the cited results, we conducted a non-exhaustive review of literature into the factors reported to contribute to spillover. Most of the literature falls outside the criteria of the systematic literature review of Section 1 (e.g. Kellner et al., 2007; Le Quesne & Codling, 2009; Molloy, 2009; Moffitt et al., 2011; Di Lorenzo et al., 2020). However, the results are relevant in the context for which the conceptual model is designed: the exploration of the potential for spillover with multiple MPA designs.

Based on the outcomes of the meta-analysis, information from the systematic literature review and the additional literature, a total list of 10 factors that can contribute to spillover was compiled (Table 9). For each factor, we described the mechanisms by which they may do so. More details on some of the driving factors, quantified from the systematic literature review, are described in Section 2
The meta-analysis did not yield a set of comparable magnitudes for the contributions of the various factors. This comparability would have allowed us to implement the number and strength of individual factors and their relative strengths. In absence of this, however, we have chosen to weigh each factor equally in the model. Each factor is associated with a multiple-choice question in the model (ten questions) and each answer is assigned a value to indicate the magnitude of its contribution to spillover likelihood and magnitude. The value increases from 0 (no contribution) in steps of one with each increasingly positive answer. Questions can have a varying number of possible answers. In other words, a yes/no question has scores 0 and 1, whereas a question with five answers has scores of 0 to 4. Before adding up the scores across the questions, each answer is normalised to the maximum score of that question so that all factors contribute equally to the total score. While qualitative scoring systems such as used here are always to some degree arbitrary, our choice to weigh all factors equally avoids the use of a subjective relative importance of the various factors.

**Table 9. Factors and mechanisms contributing to the potential occurrence and detection of spillover, as included in the SPILLEST tool.**

| Factor | Mechanism |
|---|---|
| MPA age | The likelihood of spillover will increase with the age of the protected area, as older protected areas are likely to hold much higher abundance of individuals than younger protected area; such spillover is likely to be associated with the build-up of several generations of species within the protected area (and therefore, likely based on density dependent processes, will lead to individuals moving out of the protected area in search of resources) (Molloy et al., 2009). |
| Habitat continuity outside the closed area (i.e. MPA boundary) | Habitat continuity facilitates movement of organisms across MPA boundaries. If the closed area is enclosed by unfavourable habitat for the relevant species, movement out of the closed area is unlikely (Di Lorenzo et al., 2020). |
| Located along the coast | If part of the MPA boundary is a coastline, the available area (i.e. boundary surrounding the MPA) to detect spillover will be smaller than where the MPA is completely surrounded by water, enhancing the likelihood of detecting spillover (if such spillover is occurring) (Di Lorenzo et al., 2020). |
| Network status | Is the MPA part of a network of MPAs, or is it isolated in terms of protection? A network of MPAs is more strongly associated with the occurrence of spillover (Section 2). |
| Protection level | Is the habitat fully or only partially closed? Full protection is more strongly associated with the occurrence of spillover (Section 2). |
| Buffer zone present | Where a buffer zone is present, surrounding a MPA in which fisheries are regulated, this will prevent intensive fishing along the boundary of the MPA ('fishing the line'), reducing the likelihood of measuring spillover (Kellner et al., 2007). |
| MPA size compared to species home range | Very small protected areas are likely to contain both low numbers of species (i.e. low species diversity) and low abundance of species (i.e. low numbers), reducing the likelihood that spillover will occur or be detectable (if it is occurring).<br>Protected areas which enclose the species' entire home range will lead to strong conservation benefits, but spillover will likely not occur (and if it does occur is likely to encompass a small number of individuals) (Moffitt et al., 2011) |
| Species mobility | Sessile species are unlikely to move across MPA boundaries (Le Quesne and Codling 2009; Section 2). |
| Reproductive strategy | Spillover is less likely for brooders and bearers of eggs than species with broadcast spawning or free-drifting early-life stages (Section 2). |
| Commercial value of species | Species with high value are more likely to be depleted outside of protected area than species of low value. Therefore, the abundance difference for such high value species between the protected and non-protected areas is likely to be larger than for low value species, enhancing the likelihood of detecting spillover (if such spillover is occurring) (Di Lorenzo et al., 2020). |

## 4.3 The interactive spillover likelihood tool

The questions, answers, scores and calculations were implemented in a Microsoft Excel-based interactive tool (Figure 26). We chose to implement the model in Microsoft Excel because it is readily available to our user base and does not require the installation of software or specific expertise.

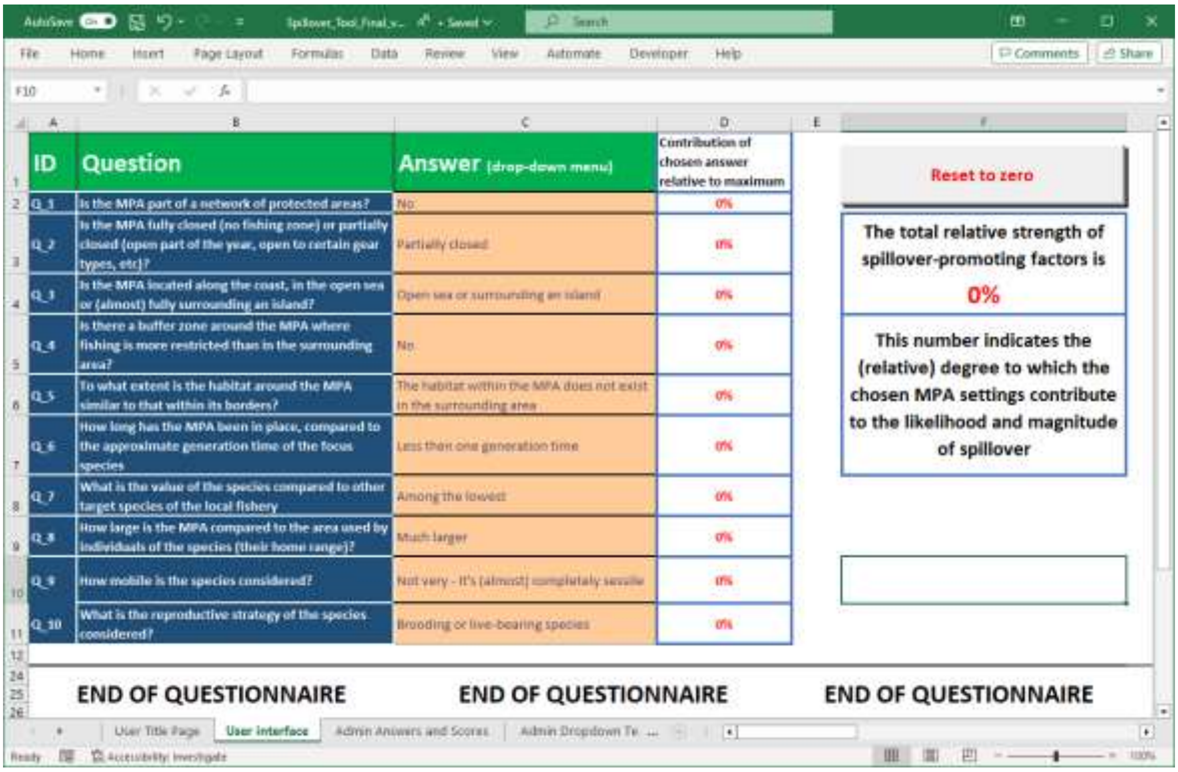


**Figure 26. Screenshot of the 'Spillover Likelihood Tool' (SPILLEST) interface, under Microsoft Excel.**

By answering the questions in the tool for an existing or planned MPA, users can obtain an estimate of the likelihood of spillover for that configuration. It is then possible to change specific answers and explore how they affect the outcomes. The tool includes a front page that details the developers, the conditions of use, the objectives and a user guide. All calculations and choices in the SPILLEST tool can be viewed by any user so the process leading to the results is completely transparent.

The main output of the model is an estimate of the relative likelihood of spillover and the relative strength of the contribution of each question/answer combination. While these quantities are expressed as percentages, they are essentially qualitative estimates. A 0% likelihood indicates that none of the drivers to which the questions refer promote the occurrence of spillover. Occurrence is thus considered highly unlikely. A likelihood of 100% means that all examined factors contribute maximally to the occurrence of spillover, so it is likely to occur. When more than two answers are possible, the contribution is divided into equal steps between 0 and 100% (i.e. with five possible answers they contribute 0, 25, 50, 75 or 100%). This approach reflects the qualitative nature of the resulting estimate. This simple coding system was decided on and implemented based on the expert judgment of the SPILLEST authors.

It is important to note that the spillover likelihood score is an integrated score. This means it includes the presence of mechanisms that affect the occurrence of spillover, magnitude and measurability. Given the available data and literature, it is not possible to disentangle the effects of our contributing factors to these aspects of spillover. So far, it is also not possible to distinguish between the likelihood of ecological and fishery spillover.

It is furthermore important to note that the outcome only refers to the contribution of the drivers considered in the model: there may be other factors preventing or promoting spillover, despite the score. This is because we can never be certain that all: (a) contributing factors have been studied; and (b) negative effects (factors preventing spillover) have been reported due to detection problems and publication bias favouring positive results. Both (a) and (b) are reasons why certain factors may be missing from the model. The model can, however, be used to guide more in-depth studies into the spillover potential of a specific MPA designation and/or implementation, even though it cannot replace such work.

## 4.4 Validation of the spillover likelihood tool

The SPILLEST tool was tested and validated for various MPAs. The instructions for applying the model were sent out to the leaders of all case studies (see list of case studies in Section 5; Table 10). The validation was intended to test applicability and whether the setup (what would you add/remove/change?), the process (did it work? was it useful?), the results (did it match findings/expectations?) were clear and relevant. Feedback was received for 11 case studies. The received responses are provided in Annex 3. There is a slight difference between the version sent out to the case study leaders and the version presented here (Figure 26). In the version used for the validation, question 10, about reproductive strategies was not yet implemented because the results of the species traits contributing to spillover (Section 2.3.2) were not available at the time.

The outcome of the application of the tool varied between 31% and 58% total relative strength of spillover-promoting factors. It is reassuring to observe that these real-world applications do not lead to extreme outcomes of 0 or 100%, as such outcomes would suggest the tool does not have a sufficiently wide scope of questions and answers.

Generally, case study leaders expressed that they felt the outcome corresponded with what was found or expected in terms of spillover for their case studies. Some found the tool results to be optimistic. However, it appears that in at least one case, they referred more to the detection of spillover than to its occurrence. The tool purely estimates occurrence and, as long as potential occurrence is higher than detection, discrepancy can be explained if factors (e.g. heavy fishing around an MPA or sparse monitoring data) reduce detection probability.

Several case study leaders expressed that the reference to 'species' in the tool was hard for them to understand. While this is understandable when considering MPA effects in hindsight, such as in this feedback round, the likelihood of spillover from a potential future MPA is expected to always be on the species level. Since we see this as the main application of the tool, we have not implemented any changes based on these remarks.

Two other points were raised about potential additional questions.

One case study leader asked if it would be worth adding a question about the role of the MPA as a spawning ground, as this increases the likelihood of larval spillover. We did not encounter this mechanism in the empirical literature, but there is support from theoretical work. A question like this could be added at a later stage, but its absence in empirical work led us to not add it at this stage.

A second suggestion was to add a question regarding the recovery of benthic habitat, which may increase the likelihood of spillover in target fish/crustacean species. While this is a valid mechanism, it appears that the question about age of the MPA covers this (at least in a phenomenological sense).

## 4.5 Conclusions

A conceptual model tool was developed, SPILLEST, which integrates the potential environmental, social and economic factors contributing to the occurrence, magnitude and detectability of spillover from MPAs. This interactive tool allows users to **explore various MPA configurations, their contribution to spillover and the total likelihood score for spillover**. It integrates the analyses conducted in this study and the outcome of other peer-reviewed literature that was surveyed. It has been stakeholder-tested by case study leaders in this study and was found to generally conform with expectations. The SPILLEST tool is provided with this report and is available for downloading (spillest-spillover-likelihood-tool).

The current version of the tool can be used as an **estimate of the likelihood of spillover related to MPA designs, either already in place or in development, for any relevant species**. By varying the answers to individual questions, stakeholders can get a feeling for how various aspects of governance, positioning, ecology and exploitation of the species considered affect the likelihood of spillover. The questions in the tool are based on literature and a meta-analysis of data from studies estimating spillover. When new literature, new data, or new methods to analyse existing data become available, this could lead to the uncovering of novel contributing factors. These can then be added in the current tool.

Further potential improvements could come from including the relative strength of the contribution of each factor (currently all factors contribute equally). This would require either that all factors included come from a single analysis, or that an appropriate process for aligning each factor is implemented. Such a process would most likely be based on expert judgement. The tool is built in such a way that it is also possible to widen the scope to accommodate a distinction between ecological spillover and fishery spillover. However, that would require substantially more data and analysis on the contribution of the various factors to each type of spillover.

# 5 ASSESSMENT OF SPILLOVER AND ADVISORY PROTOCOL

**Key highlights**

- It is challenging to source enough case studies in the regional seas surrounding Europe with suitable data for the analysis of spillover effects.
- Half of the case studies showed evidence of spillover effects or the potential of spillover effects. Their non-uniform nature makes it difficult to attribute common factors to the occurrence of spillover.
- MPAs can lead to increased spillover of species, but the patterns will be species-specific, and spillover effects will take a long time to be relevant for fisheries.
- While all stakeholders acknowledge the MPAs' role in protecting biodiversity, fishers express concerns about the impacts of fishing restrictions on their livelihoods.
- There is hope amongst stakeholders that MPAs can provide benefits to both biodiversity and fisheries, but empirical spillover evidence is lacking in many cases.

## 5.1 Introduction and objective

Assessing spillover from MPAs is important for understanding ecological processes, evaluating the effectiveness of MPAs, maximising economic benefits and promoting sustainable fisheries and conservation (Di Lorenzo et al., 2020). Spillover is an important factor to examine when measuring the success of an MPA in relation to both ecological and socio-economic goals (Di Lorenzo et al., 2016). Success on both fronts helps to secure positive engagement amongst stakeholders, leading to a common goal in sustainable fisheries management. In this context, there is a need to understand the perceptions of stakeholders on spillover effects and to ensure that any analysis of data to effectively quantify patterns of spillover is both statistically rigorous and replicable.

The objective of this section, therefore, is to assess whether there is spillover from a range of MPAs in the regional seas surrounding Europe, using both a qualitative and quantitative approach, with the ultimate goal of designing a methodology to better monitor and assess spillover effects in MPAs. To address whether spillover does or does not occur in MPAs, case studies were used to address the following specific objectives:

1. Evaluate whether the perceptions of stakeholders indicate a likelihood of spillover effects occurring because of the MPA establishment.
2. Where data are available, use a quantitative approach to evaluate the spillover effects that could be taking place, using metrics found through literature review.
3. Develop a general spillover assessment protocol (the 'advisory protocol') and provide recommendations for refining or improving the methodology for future spillover assessments in MPAs.

For each case study, the methodology involved desk-based research (literature review, data collation) and stakeholder interviews based on an online survey. Here, the two methodologies to evaluate spillover effects are outlined, together with an overview of the case studies that they were applied to. These include a **qualitative approach**, which assesses spillover effects based on stakeholder interviews (Section

5.2) and a **quantitative approach** (i.e. the advisory protocol), which allows for a statistical assessment of spillover (Section 5.3).

## 5.2 Qualitative approach: stakeholder interviews

The success of MPAs ultimately depends on the engagement of stakeholders involved in the establishment and management of the protected areas. Accordingly, it is critical to understand the direct and perceived impacts that these MPAs can have. We developed a questionnaire to assess the perceptions of key stakeholders on the potential spillover effects in their nearby MPAs.

The questionnaire (Annex 4) was comprised of open-ended and closed questions to elicit stakeholder views and experiences on the different aspects of MPAs and fisheries. The **open-ended questions** aimed to capture stakeholder opinions and provided the stakeholder a chance to discuss the topic in more detail. These included questions such as 'Are you experiencing changes in catch since the implementation of the MPA? If so, what are these changes?' and 'Do you think fisheries in this area benefit economically by having the no-take MPA? If yes, how?'. The **closed questions** were statement-based and used Likert scale answer categories for stakeholders to choose from. They included questions such as 'I benefit economically by fishing next to a no-take MPA or an area where fishing is limited', 'Designation of a no-take MPA / area where fishing is limited in this area has led to an increase in revenues for fishers' and 'In order to develop commercial fisheries, certain areas of the MPA should be permanently closed to fishing'. Each of these questions required the respondent to select their answer from a list comprised of 'Strongly agree; Agree; Neutral; Disagree; Strongly Disagree'.

The open-ended and closed questions were grouped into **four broad categories** to encapsulate the key issues being studied. These were:

1. Respondent information. The first section required basic information from the respondent, including their name, institution and the type of stakeholder category they belonged to.
2. Background information. This section gathered background information from the stakeholder to understand more about the respondent and how they used the MPA. Questions included knowledge of when the MPA was established, the type of restrictions in place and how long the stakeholder had been associated with the MPA either through research, fishing or managing it.
3. Fishery impacts of MPAs. The third section explored the respondent's perceptions of the socio-economic impacts of spillover from the MPA. Stakeholders were asked to state whether the designation of an MPA/area where fishing is limited has led to an increase in revenues for fishers, whether the fishing community in the area felt that their livelihoods were more secure after the MPA was established, and the extent to which they believe spillover from the MPA has influenced the catch composition in adjacent fishing grounds.
4. MPAs as management tools. The fourth section of the questionnaire focused on the respondent's perceptions of whether MPAs were tools for conservation and/or fisheries management. Stakeholders were asked to state whether their local MPA functioned as a conservation tool, a fisheries management tool or both. Other questions in this section required stakeholders to state whether they agreed or disagreed on whether the establishment of MPAs was an effective conservation strategy for supporting fish populations and commercial fisheries in their area. Respondents were also asked to indicate what factors they thought contributed to spillover effects.

A stakeholder mapping exercise was conducted to identify key stakeholders. Four **key stakeholder groups** were identified and targeted in this consultation, including the (i) fisheries sector; (ii) fisheries management authorities; (iii) scientists; and (iv) environmental non-government organisations (eNGOs). Therefore, while the four broad categories of the questionnaire were the same, specific questions were included for each of the respondent groups. The questionnaire (in English) was translated into Spanish, French and Portuguese, and disseminated online.

An initial email detailing the aims and objectives of the study was circulated, along with a link to access the online survey housed on LimeSurvey. Once initial contact had been made, an invitation to a one-to-one interview was proposed; either remotely via Microsoft Teams or in person. Given the summer period and stakeholders' workloads, every effort was made to accommodate stakeholders' preferences. Most stakeholders took part in the survey through the link sent to them for the online questionnaire.

The quantitative data on the responses to the Likert scale questions in the online survey were sorted based on the questions for the different stakeholder groups and analysed using the R statistical package (rStudio Team, 2020). The mean scores provided by the four main stakeholder groups (fisheries sector, fisheries management authorities, scientists and eNGOs) were plotted for the key questions under study.

## 5.3 Quantitative approach: the advisory protocol

Statistical data analysis for effectively quantifying spillover patterns should be both rigorous and replicable. Accordingly, a spillover assessment advisory protocol (Annex 5) was developed. This protocol and other quantitative analytical methodologies were tested on some of the case studies that analyse spillover in different MPAs across Europe. Every case study partner conducted individual analysis on spillover using data that was available to them. The advisory protocol served as a guide for the case study partners and future spillover assessments by scientists and managers, outlining essential analytical procedures and considerations for studying ecological and /or fishery spillover. As the ideal study design depends on the quantity and type of data available, it offers adequate flexibility to adapt to different study designs, with a primary focus on comparative fish biomass analysis.

The advisory protocol consists of the following content, described in detail in Annex 5. The introduction provides an overview of the concept of spillover in the context of MPAs and fisheries. It discusses challenges in observing and detecting spillover, which may arise due to factors like the time since an MPA's establishment, the ecological value of an MPA, species-specific responses, MPA size, the presence of pelagic larval stages and population-level effects. Additionally, fishery responses, such as 'fishing the line', can influence spillover effects and need consideration.

The advisory protocol discusses various approaches for detecting and measuring spillover effects from MPAs in fisheries management. The main data types for studying spillover are identified, including automatic identification system (AIS) data, vessel monitoring system (VMS) data, logbook data, visual census and capture-recapture. As response variables, there is a focus on quantitative data sources, such as fish abundance and biomass data. The comparative approaches for assessing spillover are explained. The Before After Control Impact (BACI) design is introduced, which involves comparing data from inside an MPA (i.e. impact) to data from outside the MPA (control) before and after its establishment. However, it is noted that this approach may not always be ideal for detecting spillover.

A theoretical scheme on possible outcomes when comparing data in the MPA and reference sites before and after MPA establishment was set-up to indicate what outcomes we can conclude potential spillover for. It demonstrates that only a handful of the outcome scenarios could potentially indicate spillover as it is still challenging to attribute observed spillover solely to MPAs. Alternative comparative approaches are introduced, emphasising the importance of sufficient data quantity and quality, both spatially and temporally. The different combinations of spatial and temporal data are discussed, highlighting the suitability of each for detecting spillover. In summary, the advisory protocol provides insights into the complexities of assessing spillover effects and suggests various approaches and data requirements for effective evaluation.

Next, the document discusses how to choose appropriate reference points in space and time. When studying spillover effects from MPAs, it is key to choose reference areas similar to an MPA that are not subject to different fishing pressures after the MPA is established. Ideally, multiple references should be chosen at varying distances too. Thereafter, one must ensure a time gap between pre- and post-MPA data, consider species' life cycles, and account for natural variability. Lastly, it is recommended to focus on species with robust data, stakeholder relevance, ecological significance, or conservation priority. Studying multiple species can provide a broader perspective, as the response to the implementation of an MPA can vary between species. This provides a comprehensive understanding of the consequences for multiple species in the ecosystem.

Other considerations important for the study of spillover are also discussed in the advisory protocol. Both total catches and fishing effort should be examined together, as focusing solely on one can yield incomplete conclusions. Using catch per unit effort (CPUE) to assess MPA effectiveness has limitations as changes in CPUE can result from factors beyond fish biomass. Changes in fishing practices and technology can inflate CPUE values, requiring differentiation between MPA-driven effects and fishing efficiency improvements. Non-linear population growth patterns could be studied in analyses, especially when assessing CPUE. Temporal effects like seasonality should be avoided or accounted for, and collinearity between variables like water temperature and time may be present.

Lastly, it is recommended to ensure reliability by applying the same methodology to a subset of data or settings with no expected effects. At the end of the protocol, a list of potential variables for assessing spillover effects also linked to the SPILLEST tool are given (see Section 4), including distance from the protected area, time since establishment, habitat characteristics and fishing effort.

## 5.4 Spillover assessment

This section presents a general overview of the case studies investigated in the regional seas surrounding Europe (Section 5.4.1), the results of the general analysis of stakeholder perceptions (Section 5.4.2) and the summary of the main outcomes of each case study (Section 5.4.3) related to the assessment of spillover effects using the qualitative and/or quantitative approaches.

### 5.4.1 Selection and overview of case studies

In total, **fifteen case studies** in the Baltic Sea, North Sea, Atlantic EU Western Waters and some Outermost Regions (focusing on the Azores, Madeira and Canary Islands) were used to gather insights into potential spillover effects of different types of MPAs. Areas exist in the ocean where access or activities are restricted by law for reasons other than conservation (Grober-Dunsmore et al. 2008). Such areas, collectively known as 'other effective area-based conservation measures' (OECMs) were also investigated in this section of the study, in addition to typical MPAs, as they may be relevant in the study of spillover effects. OECMs represent sites outside formal protected areas but contribute to effective and long-term conservation of biodiversity (Day et al. 2019). For the purposes of this section, OECM cases will be collectively referred to as MPAs unless specifically referring to OECMs.

The selection of case studies was made mainly based on geographical coverage and data availability. A systematic literature review was used to gain information about the potential case studies. A reporting template was created to facilitate structured documentation for each case study. This template covered key sections, including introduction, methods, results and discussion. The complete case study reports are presented in Annex 6. In this section, a summary of the case studies is described and discussed, including their methodologies and results. An overview of the selected case studies, their main characteristics and geographic locations is given below (Table 10; Figure 27).

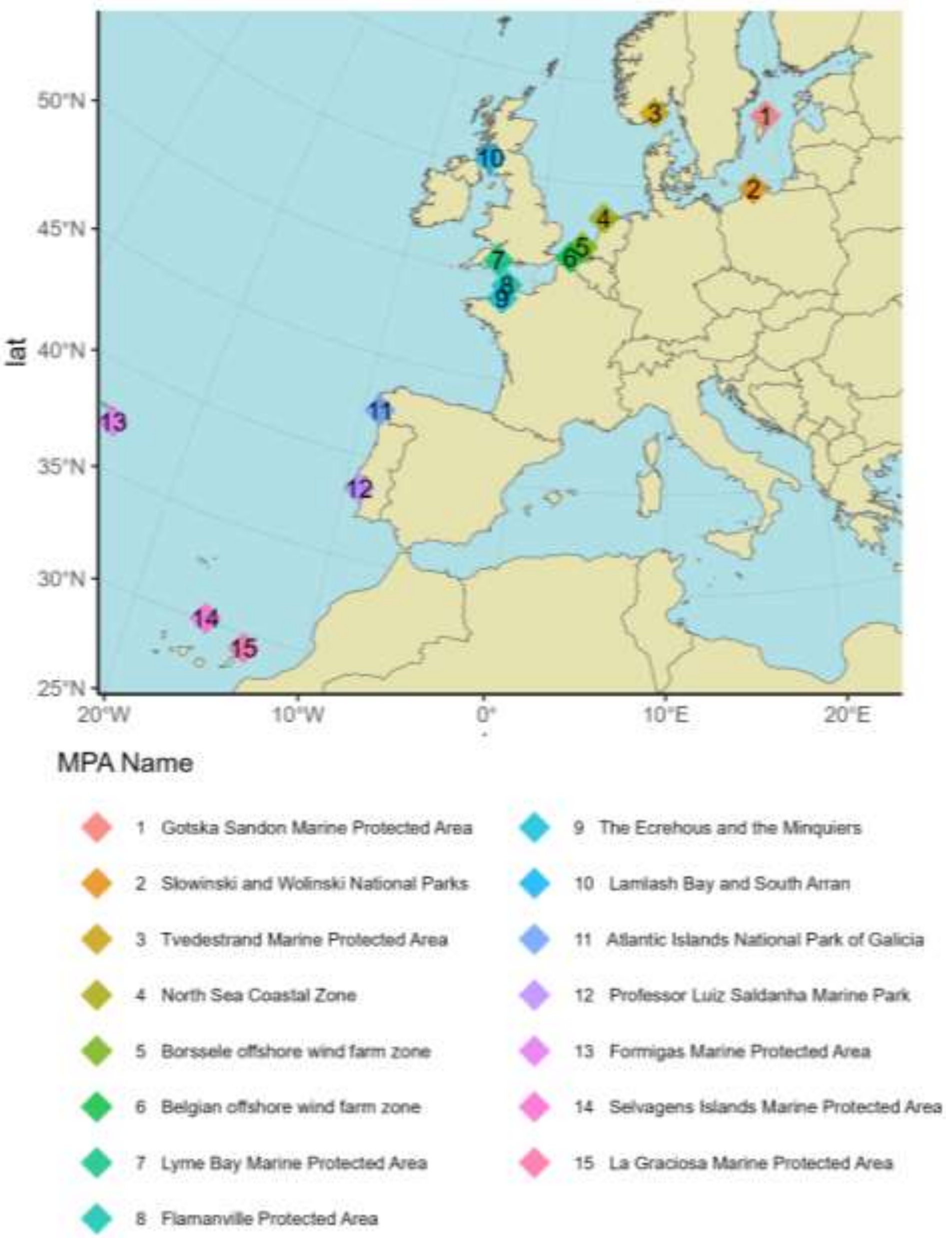


**Figure 27. Geographic distribution of the selected case studies assessed for spillover.**

In the **Baltic Sea, two case studies** were selected comprised of the Gotska Sandön MPA (Sweden) and the Słowinski and Wolinski National Parks (Poland). In the **Skagerrak**, **one case study** was selected, namely the Tvedestrand MPA (Norway) (Table 10; Figure 27). The selected case studies varied in the type of species researched (e.g. fish, crabs, lobsters) and type of data available (e.g. fishery data, capture-recapture, video, tagging). One (Gotska Sandön MPA) had data to perform quantitative analysis while in the other two both quantitative and qualitative approaches were undertaken.

In the **North Sea**, **three case studies** were selected, including two offshore wind farm areas, both classified as OECMs (Borssele offshore wind farm zone, Netherlands; and Belgian offshore wind farm zone) and one MPA (North Sea Coastal Zone, Netherlands). Biodiversity conservation and fisheries are not the primary purpose of windfarms, but as these areas are closed for fisheries, they have the potential to create spillover effects (Ashley et al., 2014). Similar to the Baltic Sea, the case studies selected in the North Sea enabled both a qualitative analysis (based on stakeholder perceptions) and a quantitative analysis (based on fishing effort and landings data). In most cases, this allowed for a comparison of data in or near the MPA to the areas surrounding the MPA (sometimes even along a gradient of distances from the MPA).

In the **English Channel**, **three case studies** were selected. One no-take area in France is part of the establishment of a nuclear power plant, inside an OECM (Flamanville Protected area). The two other cases are MPAs located in the UK and Jersey. The case studies present protected areas characterised by moderate to high protection and various taxa (e.g. species of fish and crustaceans). In all case studies, research studies have been published focusing on commercial shellfish including edible crab (*Cancer pagurus*) and European lobster (*Homarus Gammarus)*. Time series data were envisaged to be available from both the Flamanville and Lyme Bay as these MPAs have long-term monitoring programmes looking at their ecological effectiveness and socio-economic benefits. Although recently established, both the Écréhous and the Minquiers MPAs also have ongoing studies looking at their epibiotic and infaunal assemblages including impacts on local fisheries. The case studies therefore enabled this project to perform both a quantitative and qualitative analysis of spillover effects.

In the **Atlantic EU Western Waters and Outermost Regions** (focusing on the Azores, Madeira and Canary Islands**), six case studies** were selected that covered MPAs in two EU Member States (Portugal and Spain) and the UK. The case studies varied in terms of research studies that have been undertaken with some (e.g. Professor Luiz Saldanha Marine Park) being well-studied while others not so. The selected case studies also comprised of MPAs with low protection (e.g. the Atlantic Islands National Park of Galicia), through moderate (e.g. La Graciosa MPA) with others highly protected (e.g. Professor Luiz Saldanha Marine Park). These case studies provided substantive information on spillover from MPAs and therefore both qualitative and quantitative approaches were employed.

**Table 10. Overview of the 15 selected case studies in the regional seas surrounding Europe. MPA characteristics and the main methodologies used (either quantitative, or both quantitative and qualitative) are indicated.**

| Regional sea | Location | MPA | Establishment | Protection* | Size km² | Approach (quali., quanti, both) |
|---|---|---|---|---|---|---|
| Baltic Sea | Sweden | Gotska Sandön Marine Protected Area | 2006 | High | 360 | Quantitative |
| | Poland | Słowinski and Wolinski National Parks | 2005** | Low | 111 & 47 | Both |
| Skagerrak | Norway | Tvedestrand Marine Protected Area | 2012 | High | 4.9 | Both |
| North Sea | Netherlands | North Sea Coastal Zone | 2013 - 2017 | Moderate - High | 144 | Both |
| | | Borssele offshore wind farm zone | 2020 | High | 344 | Both |
| | Belgium | Belgian offshore wind farm zone | 2008 - 2020 | High | 238 | Both |
| English Channel | UK, England | Lyme Bay Marine Protected Area | 2001 (end 2006) | High | 200 | Both |
| | France | Flamanville Protected Area | 2000 | High | 1.2 | Both |
| | Jersey | The Écréhous and the Minquiers | 2004 - 2017 | Moderate | 45.5 & 15 | Both |
| Celtic Sea | UK, Scotland | Lamlash Bay and South Arran | 2008 and 2014 | High | 250 | Both |
| Iberian Coast | Spain | Atlantic Islands National Park of Galicia | 2002 | Low | 72.9 | Both |
| | Portugal | Professor Luiz Saldanha Marine Park | 2009 | High | 53 | Both |
| Macaronesia | Portugal, Azores | Formigas Marine Protected Area | 1988 | Moderate | 57.4 | Both |
| | Portugal, Madeira | Selvagens Islands Marine Protected Area | 1971 - 2021 | Low - high | 95 - 2677 | Both |
| | Spain, Canary Islands | La Graciosa Marine Protected Area | 1995 | Moderate | 707 | Both |

** The level of protection is based on Feary et al. (2024)*

*** First decree describing conservation tasks. The Slowinski National Park and Wolinski National Park were first established in 1967 and 1960 respectively, but no conservation tasks were defined.*

### 5.4.2 General analysis of stakeholder perceptions

In total **72 responses** were received across 14 case studies (with the two national parks in the Polish case study presented separately in this section), covering seven EU Member States (Netherlands, Belgium, Sweden, France, Poland, Spain and Portugal) and non-EU countries (Jersey, Norway and UK). These comprised 22 respondents from the fisheries sector, 20 from fisheries management authorities, 24 scientists and six NGOs (Figure 28). The number of respondents per case study varied widely, with the Channel Islands MPAs (the Écréhous and the Minquiers) having the highest (11) while others, like the Flamanville Protected Area, only having one.

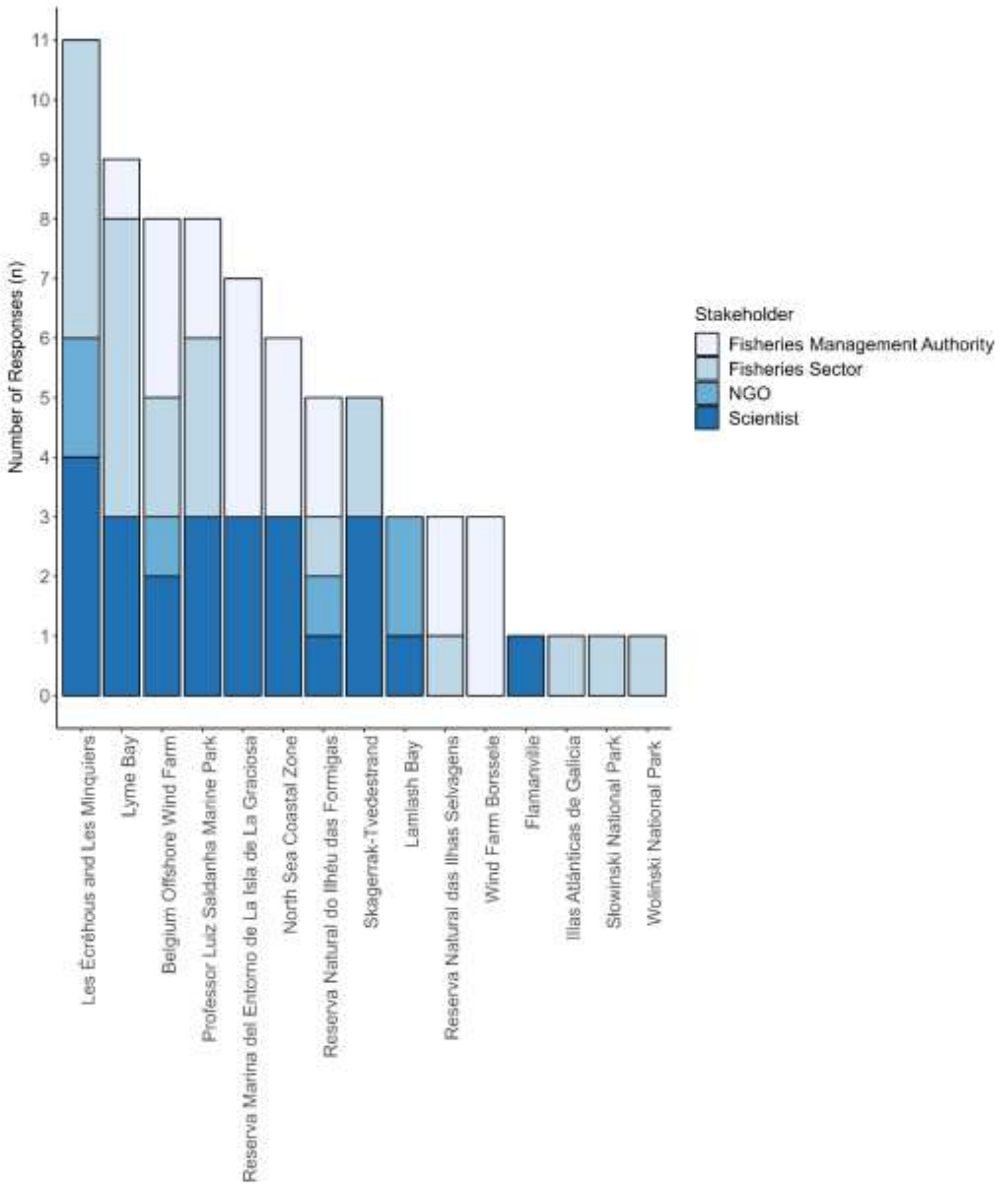


**Figure 28. Number of respondents per case study showing the stakeholder categories that fill in the online survey (n=72). The Slowinski National Park and Wolinski National Park are combined into one single case study, but presented separately in this figure.**

Survey responses show that the Formigas MPA (Reserva Natural do Ilhéu das Formigas), La Graciosa MPA (Reserva marina del entorno de la isla de La Graciosa), Professor Luiz Saldanha Marine Park, and North Sea Coastal Zone have management plans while the Lyme Bay MPA, Selvagens Islands MPA (Reserva Natural das Ilhas Selvagens), Belgian offshore wind farm zone and the Borssele offshore wind farm zone do not. Apart from the Formigas MPA and the North Sea Coastal Zone where spillover is included as a conservation objective, the other MPAs have not included spillover as a conservation objective. The majority (67%) of MPAs that have management plans also restrict fishing within the MPA (Figure 29).

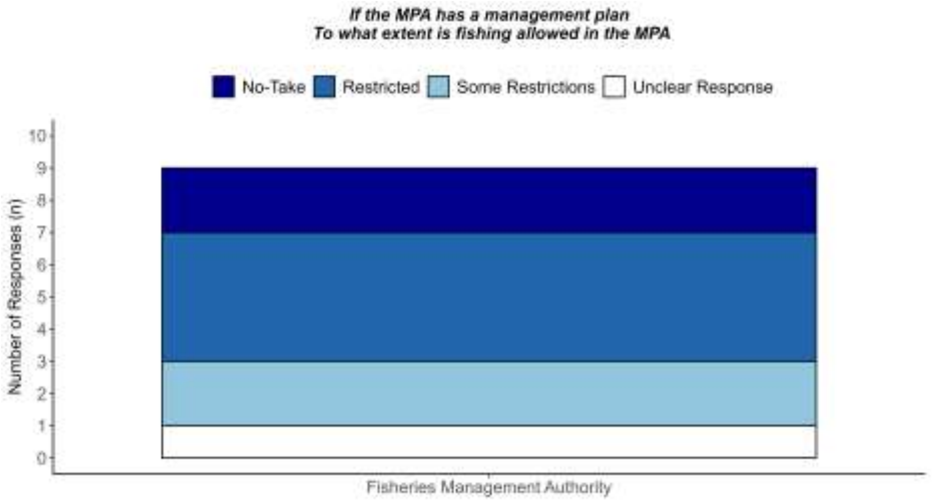


**Figure 29. Responses to the question on whether fishing is allowed within the MPAs that have a management plan (n=9).**

*Ecological changes after MPA establishment*

Apart from one respondent from Skagerrak, who indicated that they had not observed any changes in the habitats, biodiversity or structural complexity of the seabed in the MPA, respondents from all other MPAs indicated that they had observed ecological changes after MPA designation (Figure 30). Stakeholders' comments on these changes varied, with some saying that changes were more difficult to detect in the first few years after designation because there was no prior monitoring before designation in some MPAs. While respondents from the fisheries sector and scientists stated that they had observed these changes, other stakeholder groups, such as fisheries management authorities, stated that they had anecdotal evidence.

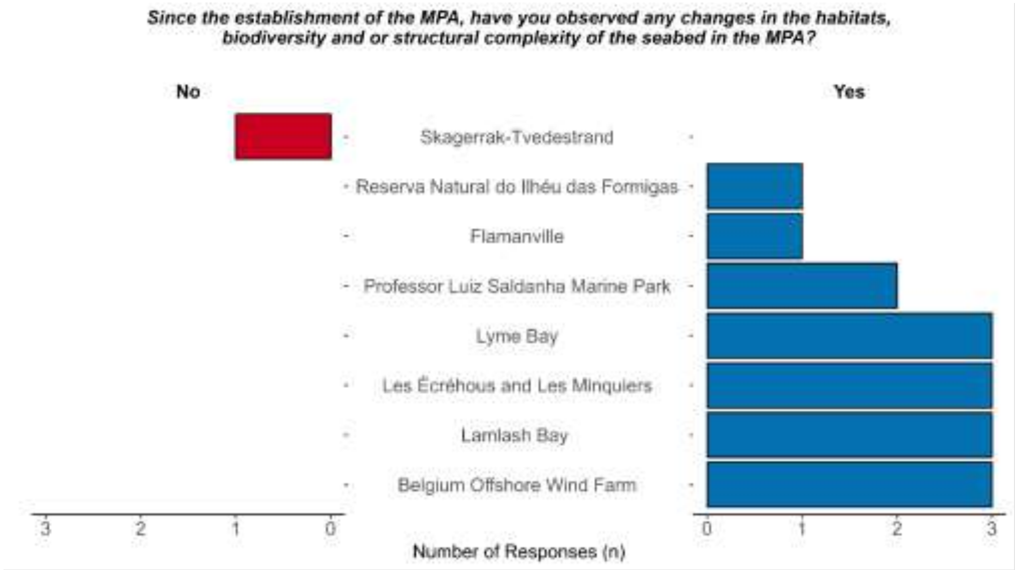


**Figure 30. Responses from the various case studies on the question of whether they have observed changes to habitats, biodiversity and structural complexity in MPAs (n=17).**

Questions on the likelihood of spillover occurring were directed to scientists and eNGO respondents. Results show that 90% of scientists perceive that spillover is occurring from the fully protected areas (Figure 31) while 46% perceived that there was likelihood of spillover occurring in partially protected areas (Figure 32).

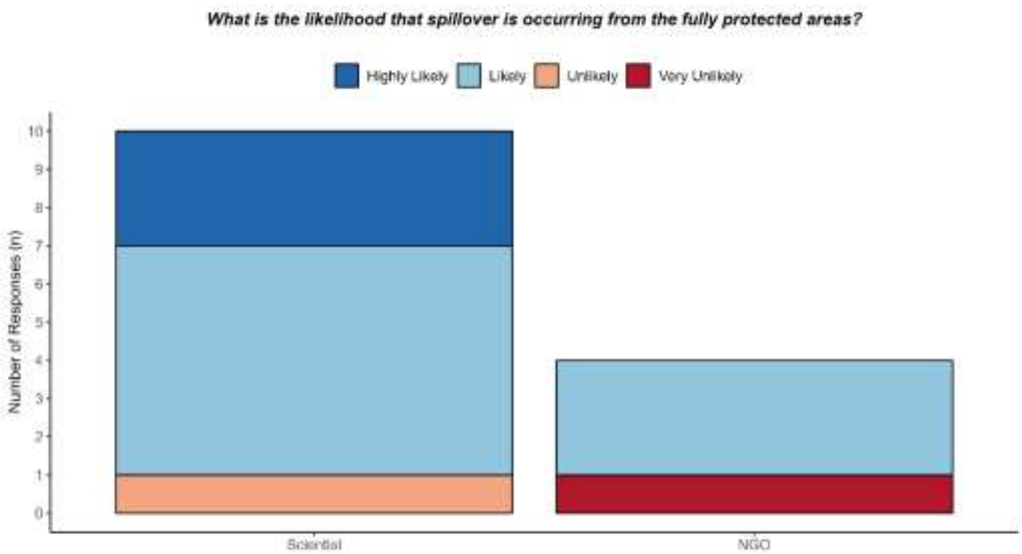


**Figure 31. Responses from scientists and NGOs on the likelihood that spillover is occurring from the fully protected areas (n=14).**

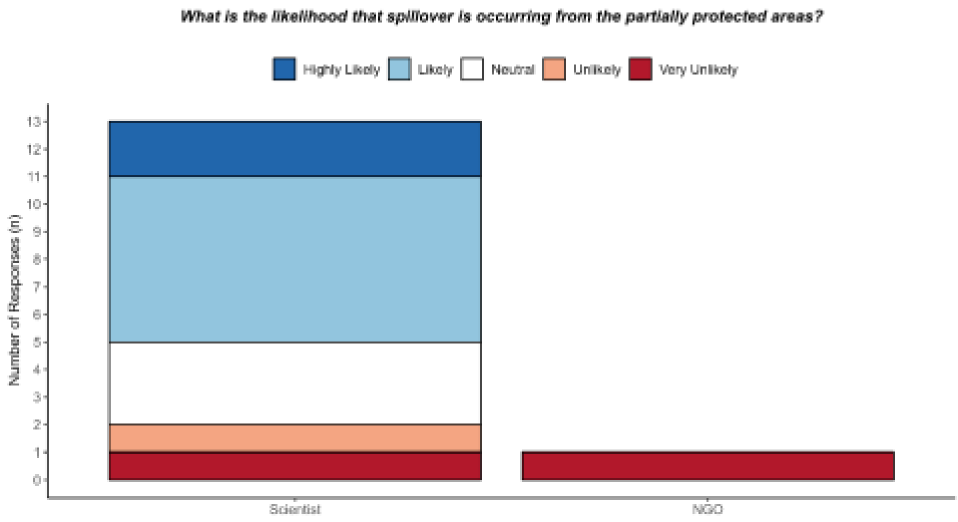


**Figure 32. Responses from scientists and NGO representatives on the likelihood that spillover is occurring from the partially protected areas (n=14).**

*Fishery impacts*

The impact of MPAs on fisheries was studied through assessment of: (i) the changes in catch and number of fishers, and (ii) economic and social benefits. Most (70%) of the respondents from the fisheries sector stated that they had experienced changes in catch after MPA establishment. When asked to state whether catches inside MPAs were higher than outside, four fishers indicated that they were not. Seven fishers stated they probably were, and five stated that catches inside MPAs were definitely higher than outside (Figure 33). In addition to what is presented in Figure 33, a response from one of the Advisory Councils was received after the analysis of the questionnaire results. This response indicates that the MPAs have had no impact on pelagic fisheries.

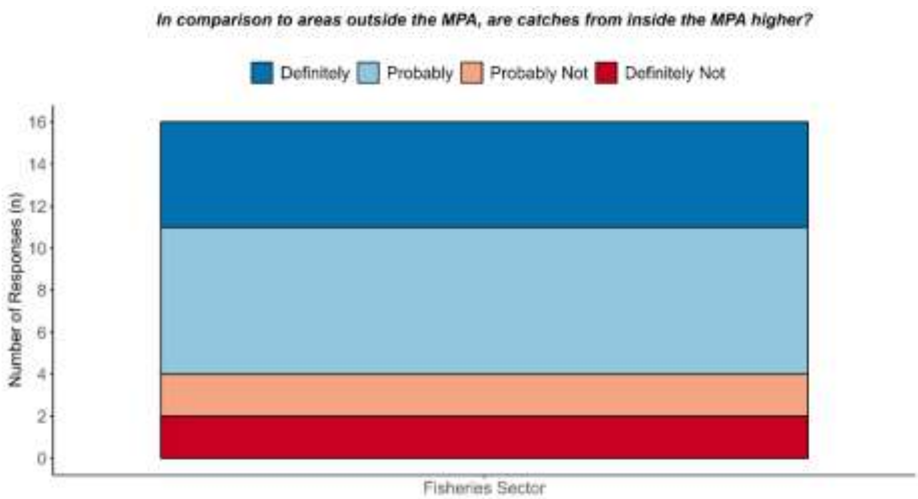


**Figure 33. Response from the fisheries sector on whether catches are higher inside MPAs compared to outside (n=16).**

In terms of economic and social benefits, there were mixed opinions on whether fisheries benefitted economically from MPAs. Of the nine fisheries managers, four agreed that MPAs had led to an increase in revenue for fishers (three of them strongly), two strongly disagreed, and three expressed neutral opinions (Figure 34). Some of the comments provided by those who strongly disagreed were due to the fact that some MPAs restrict fishing in some of the zones. **The fisheries managers that strongly agreed indicated that no-take zones enriched adjacent fishing grounds through spillover.** These mixed perceptions shed light on the practical complexities of implementing no-take MPAs.

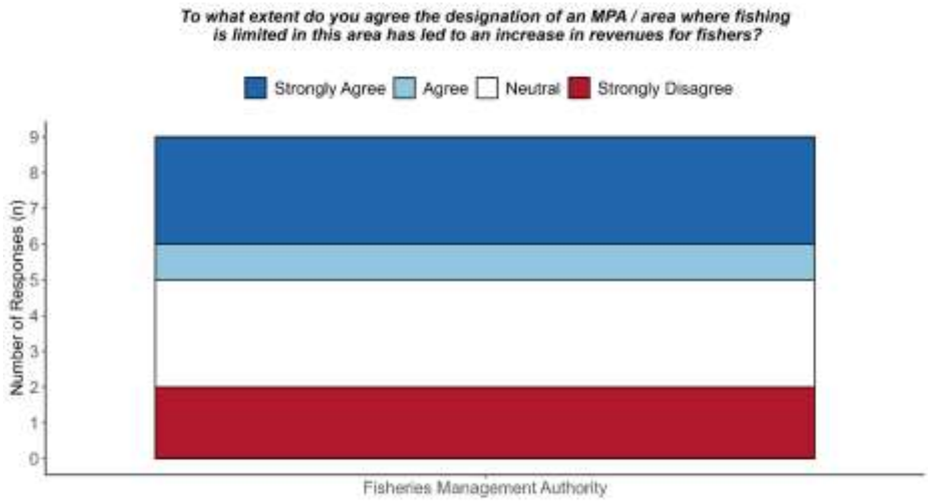


**Figure 34. Response of fisheries managers on whether MPAs increase revenue of fishers in adjacent fishing areas (n=9).**

*MPAs' role: Conservation versus Fisheries Management*

Multiple stakeholders emphasised the dual role of MPAs as a tool for both conservation and fisheries management, safeguarding marine biodiversity and subsequently benefitting the local fishing community. However, some fisheries managers and fishers argued that they saw MPAs more as a conservation tool, stating that the main reason for closing areas is to protect habitat features and not to develop fisheries. Scientists, however, advocated for MPAs to fulfil the need to have control sites to monitor the recovery of fish populations and their habitats, and progress towards achieving conservation goals and objectives.

*Spillover effect from MPAs*

The majority (64%) of respondents concurred that **spillover of fish or larvae export took place from the MPAs, leading to benefits to adjacent fisheries** to some extent. The importance of commercial fishery spillover was a topic of high priority for scientists. However, it was of less importance to some respondents from NGOs, who indicated that seabed and habitat recovery and ecological spillover were of greater interest to them. Notably, most scientists stated that spillover was occurring to a lesser extent while others stated that it was occurring to a large extent. They indicated that spillover had likely influenced the catch composition in nearby fishing. Fishers' responses on whether spillover did occur followed a similar pattern to those of scientists, with six responding that they were unsure whether spillover was occurring at all, while 12 stated that it took place to a small or large extent. Regarding the factors driving spillover effects, respondents identified key influences to be protection level (n=6), dominant habitat (n=5), years since the MPA was established (n=3) and MPA size (n=3) (Figure 35).

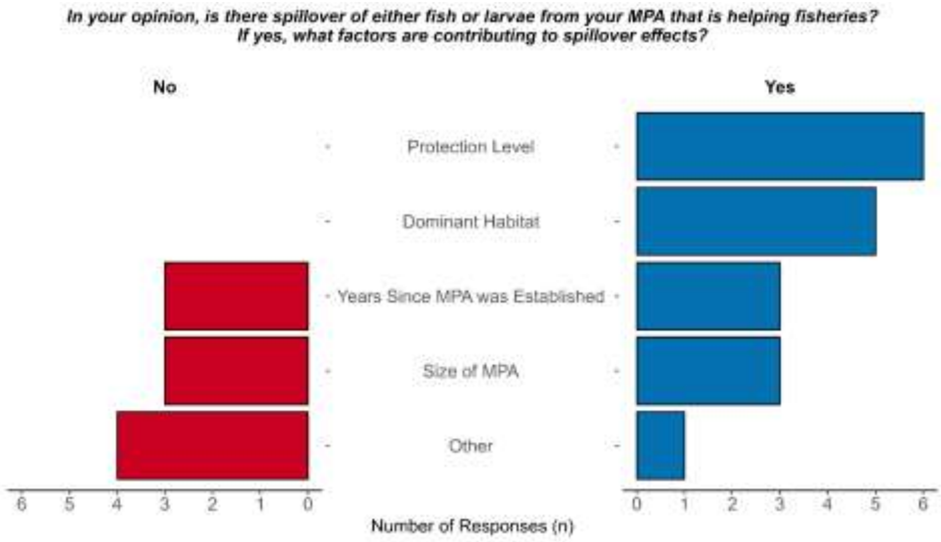


**Figure 35. Stakeholder perceptions on spillover presence and the factors contributing to spillover effects (n=28).**

It is worth noting that many stakeholders were unable to confidently address spillover-related questions, primarily because of the insufficient research available on the topic. This was supported by scientists who confirmed that investigating spillover effects was not a primary focus area in their research. Similarly, a respondent from an Advisory Council stated that offshore MPAs are a recent designation, and the results are yet to be known. Nevertheless, **there was consensus that spillover should be prioritised in future research**, and that research was ongoing using acoustic telemetry and tagging projects aimed at monitoring the movement, habitat use and residency of commercially important species, like brown crab and lobster. One scientist noted that "*spillover is a paradox where we don't know if the fish are moving inside to outside or outside to inside.*" Species may have grown within an MPA and moved outwards, or there might be an inward flow because they are safer within the MPA.

### 5.4.3 Summary of the main outcomes per case study

This section summarises the main outcomes per case study, ordered as in Table 10. Starting with the case studies in the Baltic Sea, followed by those in the North Sea (including Skagerrak), the English Channel, the Celtic Sea, the Iberian Coast and, finally, case studies in Macaronesia. At the end of this section, Table 11 summarizes the main case study outcomes. The complete case study reports are presented in Annex 6.

*Gotska Sandön Marine Protected Area (Baltic Sea, Sweden)*

The Gotska Sandön MPA is located in the central Baltic Sea in Sweden. A 360 km$^2$ no-take zone, prohibiting all fishing, was established around the island of Gotska Sandön in 2006. It had the primary aim of protecting the flatfish nursery grounds in the area. Although there were no direct estimations of biomass of fish in and around the MPA, there was information on the abundance and size structure of spawners of turbot (*Scophthalmus maximus*) and Baltic flounder (*Platichthys solemdali*), which are both of high commercial value. These data can provide insights into the biological effects of the establishment on reproducibility and larval dispersal of the species.

The main goal of this case study was to estimate the magnitude of the larval movement from the no-take zone to the reference area, based on monitoring data of densities and size structure in the no-take zone, as well as modelled larval export rates. The data consist of five years of gillnet survey data (2006−2009, 2021) providing catches per species and size group for both the no-take zone and the reference area.

Shortly after establishment, local populations of turbot and Baltic flounder thrived in the no-take zone. The estimated spillover of the flatfish larvae from the Gotska Sandön no-take zone to the fished reference area at Gotland seemed surprisingly large, especially for flounder (Figure 36). These magnitudes were surprising considering the long distance between the no-take zone and the area benefitting from the larval export (± 80-100 km). These results suggest that the fishery closure has led to spillover effects However, due to declines in turbot and flounder densities in the no-take zone in recent years, this spillover effect may have diminished over time, and there are no clear signs of a positive long-term effect on flatfish densities and fishery landings in the reference area.

Overall, this study underscores that species with pelagic drifting phases are more likely to generate spillover into areas with favourable hydrodynamic conditions. **While larval spillover from the Gotska Sandön MPA to Gotland seemed substantial, it diminished over time**. This highlights the importance of considering ecological connectivity when designing protected areas for species with pelagic life stages. Further empirical work focused on understanding spatiotemporal variability in egg and larval mortality rates, and empirical confirmation of contributions from the no-take zone is essential to complement evidence and verify the spillover effects in the area.

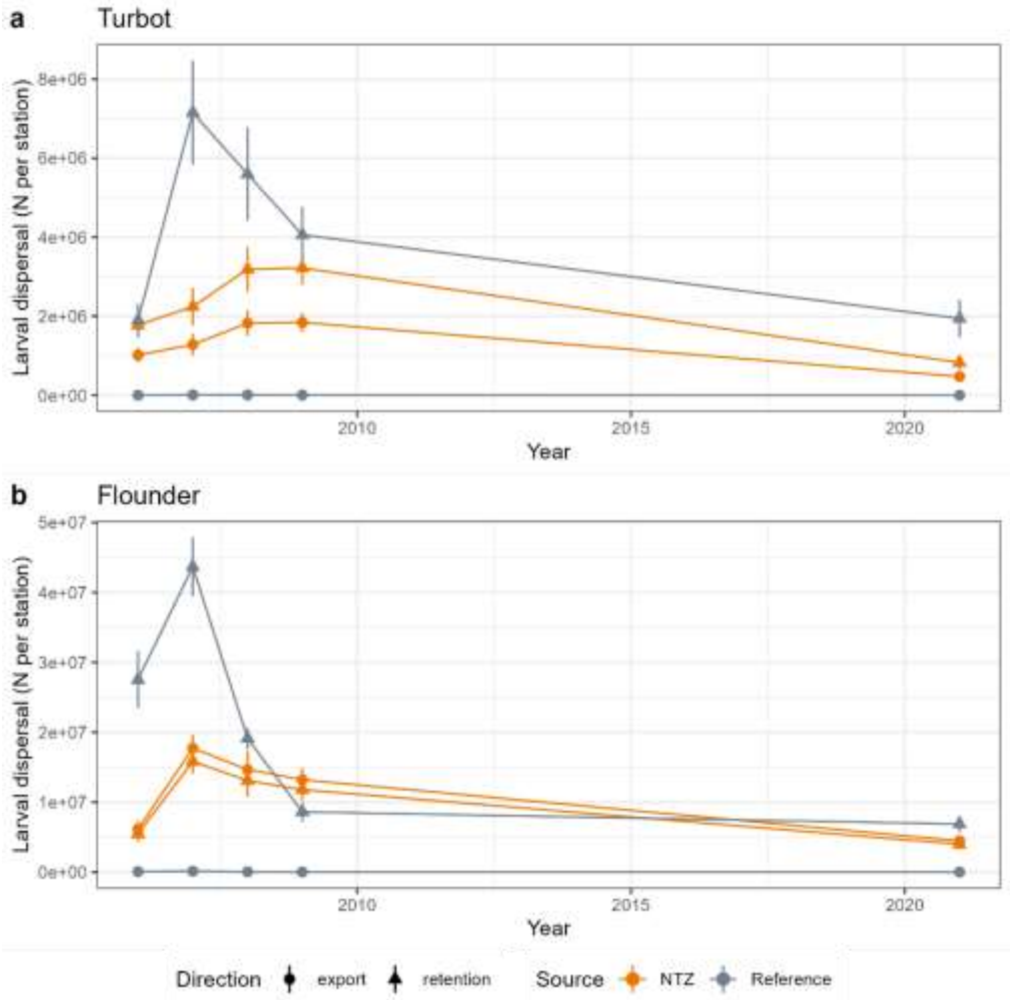


**Figure 36. The estimated larval dispersal per sampling station for (a) turbot and (b) flounder. Shape indicate direction, i.e. export (from the no-take zone (NTZ) to the reference area or vice versa) or retention (from the NTZ to the NTZ or from the reference area to the reference area). The colour (orange and grey) indicates the source population. Points represent means and error bars standard errors, as estimated from the variability in catches between stations within each area (export rates were assumed to be constant across years).**

### *Słowinski National Park & Wolinski National Park (Baltic Sea, Poland)*

One case study focused on two MPAs in Poland. The first is the Słowinski National Park, which has an area of 111 km². The second is the Wolinski National Park, which has an area of 47 km². The Słowiński National Park is located on the central coast, and the Woliński National Park is in the western part of Polish Baltic Sea coast. These MPAs cover relatively small marine areas. There are no specific management plans for the parks, but since 2005, the protected areas have only allowed 'cultural' fishing with licenses. However, catch data eventually became unavailable, and in practice, it turned out that, since their establishment in 2005, fishing practices have not changed a lot. The objective for this case study was to use data and information from past studies and stakeholder perceptions to analyse potential spillover effects.

The study used questionnaires, group and individual interviews with fishers, scientists and environmental NGOs to further study the perspectives of these MPA stakeholders on spillover. Fishers expressed social responsibility and understanding of the MPAs, although they felt the MPAs did not benefit fisheries as expected. Fishers believe that **protected status increased costs but did not raise total catches or total**

**revenue**. They saw no need to permanently close the MPAs for fishing practices. Park management and scientists believed that, in general, the MPAs are conservation and management tools that have positive effects on the environment, biodiversity and fish health. They anticipated that **spillover effects would benefit young fish in the coming years**. However, the study highlighted the need for clearer regulations and management plans for the two MPAs to function effectively.

*Tvedestrand Marine Protected Area (Skagerrak, Norway)*

The Tvedestrand MPA is located in the Norwegian Skagerrak region and spans 4.9 km². It is a no-take zone for lobsters (*Homarus gammarus*). The case study employs a combination of quantitative and qualitative methods. Catch monitoring has taken place since 2010 with the use of randomised sampling and a BACI design. This has produced a 12-year time series data on CPUE and total lengths for the European lobster. The data were collected inside and outside the MPA, which were analysed using a BACI design.

The results indicate a significant increase in CPUE inside the MPA over time. Nine years after protection started, the CPUE was 1.47 lobsters per trap day in the MPA, which is approximately three times higher than in fished areas (0.63 lobsters per trap day). The total lengths of caught lobsters are also 20% larger inside the MPA compared to outside, confirming the MPA effects in terms of protection. CPUE also increased 200 m from the borders of the MPA but stayed consistent at 1000 m distance. However, it was noted that this could also be a result of different fishing pressures. Despite these observations, **no statistically significant effect for distance to the MPA border (the spillover gradient) was found for the area** (Figure 37). Interviews with local fishers suggest that many have shifted their fishing locations closer to the MPA boundaries due to this area providing better and more stable catches.

This study demonstrates that the MPA was successful for protecting lobsters, even though it may take a long period to be felt in the fisheries. **Therefore, there was some evidence for spillover effects**, however more research needs to be done on the dynamics of spillover, fishing pressure and the influence of other fishery management tools.

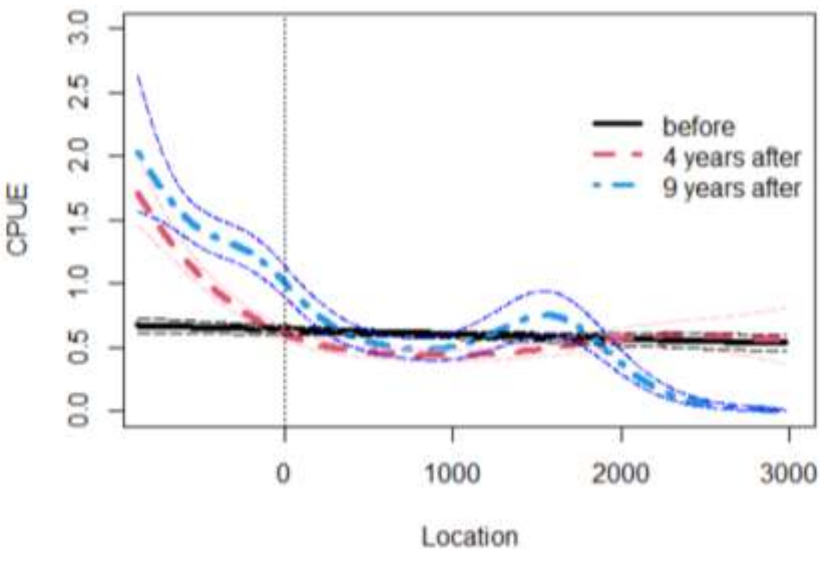


**Figure 37. Model predicted CPUE response to years of protection and distance to border (bold lines), prior to, four years and nine years after MPA implementation, at the optimal depth of 25 m. Thinner lines of the same colour indicate +/- 1 S.E. Vertical dotted line indicates the MPA boundary.**

### *North Sea Coastal Zone (North Sea, the Netherlands)*

The North Sea Coastal Zone (NSCZ) is a Natura 2000 protected area off the northern coast of the Netherlands. To make a compromise between nature conservation and the largest fisheries in the Dutch coastal zones (grey shrimp fishery), the *Fisheries In Protected Areas Agreement* (VIBEG) was concluded. Four smaller areas, totalling approximately 144 km², were completely closed for shrimp fisheries in 2017. The main goal of this case study was to evaluate and quantify potential spillover effects around the closed areas (MPAs) in the NSCZ.

Potential spillover effect was assessed by calculating fishing statistics around the four MPAs in the NSCZ over time from VMS and logbook data. Generalised linear mixed models (GLMs) were used to assess changes in biomass (in cumulative kilograms), fishing effort (in cumulative hours) and mean CPUE (kilograms per hour) per 0.05° c-square annually and tested (before and after the fisheries' adherence to the MPA's restrictions). The GLM accounted for distance to the nearest MPA, years since the MPA was established and the interaction between these two variables as predictor variables.

The analysis of shrimp dynamics in the NSCZ (post MPAs) did not provide conclusive evidence of fishery spillover. Overall, shrimping effort in the NSCZ decreased significantly after the MPAs were implemented, while total shrimp catch quantity remained largely unchanged. Consistently, **there was an increase in CPUE, but this was most likely due to reduced competition following buy-out proposals, rather than due to spillover effects. No significant evidence was found for an effect of MPA proximity or establishment duration on CPUE** (Figure 38). Interestingly, the observed reduced effort contradicts some assumptions found in the questionnaire, but it confirmed the consensus in the questionnaire that the chances of observing spillover in the area were low.

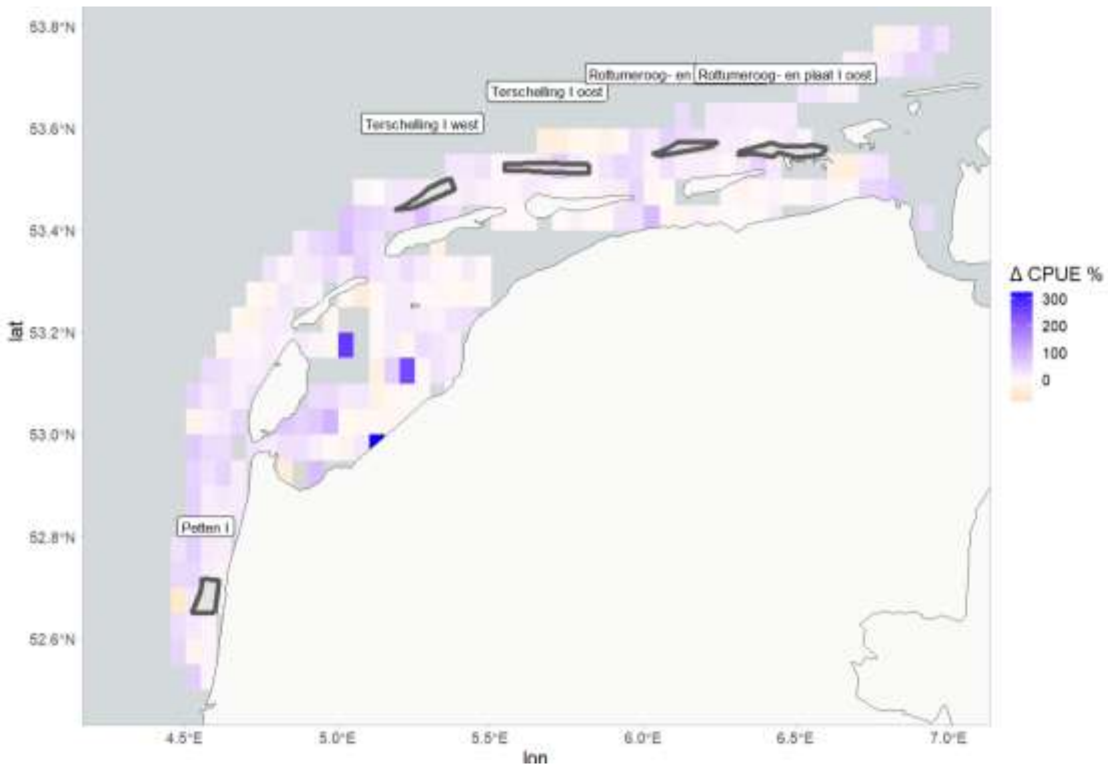


**Figure 38. CPUE change (%) in the NSCZ. This map displays the research area, with cells color-coded to represent the change in CPUE (the difference in mean CPUE per year) after establishment of MPAs in the NSCZ. Each cell is 0.05 by 0.05 degrees, totalling to approximately 16 km².**

*Borssele offshore wind farm zone (North Sea, the Netherlands)*

The Borssele wind farm zone (BWFZ) is a recently established OWF that covers 344 km² in the North Sea off the coast of the province of Zeeland, the Netherlands. It comprises two wind farms with 173 turbines and is considered in this study as an OECM. Since it has been operational in 2020, all boating and fishing activities have been prohibited within the wind farm area. This case study focuses on potential spillover effects on three species: common sole, common dab and tub gurnard.

Potential spillover effect was assessed by calculating fishing statistics around the BWFZ over time, using VMS and logbook data. GLMs were used to assess changes in biomass (in cumulative kilograms), fishing effort (in cumulative hours) or mean CPUE (kilograms per hour) per 0.05° c-square annually and tested to period (before or after establishment of the BWFZ). To examine spillover, GLMs were employed, measuring distance to the wind farm zone, years since BWFZ establishment or the interactions between these two variables as predictor variables. These variables were always put in an interactive effect with species to control for varying effects between the species.

For all species, the analysis indicated a significant reduction in total effort, total catch and CPUE after the establishment of the BWFZ, suggesting lower overall productivity. Furthermore, **no evidence for an increasing trend in biomass for the focal species in time or nearing the BWFZ boundary was found, and the slightest increase of CPUE for sole near the borders was biologically inconsequential** (Figure 39). This study suggests that the relatively recent establishment of the BWFZ may explain the absence of conspicuous spillover effects. It highlights the need for further research and monitoring to understand the long-term ecological impact of wind farms and their consequences for fisheries in similar areas.

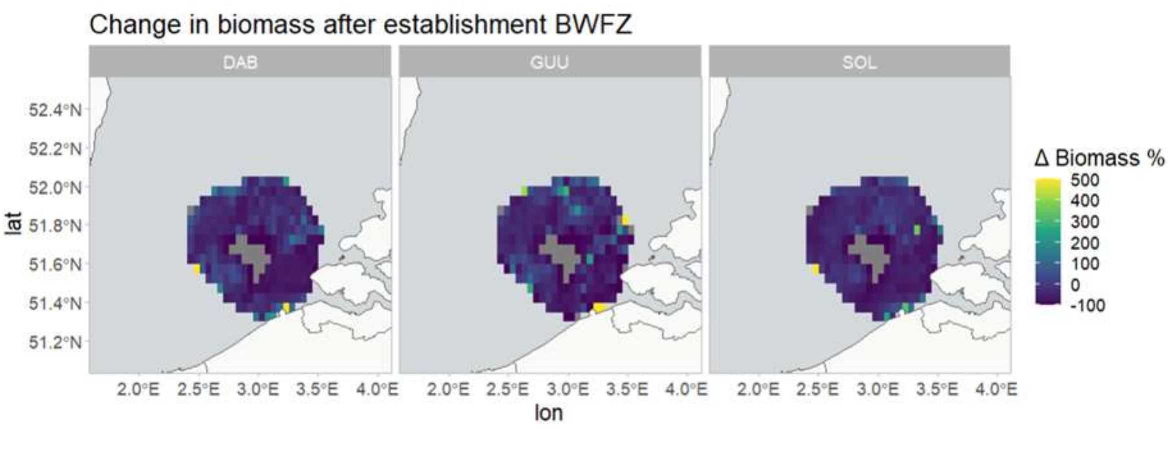


**Figure 39. Biomass Change (%) in BWFZ. This map displays the research area, with cells color-coded to represent the change in biomass percentage after the establishment of the Borssele offshore wind farm zone. Each cell is 0.05 by 0.05 degrees, totalling to approximately 16 km².**

*Belgian offshore wind farm (North Sea, Belgium)*

This Belgian case study borders the geographical focus of the Dutch case study, which is the Belgian part of the offshore wind farm (Belgian OWF, which consists of 'Belwind' and 'C-power'). The Belgian OWF zone spans 238 km² in the Belgian Exclusive Economic Zone (EEZ). It began construction in 2008 and was completed in 2020. Over the years, it has gradually been transformed into a no-fishing zone for safety reasons. This gradual shift in closure is evident in the changing fishery activities within and around the OWF zone (Verlé et al., 2023).

Besides interviews, distinct studies were conducted. The first evaluated whether the fishing patterns and catches around the Belgian OWF zone were changed, based on VMS and logbook landing data for the major commercial species, plaice and sole. It found that, while fishers adapted to the new situation, a substantial amount of fishing ground was lost. **There were significant changes in the overall effort and landings in the period after the OWF zone** (2019–2022, Figure 40). **However, no observed change could be linked to spillover.** These changes were more likely to be the result of factors like the pulse fishery ban, fuel crisis and the COVID-19 pandemic. The second study, analysed density changes in fish and epibenthic species around the OWFs, which revealed site-specific effects linked to the 'refugium effect' and 'artificial reef effect'. The third study tracked the movements of plaice within and around the Belwind part of the offshore wind farm, highlighting potential protection during the feeding season.

Overall, fishers adapted to the OWFs, but changes in effort and landings were primarily influenced by factors other than spillover effects. Potential benefits of OWFs as nursery or feeding grounds for certain species were observed. OWFs protected some species during the feeding season, although this effect diminished during spawning migrations. This study demonstrates that OWFs can offer protection and potential benefits to marine species. Larger OWF zones may be necessary to effectively mitigate impact on fishing. There is a lack of communication and understanding amongst stakeholders regarding OWFs and potential spillover effects. However, there are still uncertainties about spillover, and stakeholder perspectives vary, emphasising the need for further research and communication.

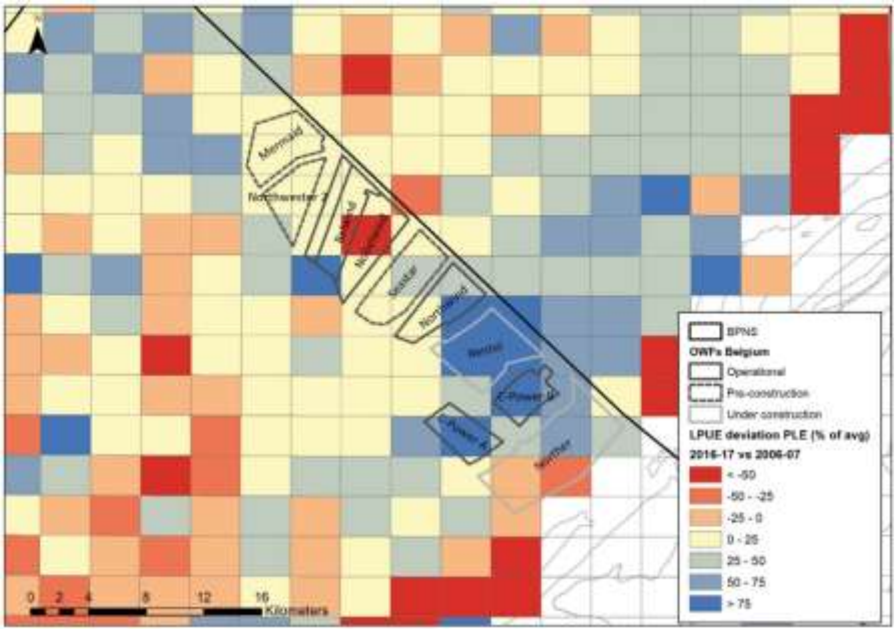


**Figure 40. Spatial changes in LPUE (Landings Per Unit Effort) for plaice based on the deviation in proportional LPUE for large Dutch and Belgian beam trawls in 2016–2017 compared to 2006–2007.**

### *Lyme Bay Marine Protected Area (The English Channel)*

The Lyme Bay MPA is a non-EU case study located in the United Kingdom. Lyme Bay (200 km²) is a protected area where mobile fishing gear has been banned for more than ten years, and other fisheries (e.g. pots, nets) are managed under a well-developed management plan. Monitoring (video based: towed cameras or baited cameras) in this area has been ongoing since 2008, and it has revealed clear recovery of the sea floor ecosystem and fish stocks (mainly crustaceans (i.e. crabs and lobsters); Pecten).

The study focuses on assessing potential spillover effects within the MPA. It takes a comprehensive approach, combining qualitative and quantitative methods to assess potential spillover effects in the marine environment. It investigates changes in fish biomass, epibenthic reef species, mobile fauna and fisher catch composition.

The study highlights the alignment between evidence obtained from the literature review and interview analysis. **While conclusive evidence of current spillover is lacking, the data suggest the potential for future spillover into adjacent fisheries over an extended period.** Changes in fish biomass within the MPA show a significant increase over time compared to unprotected sites, indicating possible spillover effects that could be detected with extended monitoring. **Stakeholder surveys also reflect a consensus that spillover likely occurs**, driven by increased species diversity and changes in fisher catch composition within the MPA. However, uncertainty exists regarding whether these changes are solely attributed to the MPA or influenced by external factors like climate change, national legislation adjustments or natural fish cycles.

The Lyme Bay MPA appears to provide benefits to both conservation and fisheries, particularly in comparison to surrounding areas open to bottom-towed gears. However, due to limited research on spillover effects, conclusive evidence is lacking. The application of the BACI approach for assessing spillover was deemed successful, primarily due to the availability of baseline data collected before and after the MPA's designation and the monitoring of reference sites outside the MPA. Future assessments should include additional reference sites positioned further from the MPA to better measure the magnitude of spillover and ensure data comparability between treatment areas.

### *Flamanville Protected Area (The English Channel, France)*

The *Zone de Cantonnement de Flamanville* is a protected marine area situated adjacent to the Flamanville nuclear power station off the northwest Coast of the Cotentin Peninsula (the Basse-Normandie region in Northern France). This protected area was established in 2000 with the backing of the Comité Régionale de la Pêche Maritime – Normandie following concerns about lobster catches (*Homarus gammarus*) declining since the 1990s (Schlaich et al. 2019). According to the legal regulations, this enforcement order prohibits all forms of 'dormant' (pots) and trawling fishing methods, with only hand lining for fish allowed. The area is classified as an IUCN Type IV (Nature Reserve) and a partially protected area (Schlaich et al. 2019), containing an inner no entry zone (1.2 km²) and de facto highly protected marine area. It is also considered as an OECM in this study.

Ecological studies on the marine environment and fisheries surrounding the site have been examined since 1975 as part of the establishment of a nuclear power plant on the coast of the municipality of Flamanville. The creation of the power plant led to a coastal area surrounding the installation to be made into a no-take marine reserve. Extensive surveys based mainly on crustacean biomass/population body size have now been undertaken. These surveys are expected to provide highly accurate models for examining the role of protection in structuring crustacean species spillover into adjacent fished areas.

**Whether spillover occurs and/or if it affects fisheries in the zone de Cantonnement de Flamanville is not clear.** While there is strong evidence to support a spillover effect on lobsters in terms of an increase in species abundance and size, this does not automatically translate to positive benefits for fishers.

Moreover, the positive effects that the protected area has on one species may be outweighed by negative impacts on others. In Flamanville, **while *H. gammarus* appear to benefit from the protection, *C. pagarus* stocks have been negatively impacted** (Figure 41). The case study also demonstrates potential impacts of seasonality, which can affect species' presence, abundance and/or activity, adding further to the clear species specificity of a protected zone.

When considering these variables, **the occurrence of spillover and whether it has an impact on fishers is somewhat fluid**. In terms of future management of protected areas, the Flamanville case study demonstrates the need to assess potential knock-on effects, which are mostly ecological, but they can lead to other socio-economic impacts. These need to be closely considered before, during and after the protected area is implemented. For example, recent news reports have highlighted problems surrounding increasing spider crab populations on mussel farms in the Manche region. While we cannot say that the protected zone in Flamanville is directly responsible for this, changes in the ecology and/or behaviour of a species can have wider effects.

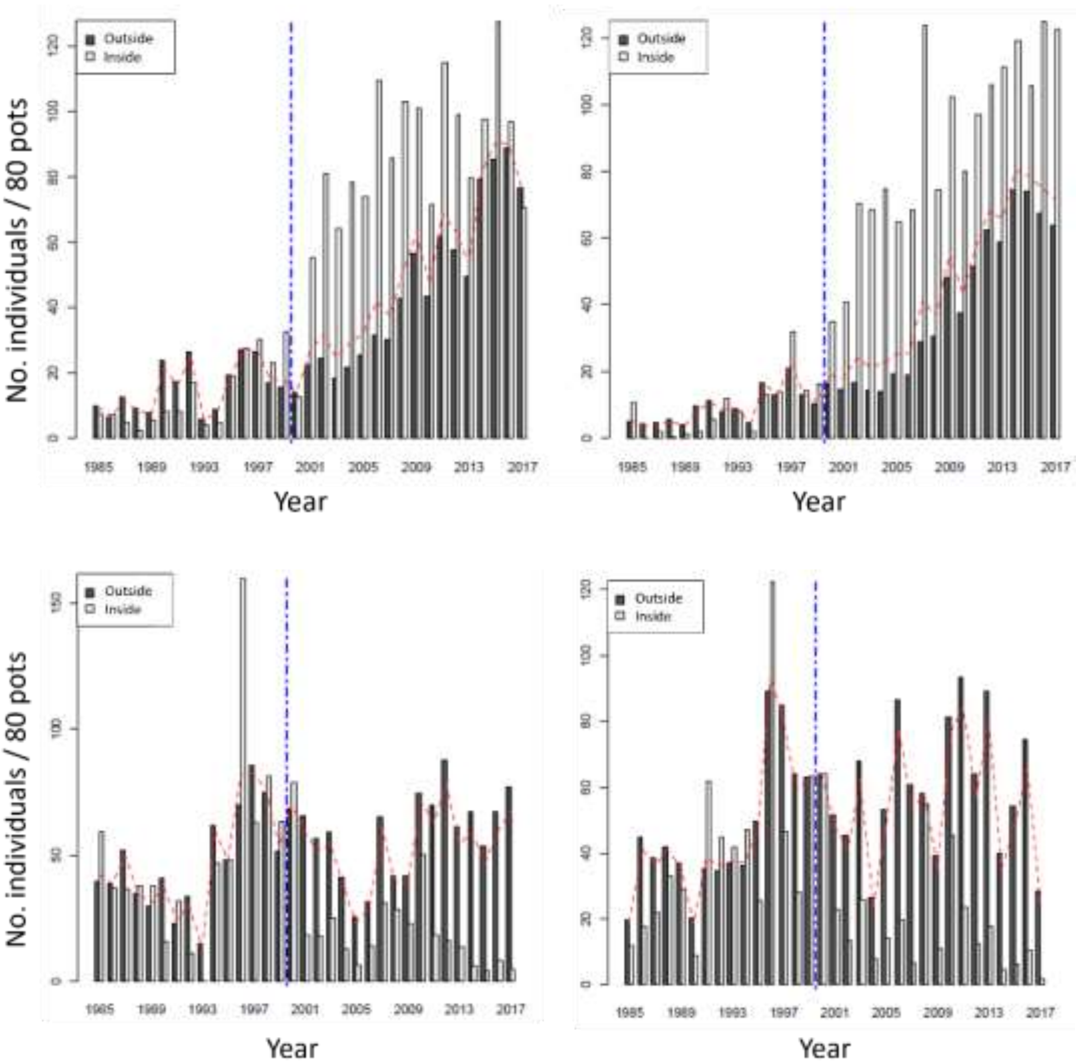


**Figure 41. Abundance (number of individuals per 80 pots) of European lobsters (*H. gammarus*) (top) and brown crab (*C. pagarus*) (bottom) between 1987 and 2017 inside and outside the protected area in June (left) and September (right). The red dotted line indicates total abundances, and the blue dotted line indicates the year of implementation of the protected area in 2000 (adapted from Le Gac et al. 2017).**

*The Écréhous and the Minquiers (The English Channel, Jersey)*

Two offshore reefs in Jersey, the Écréhous and the Minquiers, were selected as a single non-EU case study. These reefs are internationally recognised for their importance to wildlife as well as being central to local tourism and fishing industries. Both the Écréhous and the Minquiers are shallow subtidal plateaus that consist of a matrix of rocky reefs, sandbanks and intertidal areas. The Minquiers is located 18 km offshore and covers an area of around 47.5 $km^2$, while the Écréhous covers a smaller area of 15 $km^2$, roughly 9 km offshore. In 2017, both areas were closed to mobile fishing gear, although other methods of fishing (lobster pots, angling) have been unaffected by the ban. This ban is expected to have positive flow-on effects to a range of benthic dwelling fish species.

The ban was to put in place to protect sensitive biogenic habitats found at both locations, such as Seagress (*Zostera* spp.) and Maerl (*Lithothamnion* and *Phymatolithon* spp.), from mobile fishing gear (e.g. dredging and bottom trawling). Both of these have been shown to damage and disturb benthic habitats (National Research Council, 2002).

**This case study was not able to detect any direct evidence of ecological or fishery spillover.** The study's main limitations are its lack of raw data and a small body of literature on the MPAs. This is largely due to the recent designation of both MPAs. In place of quantitative analyses stakeholder surveys were carried out to gauge perceptions of both MPAs with respect to spillover. **The results from both the literature review and the stakeholder survey indicate little chance of spillover from any crustacean species.** A lack of management measures in both MPAs, despite some restrictions on parlour pot usage, have meant that populations have not increased since the designation of both MPAs. However, there was evidence of an increase in the number of lobsters below minimum landing size (MLS) at Les Écréhous, indicating that it could be a nursery for lobsters. Stakeholder perceptions typically reflected the literature on crustaceans but were largely positive that scallop catches could be increasing, partially due to the establishment of the MPAs. Stakeholders also cited a potential increase in the number of fishers targeting scallops through dredging and diving. However, no reports based on scallop surveys have been released so these claims are merely anecdotal at this stage.

This case study highlights the need for fine-scale fleet monitoring, a sound monitoring methodology that permits the BACI approach to assessing spillover and the need for strong management measures in MPAs to allow the abundance of commercial species to increase. All of these aspects are important prerequisites that are necessary to help detect spillover.

*Lamlash Bay and South Arran (Celtic Sea, Scotland, UK)*

Within the UK, Lamlash Bay and South Arran (Scotland) were selected as a non-EU case study. Arran is an island off the west coast of Scotland, situated in the Firth of Clyde. The Lamlash Bay no-take zone (NTZ) was established in 2008. This zone prohibits all types of fishing except as part of scientific surveys under Marine Scotland permits. The NTZ has been surveyed since 2010. When the South Arran MPA was established in August 2014, trawling was still allowed in most areas, but scallop dredging was completely banned in 2016. Together, these areas cover 250 $km^2$. This case study aimed to assess spillover using both qualitative data from the Scottish government and reviewing quantitative studies.

A review of the available literature and a stakeholder survey were completed to assess whether spillover occurs in the fisheries surrounding both the NTZ and the MPA. **The changes observed in commercially targeted populations after the designation of the NTZ in Lamlash Bay do not show a clear pattern**. Initially, lobster abundance increased drastically before falling to give way to lower abundance of very large and fecund individuals. This is thought to be the result of intra and inter-specific density dependence, with very large individuals driving out smaller lobsters and brown crab. Stakeholder responses from the parties involved in monitoring the reserves believe this pattern will change again. **Crustacean tagging studies showed lobsters moved both into and out of the NTZ with no significant net direction**. **It seems likely that larval export is taking place** from Lamlash Bay's NTZ (Stewart et al., 2020). This has the potential to benefit the local lobster fishery outside the reserve through spillover. **However, this has not been directly measured**. The same evidence of larval export was found for king scallops, with individuals in the NTZ and the MPA having significantly higher reproductive biomass. **Abundance of both scallops and lobsters were also negatively correlated with distance from the NTZ boundaries** (Figure 42). **This may be evidence of spillover of both populations.** However, it is difficult to tell whether this is a result of the 'halo effect' or of spillover without doing a BACI analysis (Howarth, 2014).

This study highlights the need for sound monitoring practices, ensuring a methodology that will allow the BACI approach to be used. It also highlights the complex inter and intra-specific interactions that can arise after protection is afforded to an area of seabed. Various aspects of an ecosystem need to recover before spillover of certain commercially targeted species can be observed. It appears scallop populations are able to recover faster around Arran with crustaceans taking longer. Future studies of Arran's NTZ and MPA should examine fine-scale spatial patterns of catches by the local fleet and should continue to monitor abundance, exploitable and reproductive biomass. They should also examine the fine-scale movement of individuals into and out of the reserves if possible.

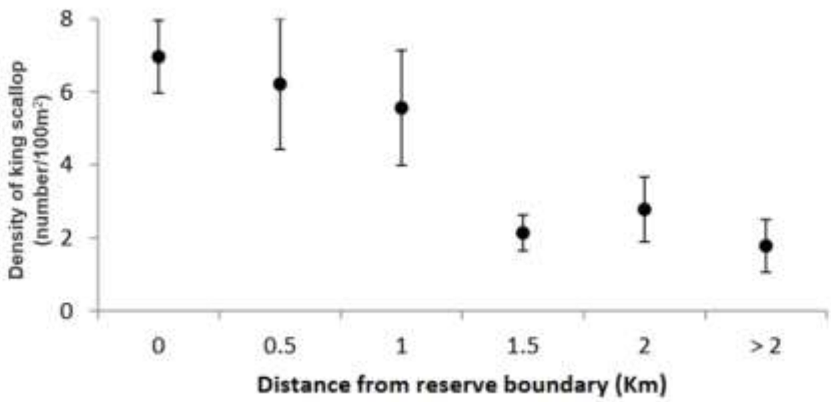


**Figure 42. Mean (±standard error) density of king scallops for the years 2010-2013 along a distance gradient from the NTZ boundary, distances of 0 represent sites located inside the NTZ boundaries (source: Howarth, 2014).**

### *Atlantic Islands National Park of Galicia (Iberian Coast, Spain mainland)*

The Atlantic Islands National Park (AINP) of Galicia, Spain, encompasses four archipelagos: Cíes, Onsa, Savora, and Cortegada (Figure 43). Recognized under Natura 2000 as Sites of Community Interest (SCI), Special Areas of Conservation (SAC), and Special Protection Areas (SPA), this group is designated a national park by the Spanish government due to its high natural and cultural value. Within this Marine Protected Area (MPA), professional fishing activities, including fishing and shellfish gathering, are permitted, but recreational fishing is prohibited.

The case study utilized both literature review and questionnaires to gather insights from local stakeholders. The literature review, which focused mainly on the Cíes archipelago, identified a scarcity of research on the MPA's ecological effects and no direct evidence of spillover effects beyond its boundaries. Two studies examined the effects of recreational fishing restrictions on trophic structure and dynamics within and outside the MPA. They found **no significant differences in the trophic structure of carnivorous fish assemblages between protected and non-protected areas**, **though one study reported a higher biomass of carnivorous fishes within the MPA**. The lack of significant differences in trophic structure suggests that it is **unlikely that there are spillover effects**, as spillover requires recovery of fish populations within the MPA to levels that allow them to move beyond its boundaries. Effective enforcement of MPAs is crucial, and the non-significant effects observed may result from the lack of restrictions on commercial fishing, which could undermine conservation outcomes.

Conservationists argue for stricter regulation of commercial fishing to protect bird populations. One small-scale fisherman, surveyed, felt that closing certain MPA areas to commercial fishing could benefit commercial fish development, noting that current measures only aid in conserving non-target species, positioning the MPA as a biodiversity conservation tool rather than a fisheries management tool. He attributed the limited recovery of fish populations in adjacent areas to reduced fishing activity, driven by the expansion of the Port of Vigo, pollution, and climate change, rather than restrictions on commercial fishing. A recent scientific assessment indicated that fishing pressure in the MPA was lower than expected, raising questions about the necessity of commercial fishing restrictions.

The literature review and stakeholder feedback highlight **limited data and high uncertainty about fishing pressure and commercial fishing impacts in the area**, underscoring the need for regular monitoring and impact assessment of fishing activities on fish stocks. Ultimately, decisions on restricting commercial fishing in the MPA will hinge on these assessments, although economic dependence on small-scale fishing in the region makes such restrictions unlikely. The review suggests that **spillover could occur and be evaluated only if commercial fishing were restricted in the MPA.**

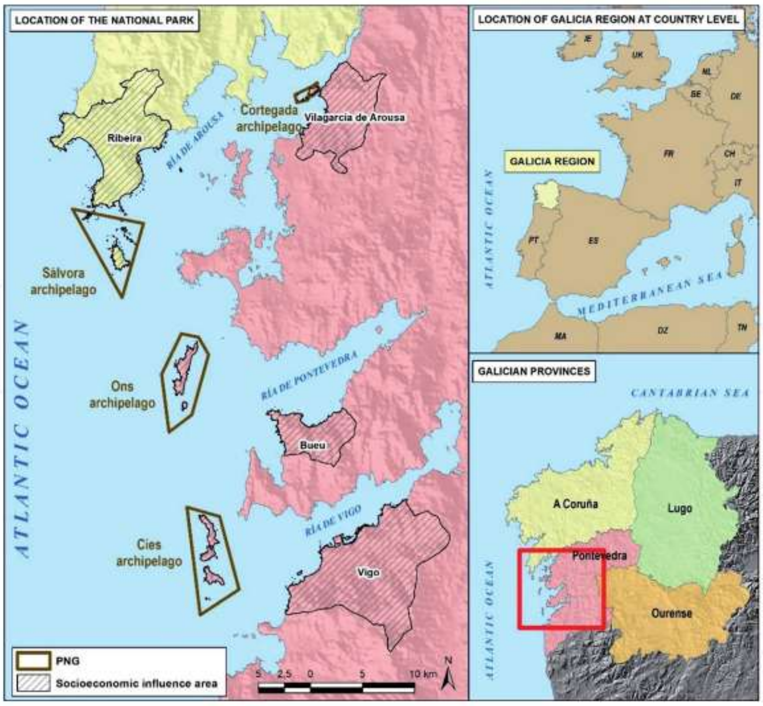


**Figure 43. Geographic location of the Atlantic Islands National Park of Galicia. PNG stands for the National Park (source: da Costa et al. 2022).**

### *Professor Luiz Saldanha Marine Park (Iberian Coast, Portugal, mainland)*

The Professor Luiz Saldanha Marine Park (PMLS) is located off the coast of Arrábida, Portugal, and is contained within the Arrábida National Park. The park stretches across 53 km², and it encompasses a 38 km section of the coastline. Arrábida's unique location makes it a biodiversity hotspot, being the northern habitat for subtropical species and the southern habitat for certain temperate species. For centuries, its rich biodiversity has been a resource for small-scale artisanal fisheries operating from the harbours of Sesimbra and Setúbal. The Natural Park of Arrábida (Parque Natural de Arrábida – PNA) was established in 1976 to safeguard one of the most significant green areas in the metropolitan region of Lisbon from escalating anthropogenic pressure and degradation. The PMLS was made fully operational by 2009 with a designated no-take zone.

In this case study, **the way well-structured MPAs can potentially promote marine biodiversity and generate positive spillover effects was demonstrated** through both reviewing the existing literature on the MPA and the stakeholder responses from researchers and governmental authorities to a questionnaire.

The actors involved in the fishing community shared their concerns about the potential socio-economic repercussions of MPAs. Although MPAs are understood to potentially enhance fish populations, there is a concurrent sentiment that they might negatively affect commercial fishing methods and the related economic dynamics. Stakeholders in the fishing community stressed the importance of creating MPA regulations with their views and needs in mind, and it highlighted issues introduced by fishing activities associated with tourism. It is understood that MPAs serve a dual purpose, functioning as conservation mechanisms and as a means of managing fisheries. However, there seems to be a divide in opinions about which role should be emphasised more. **The ecological benefits of PMLS are evident, but this area must be managed in a manner that balances both conservation needs and**

**socio-economic considerations.** Adequate monitoring is also necessary to gain a comprehensive understanding of the spillover effects of the PMLS.

*Formigas Marine Protected Area (Macaronesia, Portugal, Azores)*

The Formigas MPA, also known as the Reserva Natural dos Ilhéus das Formigas, is situated in the northeastern part of the Azores. The MPA encompasses the Formigas Islets and the Dollabarat Bank, a submerged seamount. The MPA is divided into two zones: the core zone, which includes the Formigas Islets and the surrounding waters up to a depth of 100 meters, and the buffer zone, which extends from the edge of the core zone to the outer boundary of the MPA. This case study aims to understand the potential spillover effects of the MPA in the Formigas MPA in the Azores region. It aims to achieve this through a review of the available literature and by reaching out to stakeholders involved with the MPA. It provided important insights about its potential spillover effects.

It is apparent that the Formigas MPA is a region of ecological significance. The isolation it enjoys due to its geographical and infrastructural limitations has likely contributed to its relatively lower exposure to human impacts, enabling it to maintain its distinctive ecological features. However, this protected status does not come without challenges. Studies like Afonso et al. (2011) and (2018) showcase the intricate relationship between marine reserves, fish populations, and adjacent fishing grounds. **The significance of spillover effects is acknowledged by the governmental authority stakeholder, which emphasises the role of the MPA in aiding the recovery of overexploited fish populations**. Afonso et al. (2018) highlighted that, despite its 'no-take' status, the Formigas MPA underperforms in comparison to coastal MPAs due to deficiencies in enforcement and allowances for pelagic tuna fishing. While the governmental authority stakeholder views the MPA as a dual-purpose tool for both conservation and fisheries management, other stakeholders from the fishing community adopt a more critical stance, indicating a decline in marine resources over the past decade and the need for stricter enforcement and improved protective measures. All the stakeholders agree about the need for stronger enforcement of the MPA. The significance of collaborative projects and the MPA's dual role in both conservation and fisheries management was also recognised.

Any future work would benefit from a higher participation rate among stakeholders to ensure a broader representation of perspectives. To evaluate the effectiveness of the Formigas MPA, continuous monitoring and research are imperative, given that existing studies on spillover effects within this MPA are currently limited.

*Selvagens Islands Marine Protected Area (Macaronesia, Portugal, Madeira)*

The Selvagens Islands and the nearby sea zones are situated in the North Atlantic and are an essential part of the Autonomous Region of Madeira. These islands, which mark the southern-most extent of Portugal's maritime domain, are positioned in the temperate northeast Atlantic. The natural reserve of the Selvagens Islands is bounded by the 200-metre isobath, and it includes Selvagem Grande, the Selvagem Pequena islands, Ilhéu de Fora and other smaller islets. In November 2021, its protected area expanded significantly from 95 to 2,677 km$^2$. This case study aimed to explore stakeholders' perspectives and the literature available on spillover effects in the Selvagens Islands MPA.

The perspectives obtained from the stakeholders regarding the Selvagens Islands MPA, although limited, varied significantly, highlighting several complexities and challenges associated with managing the MPA. Government officials see the MPA as a tool for conservation that could also benefit fishing through spillover effects. Fishers, on the other hand, think the MPA restricts their work. The MPA 'no take' policy has presented difficulties for the fishing community in the Madeira region, leading to scepticism about its immediate positive impact. Alternatively, the fisheries' sectors economic concerns reflect the tangible impact of these measures on local fishing communities. This point is well-supported by historical data, indicating fluctuations in landed catch over the years. The fact that the **opinions between government bodies and fishers diverged considerably** emphasises the need for comprehensive discussions on MPA management optimisation. These discussions should aim to harmoniously merge conservation initiatives with the tangible needs of local fishers.

Due to the low response rate of stakeholders, interpreting the results demands caution, especially since the insights may not fully represent all stakeholders involved in the MPA. Future research must include a broader range of perspectives, in order gain a better understanding of MPAs' impacts.

### *La Graciosa Marine Protected Area (Macaronesia, Canary Islands, Spain)*

In the Canary Islands, the Reserva marina del entorno de la isla de La Graciosa hereafter called La Graciosa MPA, was investigated. The MPA was created in 1995 to guarantee the sustainable use of fisheries and allows artisanal fishers to fish and collect shellfish in some regulated zones. Recreational fishing is also authorised if the permit is obtained from the fishing authorities. This MPA covers ~707 km², and it is one of the largest reserves in Europe. It includes a fully protected area covering 12 km², where commercial fishing has been prohibited since its inception. The MPA has had surveys undertaken in it to examine the abundance and biomass of commercial fish species, with the outputs showing a clear effect of the protection on abundance and biomass both within and outside the MPA.

This case study primarily investigates spillover effects among six fish species. The study combines findings from two research initiatives, with a primary focus on one (Brito et al., 2006) due to its comprehensive dataset. Species abundance and biomass data, to a lesser extent, were collected through underwater visual census surveys conducted before (1994) and after (2005) the MPA was established. The study analysed 11 sampling sites, comprising five within the MPA (including the fully protected area) and six outside the MPA, at distances ranging from 12 to 50 kilometres, using a BACI design (Figure 44).

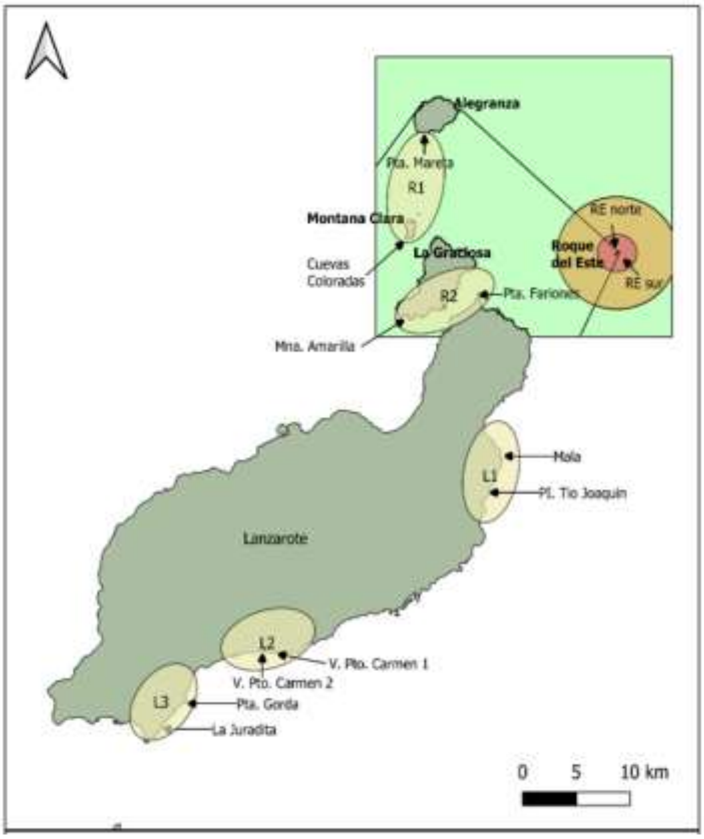


**Figure 44. Sampling sites in the La Graciosa MPA (Source: Brito et al. 2006)**

**Spillover indicators were observed for three of the six studied species after a decade of MPA protection.** Notably, two indicator species, *Sparisoma cretense* and *Serranus atricauda*, which are targeted by fishing activities, exhibited significant potential spillover effects in terms of both abundance and biomass. One non-indicator species, *Mycteroperca fusca*, indicated potential spillover effects within the reserve, focusing on abundance. Bycatch species did not exhibit significant spillover effects. Surprisingly, despite a 250% increase in abundance, *S. cretense* only showed a 2% increase in biomass, indicating complex ecological dynamics.

The study highlights the **complex and varied spillover effects among species** in the La Graciosa MPA, even among those with similar life histories and fishing exposure. Proximity to the fully protected area appears to offer the most significant benefits. To further understand and manage these dynamics, future research should expand species assessments, including biomass evaluations. Additionally, strict rule enforcement is crucial to combat poaching. Investigating fishery spillover while considering regulations and accessibility is recommended. Overall, the study underscores the need for more research and robust management strategies in the La Graciosa MPA.

**Table 11. Summary of the main outcomes for the case studies.**

| Regional Sea | MPA | Protection | Species EN | Spillover | Why? |
|---|---|---|---|---|---|
| Baltic Sea | Gotska Sandön MPA | High | Turbot & Flounder | Potentially | Larval spillover, but not consistent over time |
| | Słowinski and Wolinski National Parks | Low | Commercial fish species | No | Steady reduction in catches in the fishing squares where the parks are located. No perceptible spillover effects according to stakeholders. |
| Skagerrak | Tvedestrand MPA | High | Lobster | Potentially | CPUE increased outside MPA, but no effect of MPA proximity |
| North Sea | North Sea Coastal Zone | Moderate-High | Grey shrimp | Potentially | Increased CPUE, but reduced competition |
| | Borssele offshore wind farm zone | High | Sole, Common dab, Tub gurnard | No | No increased biomass / CPUE around the OWF |
| | Belgian offshore wind farm zone | High | Sole | No | No increased biomass / CPUE around the OWF |
| | | | Plaice | Potentially | Increased CPUE, but reduced competition |
| English Channel | Lyme Bay MPA | High | Multiple species | No | Biomass is building up only inside of the MPA |
| | Flamanville Protected Area | High | Lobster | Yes | Increase in species abundance and size around MPA |
| | | | Crab | No | Biomass lower around MPA after establishment |
| | The Écréhous and the Minquiers | Moderate | Crustaceans | No | Stakeholders indicate little chance of spillover, and no direct evidence |
| Celtic Sea | Lamlash Bay and South Arran | High | Commercial fish species | No | Changes in catches have not followed a clear pattern |
| | | | Crustaceans | No | Just as many import as export of crustaceans in MPA |
| | | | Scallops & lobsters | Yes | Higher reproductive biomass (larval export), abundances correlated with proximity of MPA, but BACI is needed |
| Iberian Coast | Atlantic Islands National Park of Galicia | Low | Nektobenthic carnivorous fish | No | Lack of comprehensive fishing restrictions in the MPA |
| | Professor Luiz Saldanha Marine Park | High | Sole, seabream and skates | Potentially | Reported movement of individuals from inside to outside of park but no reports of increased fisheries catches |
| Macaronesia | Formigas MPA | Moderate | Commercial fish species | Unclear | Conflicting views of stakeholders |
| | Selvagens Islands MPA | Low-High | Commercial fish species | Unclear | Conflicting views of stakeholders |
| | La Graciosa MPA | Moderate | Med. Parrotfish & Blacktail comber | Yes | Increased abundance and biomass around MPA |
| | | | Comb grouper | Potentially | Increased abundance in MPA, not confirmed out of MPA |
| | | | Emerald wrasse, Zebra sea bream, dreamfish | No | No changes in biomass |

## 5.5 Conclusions

Several insights were gathered in the process of collecting data and information on the case studies. First, it appeared exceptionally **challenging to source enough case studies in the regional seas surrounding Europe that had suitable data for the analysis of potential spillover effects**. The main cause for this was the quality prerequisites for the data (outlined in the advisory protocol). Second, for some case studies, it appeared that some MPAs did not enforce strict restrictive legislation for all types of fisheries, hindering them from having any protective effects, leading to the analysis of spillover effects being less relevant.

The flexibility in selecting different analytical approaches based on the data availability and diverging statistical choices led to the case studies employing a variety of methodologies to test indicators of spillover. **Half of the case studies showed indications of spillover effects**, with some demonstrating only potential spillover effects, but others concluding on the presence of spillover. **The non-uniform approach makes it challenging to attribute what shared factors have led to the absence or presence of spillover effects**.

Distinguishing between methodological limitations, capturing spillover, and establishing spillover absence is inherently complex. Even if identical statistical methods were applied, this challenge would persist. For example, if one wanted to determine the effect of location on MPAs, one would need case studies of MPAs with identical characteristics in terms of size, study periods and species focus before one could draw definitive conclusions. For such conclusions, future research should consider meta-analysis or theoretical-model-based approaches.

Several case studies have also noted the need for additional empirical validation of their results. Some case studies concluded the presence of spillover effects primarily based on an increase in CPUE, regardless of whether this increase intensified over time or exhibited proximity effects. Although CPUE increases can be informative indicators of spillover, alone, they may not be adequate to conclusively confirm the existence of these effects. It is crucial to underscore the **importance of examining these effects in relation to space and time**.

However, some **commonalities were found amongst the case studies** using a quantitative approach. For example, **fully protected areas (no-take areas) are not beneficial for all species or they do not lead to spillover for all species**. Interspecific competition between species in fully protected areas can cause this, as seen in case studies between lobsters and crab species (see Flamanville Protected Area, Lyme Bay MPA, Tvedestrand MPA). The higher or recurrence of top predators can also influence the success of commercial fish species in no-take areas (e.g. Gotska Sandön MPA). In some cases, a significant increase in abundance (sometimes temporarily) was observed, but this was less pronounced for biomass (e.g. La Graciosa MPA). The length of specimens (data only available for Crustacean species (lobster, crabs)) is largely bigger in no-take areas (e.g. Tvedestrand MPA, Flammanville Protected Area). The same is true for the case studies showing spillover potential with MPAs where the measures had been implemented for some time (e.g. Flammanville, Lamlash Bay and La Graciosa). The case studies that did not quantitatively demonstrate spillover were typically newer MPAs.

**Most stakeholders, including scientists, fisheries management authorities, eNGOs and fishers, agreed that significant ecological change takes place in the years after an MPA is implemented**. Stakeholders agreed they had observed increases in abundance, habitat complexity and functional biodiversity, with a more diverse range of species being found inside MPA than outside.

There are notable changes in fishers' catches after the MPAs were established in several case studies. However, the various **stakeholders have different perspectives on whether catches increase or decrease** following the establishment of an MPA. The consensus among the scientists and fisheries management authorities is that catches increase as a result of the MPAs, meaning they lead to positive ecological results. Fishers, on the other hand, were keen to point out the fact that MPAs reduce the size of fishing grounds and are, therefore, associated with negative economic consequences once an MPA has been designated. Accordingly, **while stakeholders acknowledge MPAs' role in biodiversity protection, fishers express concerns about the impacts of fishing restrictions on their livelihoods**.

There is **hope amongst stakeholders that MPAs can provide benefits to both biodiversity and fisheries.** Stakeholders felt that if the correct habitats that harbour exploitable stocks were protected (e.g. nursery and breeding grounds), there would be benefits to neighbouring fisheries. Accordingly, some scientists stated that protected areas would be of most benefit where sensitive habitats were present, such as maerl beds.

While fishing in MPAs is still allowed, stakeholders favoured the use of lower impact fishing methods such as static gear. Some MPAs lack a comprehensive management plan. There are also overarching challenges in the practical implementation, monitoring and enforcement of MPA regulations. The practical implementation of regulations in MPAs is also an ongoing challenge. Effective enforcement, compliance and monitoring is needed to realise the full benefits of MPAs.

There are different perspectives on the presence and absence of spillover in the case study MPAs, even within the same stakeholder groups. For instance, some scientists stated that there is a high likelihood of spillover occurring while others stated that they had not seen concrete evidence of spillover. Similarly, some fishers were sceptical of MPAs' effects on spillover for commercial stocks, with some citing a lack of proper management of the MPAs. **Spillover effects, which are often a major focal point when discussing how MPAs affect local fisheries, are therefore still a topic of debate amongst the stakeholders.** This in part is due to the lack of appropriate data in several cases for detecting spillover.

To conclude, the case studies demonstrate that **MPAs can lead to increased spillover of species, but the patterns will be species-specific, and spillover effects will take a relatively long time to be relevant for fisheries**. The dynamics of spillover and fisheries around MPA borders and the interaction between protection time with other fishery management tools needs to be investigated further. Future work also needs to use data that has been rigorously collected from a diverse range of habitats and commercial species with spillover in mind i.e. data purposely collected to test spillover effect. This work will be vital in developing sustainable fisheries and enhancing the conservation of marine resources.

## 6 LESSONS LEARNT AND RECOMMENDATIONS

The overall goal of this study was to assemble existing information and collect new data to provide an overview of the role that the MPAs may play for local fisheries through spillover effects. Scientific insights were gathered and refined through a systematic literature review, a meta-analysis, the development of a conceptual model tool and the analysis of case studies, through the application of qualitative and quantitative approaches. The findings and conclusions derived from the various analyses covered in this study, were discussed and presented at the end of each section of the report (sections 1 to 5). This section provides a synthesis of the key lessons learnt and recommendations.

This study documents the first systematic review of empirical evidence for spillover from MPAs in the EU and other temperate regions. Although evidence is relatively sparse, this study shows that **there is evidence for spillover from MPAs to adjacent waters**. The meta-analysis of the various factors related to MPA characteristics and species traits has shown a number of emergent patterns in relation to spillover effects. Some identified drivers for spillover are the combination of MPA characteristics: its age, local context (i.e. island versus estuary), and whether it is part of a network. Relevant species traits for spillover are species mobility (free swimming versus sessile or walking) and reproductive strategies (broadcasts spawners versus brooders). These findings indicate under which conditions ecological spillover may be expected, allowing stakeholders to develop sound strategies when designing an MPA, where spillover is an objective. The identification of these drivers and their relative contribution should be further developed once more empirically based knowledge becomes available.

Although the scientific knowledge on spillover increased substantially in this study, future research is needed. The main recommendations for future spillover research are:

- To better **understand the drivers of spillover**, future research should be based on larger datasets related to the outcomes of studies on spillover, including negative results. No detections of spillover are more difficult to get through the peer review process for scientific publications. Therefore, researchers and publishers should be encouraged to report results where spillover is investigated but not detected. This demands that further field studies are both promoted and undertaken and then published in the primary literature, regardless of the results. This can be overcome with more investment in this type of research, data collection in the field and development of activities for this specific purpose.
- More information on the **magnitude and scale of spillover** is needed. Therefore, empirical studies should start quantifying magnitudes (the export of numbers of individuals or biomass), and the temporal frequency and spatial scale (distance of effect) with which spillover occur. Only when the magnitude and scale of spillover can be determined, its value to fisheries (monetarily) and conservation (in terms of population dynamics) can be quantified.
- There is a need to investigate a **broader range of protection levels** in MPAs. Our analyses were limited to aggregated levels of protection status, based primarily on authors' choices in reporting. In addition, other study areas where fishing activities are excluded could be used, such as 'other effective area-based conservation measures' (OECMs), including offshore windfarms (OWFs).
- There is also a need for further emphasis on using data that have been rigorously collected from a **diverse range of habitats and commercial species**, as well as determining the **level of juvenile and sub-adult spillover**. The aim would

be to quantify the level of this spillover from protected juvenile habitats (i.e. all of those habitats used specifically by juvenile stages of a given species) into both unprotected and protected adult habitats.

- To better understand the relationship between (changes in) fishing activities and spillover, more knowledge is needed on **fishing activities inside and outside MPAs** with a distance gradient. To this end, more data are needed on effort, catch and Catch Per Unit of Effort inside the protected area and outside, with varying distances to the protected area. Ideally, also data on size and sex of caught specimen would be collected.
- It would be beneficial to **distinguish ecological and fishery spillover**. One of the purposes of this study was to enhance scientific understanding regarding ecological and fishery spillover. However, due to the limited availability of studies and underlying data, this distinction could not be thoroughly explored. Nevertheless, making this differentiation would be valuable; there is a need to operatively distinguish the ecological versus the fishery components of spillover (Di Lorenzo et al., 2016). Fishery spillover is the main component of MPAs that can provide direct benefit to local fisheries. It could serve as an incentive for the fishing sector, potentially offsetting the impact of fishery restrictions. Being able to predict and quantify fishery spillover more thoroughly would help in the dialogue among stakeholders.
- Perspectives on absence or presence of spillover varies between stakeholders, sometimes even within stakeholder groups. This difference in perspective may be partly due to the lack of appropriate data or to a shortcoming in knowledge about what spillover is. This challenge of **varying perspectives on absence or presence of spillover** can be overcome by the development of knowledge about spillover, on the one hand by more data collection (see bullet points above) and on the other hand by raising awareness on spillover effects and benefits. The SPILLEST conceptual model developed in this study may be a tool that can be used in the dialogue between stakeholders, when discussing drivers for spillover or designation of MPAs.

For future investigations, the following steps are essential when investigating spillover, as outlined in more details in the methodological evaluation (Section 3) and the 'advisory protocol' (Annex 5):

- For **monitoring (data collection)**: it is important to use a BACI design with a distance gradient sampling scheme that is integrated over time when implementing an MPA. When feasible for data collection, it is advisable to use a combination of traditional (biological) sampling and tagging studies, as it provides a much more complete picture of potential spillover effects. Also, it is worth to assess different response variables simultaneously in the same investigation (e.g. abundance, biomass, reproductive index). Nevertheless, the ideal sampling method should address the research question being asked and be adapted to the species of interest and the MPA site characteristics.
- For **assessing spillover (data analyses)**: the ideal data analysis method is largely dependent on the sampling design, method and data availability. Therefore, it is important to take into account spatial and temporal ranges, the number of observations, MPA characteristics (MPA age, MPA ecological objective), species characteristics (exploitation history, local importance in terms of exploitation, mobility and reproductive strategies), potential population-level effects and fisheries' response to the MPA. Some more detailed guidance for future assessments by scientists and MPA managers is given in the 'advisory protocol', developed as part of this study.

Despite the limited empirical evidence on spillover in many cases, it has been evidenced that there is hope amongst stakeholders to perceive MPAs as potentially providing benefits to both conservation and fisheries. The SPILLEST conceptual model tool, developed in this study, can be utilized to assess the likelihood of spillover in existing and proposed MPAs. It enables users to explore various MPA configurations and their potential contribution to spillover. Stakeholders can gain insight into whether specific features driving spillover should be incorporated into conservation objectives and management plans, especially where fishing activities are present. In the future, as the knowledge base on spillover improves, the tool can be updated accordingly. The tool could notably widen its scope to accommodate a distinction between ecological and fishery spillover which would provide a more precise indication of the benefits to local fisheries.

Finally, this work provides several elements that could **guide strategies to enhance local fishery management using MPAs**. With the targets of the EU biodiversity strategy, where of 30% of the EU's seas should be legally protected by 2030, it is vital to have a better understanding of mechanisms behind MPA spillover and what the conditions are for spillover to benefit fisheries.

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# ANNEX 1: THE PROTOCOL FOR A SYSTEMTATIC REVIEW

## Introduction

### Rationale

Marine protected areas (MPA) have become a highly prioritised management measure in European efforts to improve marine biodiversity, restore marine habitats, and protect threatened species. While restrictions on human activities within MPAs vary greatly both between and within Nation States, the MPA designation often provides the legal definition of a space to which further regulations can be imposed. Many of these regulations restrict fishing activities by banning certain gear types or practices, or excluding fisheries completely. The restrictions that are imposed often depend on the objectives of the MPA, however, fishers and their communities often react to the proposal of MPAs as reduction in the space available to them to extract their resource. There is evidence that the protection of certain habitats and species there-in may lead to net benefits to local fisheries via the "spillover" of individuals from within the MPA to fishable areas, either in the form of increased recruitment of juveniles from adults reproducing within the MPA, or in the form of direct export of fishable biomass from the MPA. The evidence for these benefits of MPAs to fisheries are ambiguous and often only addressed at small local scales in narrow contexts.

### Objectives

The primary objective of this systematic review is to collate evidence of where and when spillover can and cannot be detected from European MPAs, together with information on the ecological context in which it is being measured. Ultimately, this review be combined with information, collected independently, on EU MPAs and these data will be utilised in a meta-analysis of the conditions in which "spillover" from MPAs can be expected. When not enough literature of EU MPAs is available, the scope is enlarged to MPA studies of other temperate regions (excluding tropics).

A secondary objective of this review is to document, categorise and characterise all of the methods that are employed in studies trying to detect or quantify spillover from MPAs. These data on methodologies will be used to deduce best practice and cost-benefit trade-offs for future studies planning to investigate spillover from MPAs.

## Methods

Review of literature has been undertaken according to the PRISMA Eco-Evo approach (O'Dea et al., 2021).

### Eligibility Criteria

Primary literature (peer reviewed) documenting empirical investigations of spillover will be the main focus of this review. Grey literature and unpublished studies (such as PhD theses and local reports) will be considered where they are available to project participants. Primary literature will be restricted to those articles published in English, while grey literature from various languages will be considered eligible where project participants can translate results into English for the data extraction phase.

### Information Sources

For academic articles, both Scopus (https://www.scopus.com/home.uri) and Web of Science (www.webofscience.com) indexing databases will be searched. For grey literature, project partners are expected to investigate the local sources available to them.

**Search Strategies**

Academic articles

Searches for academic articles will employ a combination of four clusters of search terms joined internally by "OR" operators and joined together using the "AND" operator. The four clusters are organised into themes of "Context", "Location", "MPA", and "Spillover". These search terms will be searched for within the fields "Title-Abs-Key", from Scopus and within the fields "TI", "AB" and "AK", from Web of Science. The Web of Science fields intentionally excludes the "Keyword plus" and "Topic Search" fields (of which the latter includes the former), because of the opaque method used to algorithmically augment keywords based on those provided in the search string.

**Table 12. Overview of keywords for the search strategy.**

** can be added to words (when undertaking a literature database search) to infer that a letter or several letters could be added in its place; $ can be added to a word to infer a gap between letters or a hyphen could be placed within that word.*

| Context | Location | MPA | Spillover |
|---|---|---|---|
| Marine | Algeria | Marine Protected Area | Spillover |
| Oceanic | Argentina | MPA | Spill*over |
| Sea | Australia | Marine Reserve | Dispers* |
| Estuarine | Azores | Protected Area | Migrat* |
| Coastal | Baltic Sea | Reserve | Export |
| Brackish | Bay of Biscay | Natura$2000 | Overflow |
| | Belgium | National park | Recruitment subsid* |
| | Canary Islands | Natural monument | |
| | Celtic Sea | Marine park | |
| | Chile | No$take zone | |
| | China | Fish* clos* | |
| | Denmark | Ntz | |
| | England | | |
| | English Channel | | |
| | Estonia | | |
| | Finland | | |
| | France | | |
| | Germany | | |
| | Greenland | | |
| | Iceland | | |
| | Iran | | |
| | Ireland | | |
| | Irish Sea | | |
| | Japan | | |
| | Korea | | |
| | Latvia | | |
| | Libya | | |
| | Lithuania | | |

| Context | Location | MPA | Spillover |
|---|---|---|---|
| | Madeira | | |
| | Mexico | | |
| | Morocco | | |
| | New Zealand | | |
| | North America* | | |
| | North Sea | | |
| | Norway | | |
| | Poland | | |
| | Portugal | | |
| | Russia | | |
| | Saudi Arabia | | |
| | Scotland | | |
| | Spain | | |
| | Sweden | | |
| | temperate | | |
| | The Netherlands | | |
| | The United Kingdom | | |
| | Tunisia | | |
| | Turkey | | |
| | United Arab Emirates | | |
| | Uruguay | | |
| | Wales | | |
| | Western Waters | | |

Grey literature

Searches of grey literature should be made by individual project partners, within the institutional databases available to them. While the search term structure will not necessarily match that employed in the primary literature search, searches should fall within the terms defined above.

**Study records**

Downloading Records

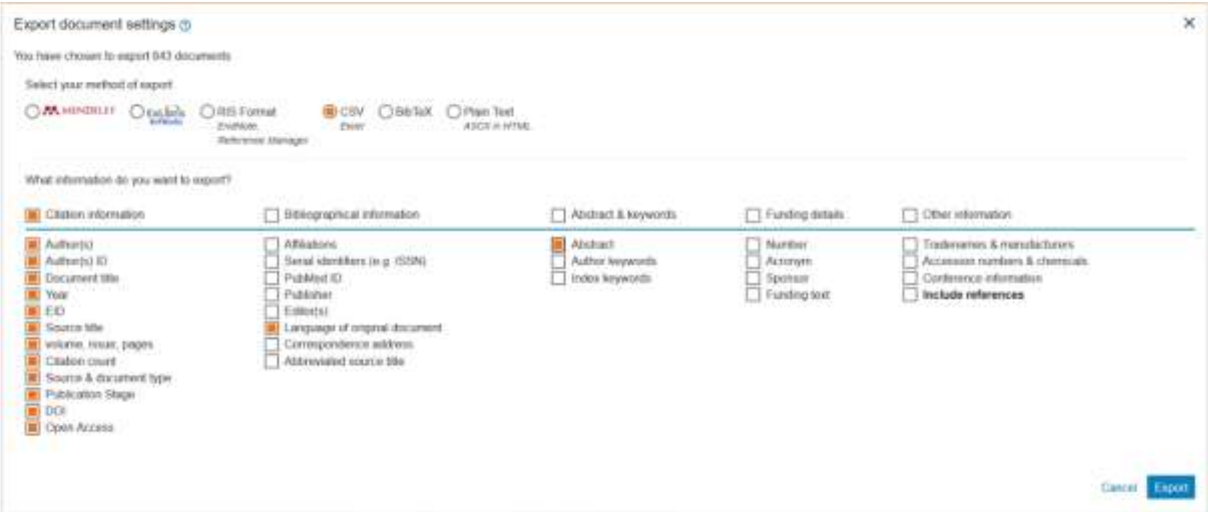
This record management strategy is adopted from the Horizon 2020 project SEAwise (Deliverable Report 1.1). The first step in record management is to coordinate searches across different sources, download the records' metadata, and de-duplicate records.

*Scopus*

To collect all records from Scopus:

Check the "All" box at the top of the search results, to make the "Export" link available.


In the export option, select "CSV" as the format, and ensure both "Language" and "Abstract" boxes are checked in addition to the default citation information.



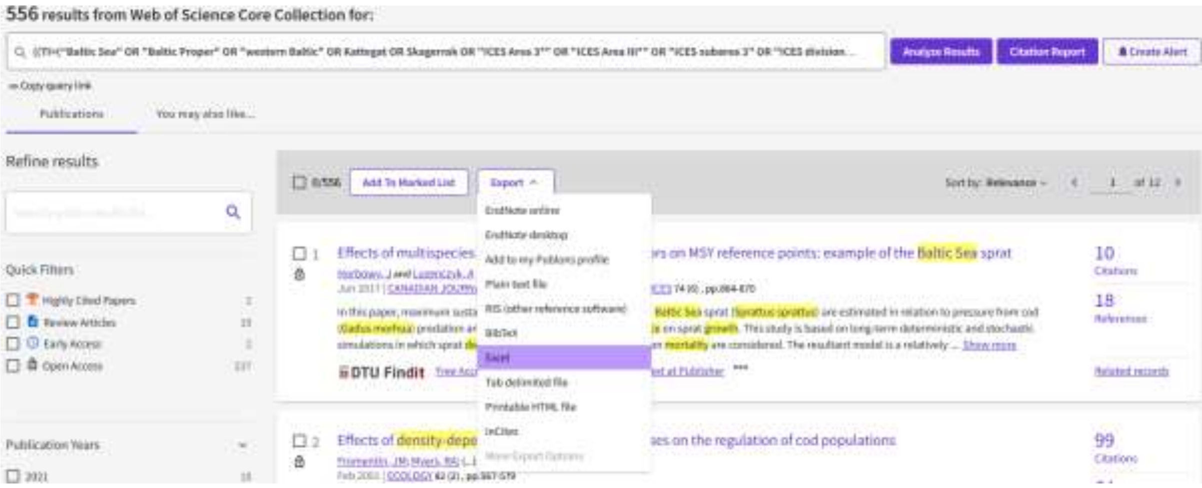

Select export to download the comma separated file containing all records and save it with an appropriate name (e.g. "Spillover_Scopus_20230130.csv").

*Web of Science*

To collect all records from Web of Science:

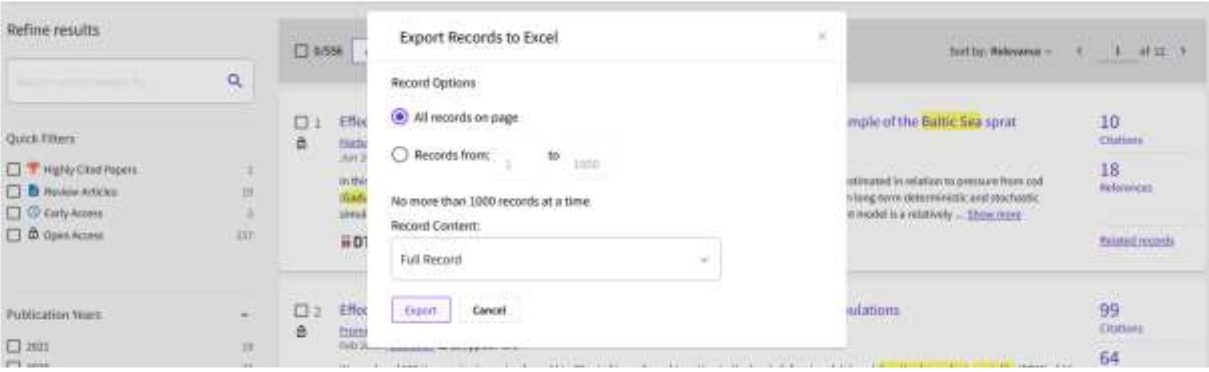
Do NOT select the check-box at the top of the search results indicating selecting all records.

Select "Export" and then choose "Excel" from the drop-down menu.



Select "Records from: 1 to 1000".

From the "Record Content" dropdown menu select "Full Record", then click "Export".




Save the .xls file with an appropriate name (e.g. "Spillover_WoS_20230130.xls").

**Merging and De-duplicating Records**

<u>Academic records</u>

The below R-script can be used to merge and de-duplicate records from Scopus and Web of Science searches.

```
#===
# Packages and Dependencies
#====
# install.packages("xlsx")
library(xlsx)
#=====

#===
# Read in Records - Change filenames and directories to match your own
circumstances
#====
spill_sco <- read.csv(file = " Spillover_Scopus_20230130.csv", header =
TRUE)
spill_wos <- read.xlsx(file = " Spillover_WoS_20230130.xls", header =
TRUE, sheetIndex = 1)
#=====

#===
# Reformat and simplify Scopus Record format
#====
colnames(spill_sco)[colnames(spill_sco) == "ï..Authors"] <- "Authors"
colnames(spill_sco)[colnames(spill_sco) ==
"Language.of.Original.Document"] <- "Language"
colnames(spill_sco)[colnames(spill_sco) == "Source"] <- "Database"
spill_sco[, c("Author.s..ID", "Art..No.", "Page.count", "Cited.by",
"Publication.Stage", "EID", "Link")] <- NULL
#=====

#===
# Convert WoS record format to Scopus Record format (and remove extra
fields)
#====
colnames(spill_wos)[colnames(spill_wos) == "Article.Title"] <- "Title"
colnames(spill_wos)[colnames(spill_wos) == "Source.Title"] <-
"Source.title"
colnames(spill_wos)[colnames(spill_wos) == "Start.Page"] <- "Page.start"
colnames(spill_wos)[colnames(spill_wos) == "End.Page"] <- "Page.end"
colnames(spill_wos)[colnames(spill_wos) == "Open.Access.Designations"] <-
"Open.Access"
colnames(spill_wos)[colnames(spill_wos) == "Publication.Year"] <- "Year"
spill_wos$Database <- as.character(rep_len("Web of Science",
nrow(spill_wos)))
spill_wos <- spill_wos[, c(colnames(spill_wos)[colnames(spill_wos) %in%
colnames(spill_sco)])]
#=====

#===
# Merge all records and delete duplicates
#====
all <- rbind(spill_sco, spill_wos)
dedup <- all[!duplicated(all$DOI) | all$DOI == "", ]
dedup <- dedup[!duplicated(dedup$Title), ]
#=====

#===
# Assign unique identifier to all records
#====
dedup$MF_ID <- paste0("SPILLOVER", "_", formatC(1:nrow(dedup), width = 3,
format = "d", flag = "0"))
#====
```

Grey literature

Metadata from grey literature searches should be entered into the above merge and deduplication procedure according to the metadata that is available.

Upon final collation and de-duplication all records will be given a unique ID consisting of the project abbreviation and a three digit unique integer, each separated by an underscore, i.e.: "SPILLOVER" + "_"+ [unique number of three digits] (e.g. "SPILLOVER_001").

### Selection and Screening

Once collated and de-duplicated, the academic records' titles and abstracts will be screened to exclude those that match the pre-defined exclusion criteria outlined below. Due to resource constraints a single individual will be responsible for screening within this case study review. This provides consistency but does not account for bias. The geographic exclusion criteria will allow for post-screening review of the number of records and to potentially increase the scope of the review as necessary.

**Table 13. Overview of the exclusion criteria.**

| Criteria Symbols | Exclusion Criteria | Explanation |
|---|---|---|
| Retain | NA | No reason defined for excluding the article based on this level of search |
| A | Not trying to document spillover | The aims or purpose of the study are not to document spillover, in any form, from an MPA to unprotected marine areas. |
| B | Theoretical modelling study | Study does not use any empirical observations of spillover but implies spillover via theoretical dispersal models. |
| C | Outside geographic limits 1 | Study outside of the consortium scope (European waters excluding the Black Sea, Mediterranean and distant outermost regions) |
| D | Outside geographic limits 2 | Study outside of European waters |
| E | Outside geographic limits 3 | Study outside of the Atlantic / Atlantic Southern Ocean / Atlantic Arctic |
| F | Not Temperate | Study is based in tropical or polar clines. |
| G | Review | Study is a review without introducing any new observations |
| H | Not Fish | Study is not documenting spillover of fish (teleost or cartilaginous), crustaceans or molluscs (e.g. mammals, birds, or reptiles) |

### Data Collection

Data Items

The information to be collated is in four broad categories, namely bibliographic information, standard extraction, methodology, and documenting spillover. Should the review consider studies in MPAs outside of the MAPAFISH database, then an extra category of information on MPA Characteristics should also be filled in. The bibliographic information, comes primarily from the downloads of records from databases but is to be supplemented by records from grey literature sources. Standard extraction fields should be extracted from all records. The methodology section of data is in support of the SPILLOVER study's Task 3 (Section3), while the "documenting spillover" category is in support of Tasks 1 and 2 (Sections 1 and 2). The data in the final, contingent category "MPA characteristics", are limited to data in the MAPAFISH database and what might reasonably be expected to be included in an introduction/method for a study of spillover. The specific fields of information to be extracted are listed in the table below. Many of which are limited to a set of responses, and some of which are free text. A descriptive explanation of what should precisely be extracted is included in the extraction form.

**Table 14. Data extraction scheme: overview of the fields to be documented in the literature review.**

| Bibliographic data | Standard extraction | Methodology | Documenting spillover | MPA characteristics (contingent) |
|---|---|---|---|---|
| MF ID | Exclusion Criteria | Spillover Response | Spillover Detected? | MPA Size (square kilometers) |
| Authors | MPA Name | Year of Field Study Observations | Type of Spillover Investigated | Dominant Habitat |
| Title | Country of MPA | Quarter of Field Observations | Spillover Mechanism | Part of Designed Network? |
| Year | MAPAFISH SITECODE | Methodology to Assess Spillover | Maximum Distance from MPA border, Spillover was Detected (km) | MPA Age @study time |
| Source title | Species Investigated | Sampling Design | Maximum Distance from MPA border Spillover was Investigated (km) | Protection Level (one protection level per row, if independently assessed) |
| Volume | | Evidence Gathered | Estimated Annual amount of Spillover | Fisheries Regulation Level (one regulation level per row, if independently assessed) |
| Issue | | Data Utilised | Units of estimated spillover (kg / number) | Combined Fully Protected and Partially Protected Complex? |
| Page start | | Scale of Application (spatial) | Is spillover of commercial relevance? | MPA Context |
| Page end | | Statistical Methods | Is spillover of recreational importance? | |

| | | | | |
|---|---|---|---|---|
| DOI | | Skills and Expertise required | Estimated Value of Spillover to Commercial Fisheries (local currency value) | |
| Link | | | Estimated value of Spillover to Recreational Fisheries (local currency value) | |
| Abstract | | | Estimated Value of Spillover to other Industries (local currency value) | |
| Language | | | Currency Reported | |
| Document Type | | | Year in which values are reported | |
| Open Access | | | Spillover connectivity to other MPAs? | |
| Database | | | Temporal Patterns of Spillover | |
| | | | Frequency | |

Procedure

Extractions of data from academic articles will be split between two people. The bibliographic information will be populated as a result of the search and de-duplication procedure. The "standard extraction", the "documenting spillover" and, if necessary, the "MPA characteristics" sections will be extracted by one person, while the "methodology" section will be extracted by one other person. The same individual will complete all extractions within each data field, which will ensure consistent interpretations and use of extraction fields.

The first step is to find and download the full-text record, and save this with a filename matching the "SPILLOVER_ID" assigned to the record. During the extraction, the details of the full text will be considered against the exclusion criteria once again, and the result of this consideration is recorded in the extraction form.

## Data Synthesis

### Risks of biases and meta-biases

A key risk for bias in this study will be the small number of articles we expect to retain through our search and screening, which will magnify publication bias (only significant effects published). Another bias will be the focus on commercially relevant species, due to the availability of data from fisheries reports or fisheries monitoring/surveys. The first risk can only be addressed and evaluated, subsequent to data extraction, at the beginning of analysis. Because this study is particularly interested in the impacts of spillover on fishing, the second bias is of less consequence, however, comparisons between species should be made only with specific reference to this bias.

**Meta-analyses and synthesis**

There are three purposes to this review. The first is to collate investigations into the presence and mechanism of spillover from MPAs in the EU and other temperate regions, and this goal does not require any meta-analyses.

The second goal is to investigate the characteristics and contexts in which spillover from MPAs occurs. To investigate this, we will combine the results of our review with a catalogue of MPA characteristics and publicly available data on species traits and attempt to correlate the presence/extent of spillover to these characteristics, as well as considering the different types of fishing activities or the different levels of effort (as available).

Initial analyses will involve dimensionality reduction (e.g. principal component analyses or correspondence analysis) applied to the impact group, in order to identify shared characteristics of MPAs with documented spillover. Subsequent methods will be dependent on data availability but may include logistic regression of impact and non-impact groups with spillover presence/absence as the response and variables identified in the dimensionality reduction as explanatory variables.

These comparisons will allow the detection of various features that are more or less prevalent in cases where spillover is present or not detectable compared to the studies average.

Furthermore, the species reported on, in cases where detecting spillover was the goal of the study, will be compiled and key morphological (e.g. tail profile), or life-history (e.g. egg habit and duration) traits will be gathered from publicly available databases (e.g. FishBase). A cluster analysis of traits will be used to compare species for which spillover has or has not been detected, to determine any common traits supporting fishery spillover.

Finally, the third goal of this review is to catalogue the methods used in various attempts to detect and quantify spillover in the field. This goal, like the first, does not require any meta-analyses, only an aggregation of methods and some collation of authors' own perceptions of their methods strengths and limitations, as well as the potential support for such methods from the literature.

# ANNEX 2: SELECTED LITERATURE FOR DATA EXTRACTION AND ANALYSES


Afonso, Pedro, Abecasis, D., Santos, R. S., & Fontes, J. (2016). Contrasting movements and residency of two serranids in a small Macaronesian MPA. Fisheries Research, 177, 59–70. doi:10.1016/j.fishres.2015.12.014

Afonso, Pedro, Fontes, J., Guedes, R., Tempera, F., Holland, K. N., & Santos, R. S. (2009). A multi-scale study of red porgy movements and habitat use, and its application to the design of marine reserve networks. In Reviews: Methods and Technologies in Fish Biology and Fisheries (pp. 423–443). doi:10.1007/978-1-4020-9640-2_25

Afonso, P., Fontes, J., Holland, K. N., & Santos, R. S. (2008). Social status determines behaviour and habitat usage in a temperate parrotfish: implications for marine reserve design. Marine Ecology Progress Series, 359, 215–227. doi:10.3354/meps07272

Afonso, Pedro, Fontes, J., & Santos, R. S. (2011). Small marine reserves can offer long term protection to an endangered fish. Biological Conservation, 144(11), 2739–2744. doi:10.1016/j.biocon.2011.07.028

Attwood, C. G., & Bennett, B. A. (1994). Variation in dispersal of galjoen (Coracinus capensis) (teleostei: Coracinidae) from a marine reserve. Canadian Journal of Fisheries and Aquatic Sciences, 51(6), 1247–1257. doi:10.1139/f94-124

Barrett, N., Buxton, C., & Gardner, C. (2009). Rock lobster movement patterns and population structure within a Tasmanian Marine Protected Area inform fishery and conservation management. Marine & Freshwater Research, 60(5), 417. doi:10.1071/mf07154

Beukers-Stewart, B. D., Vause, B. J., Mosley, M. W. J., Rossetti, H. L., & Brand, A. R. (2005). Benefits of closed area protection for a population of scallops. Marine Ecology Progress Series, 298, 189–204. doi:10.3354/meps298189

Brouwer, S. L., Griffiths, M. H., & Roberts, M. J. (2003). Adult movement and larval dispersal ofArgyrozona argyrozona(Pisces: Sparidae) from a temperate marine protected area. African Journal of Marine Science, 25(1), 395–402. doi:10.2989/18142320309504028

Boulcott, P., Stirling, D., Clarke, J., & Wright, P. J. (2018). Estimating fishery effects in a marine protected area: Lamlash Bay. Aquatic Conservation: Marine and Freshwater Ecosystems, 28(4), 840–849. doi:10.1002/aqc.2903

Cole, R. G., Villouta, E., & Davidson, R. J. (2000). Direct evidence of limited dispersal of the reef fishParapercis colias (Pinguipedidae) within a marine reserve and adjacent fished areas. Aquatic Conservation: Marine and Freshwater Ecosystems, 10(6), 421–436. doi:10.1002/1099-0755(200011/12)10:6<421::aid-aqc423>3.0.co;2-e

Crec'hriou, R., Alemany, F., Roussel, E., Chassanite, A., Marinaro, J. Y., Mader, J., … Planes, S. (2010). Fisheries replenishment of early life taxa: potential export of fish eggs and larvae from a temperate marine protected area. Fisheries Oceanography, 19(2), 135–150. doi:10.1111/j.1365-2419.2010.00533.x

de Pontual, H., Lalire, M., Fablet, R., Laspougeas, C., Garren, F., Martin, S., … Woillez, M. (2019). New insights into behavioural ecology of European seabass off the West Coast of France: implications at local and population scales. ICES Journal of Marine Science: Journal Du Conseil, 76(2), 501–515. doi:10.1093/icesjms/fsy086

Díaz, D., Mallol, S., Parma, A. M., & Goñi, R. (2011). Decadal trend in lobster reproductive output from a temperate marine protected area. Marine Ecology Progress Series, 433, 149–157. doi:10.3354/meps09182

Félix-Hackradt, F. C., Hackradt, C. W., Treviño-Otón, J., Pérez-Ruzafa, Á., & García-Charton, J. A. (2018). Effect of marine protected areas on distinct fish life-history stages. Marine Environmental Research, 140, 200–209. doi:10.1016/j.marenvres.2018.06.012

Follesa, M. C., Cannas, R., Cau, A., Cuccu, D., Gastoni, A., Ortu, A., … Cau, A. (2011). Spillover effects of a Mediterranean marine protected area on the European spiny lobster Palinurus elephas (Fabricius, 1787) resource. Aquatic Conservation: Marine and Freshwater Ecosystems, 21(6), 564–572. doi:10.1002/aqc.1213

Forcada, Aitor, Bayle-Sempere, J. T., Valle, C., & Sánchez-Jerez, P. (2008). Habitat continuity effects on gradients of fish biomass across marine protected area boundaries. Marine Environmental Research, 66(5), 536–547. doi:10.1016/j.marenvres.2008.08.003

Forcada, A., Valle, C., Bonhomme, P., Criquet, G., Cadiou, G., Lenfant, P., & Sánchez-Lizaso, J. L. (2009). Effects of habitat on spillover from marine protected areas to artisanal fisheries. Marine Ecology Progress Series, 379, 197–211. doi:10.3354/meps07892

Freeman, D. J., MacDiarmid, A. B., & Taylor, R. B. (2009). Habitat patches that cross marine reserve boundaries: consequences for the lobster Jasus edwardsii. Marine Ecology Progress Series, 388, 159–167. doi:10.3354/meps08122

Goñi, R., Adlerstein, S., Alvarez-Berastegui, D., Forcada, A., Reñones, O., Criquet, G., … Planes, S. (2008). Spillover from six western Mediterranean marine protected areas: evidence from artisanal fisheries. Marine Ecology Progress Series, 366, 159–174. doi:10.3354/meps07532

Goñi, R., Hilborn, R., Díaz, D., Mallol, S., & Adlerstein, S. (2010). Net contribution of spillover from a marine reserve to fishery catches. Marine Ecology Progress Series, 400, 233–243. doi:10.3354/meps08419

Goñi, Raquel, Reñones, O., & Quetglas, A. (2001). Dynamics of a protected Western Mediterranean population of the European spiny lobster Palinurus elephas (Fabricius, 1787) assessed by trap surveys. Marine & Freshwater Research, 52(8), 1577. doi:10.1071/mf01208

Goñi, R., Quetglas, A., & Reñones, O. (2006). Spillover of spiny lobsters Palinurus elephas from a marine reserve to an adjoining fishery. Marine Ecology Progress Series, 308, 207–219. doi:10.3354/meps308207

Guidetti, P. (2007). Potential of marine reserves to cause community-wide changes beyond their boundaries. Conservation Biology: The Journal of the Society for Conservation Biology, 21(2), 540–545. doi:10.1111/j.1523-1739.2007.00657.x

Hoskin, M. G., Coleman, R. A., von Carlshausen, E., & Davis, C. M. (2011). Variable population responses by large decapod crustaceans to the establishment of a temperate marine no-take zone. Canadian Journal of Fisheries and Aquatic Sciences, 68(2), 185–200. doi:10.1139/f10-143

Howarth, L. M., Dubois, P., Gratton, P., Judge, M., Christie, B., Waggitt, J. J., … Stewart, B. D. (2017). Trade-offs in marine protection: multispecies interactions within a community-led temperate marine reserve. ICES Journal of Marine Science: Journal Du Conseil, 74(1), 263–276. doi:10.1093/icesjms/fsw166

Howarth, L. M., Roberts, C. M., Hawkins, J. P., Steadman, D. J., & Beukers-Stewart, B. D. (2015). Effects of ecosystem protection on scallop populations within a community-led temperate marine reserve. Marine Biology, 162(4), 823–840. doi:10.1007/s00227-015-2627-7

Huserbråten, M. B. O., Moland, E., Knutsen, H., Olsen, E. M., André, C., & Stenseth, N. C. (2013). Conservation, spillover and gene flow within a network of northern European marine protected areas. PloS One, 8(9), e73388. doi:10.1371/journal.pone.0073388

Kelly, S., & MacDiarmid, A. B. (2003). Movement patterns of mature spiny lobsters,Jasus edwardsii, from a marine reserve. New Zealand Journal of Marine and Freshwater Research, 37(1), 149–158. doi:10.1080/00288330.2003.9517153

Kelly, S., Scott, D., & MacDiarmid, A. B. (2002). The value of a spillover fishery for spiny lobsters around a marine reserve in northern New Zealand. Coastal Management: An International Journal of Marine Environment, Resources, Law, and Society, 30(2), 153–166. doi:10.1080/089207502753504689

Kerwath, S. E., Winker, H., Götz, A., & Attwood, C. G. (2013). Marine protected area improves yield without disadvantaging fishers. Nature Communications, 4(1), 2347. doi:10.1038/ncomms3347

López-Sanz, À., Stelzenmüller, V., Maynou, F., & Sabatés, A. (2011). The influence of environmental characteristics on fish larvae spatial patterns related to a marine protected area: The Medes islands (NW Mediterranean). Estuarine, Coastal and Shelf Science, 92(4), 521–533. doi:10.1016/j.ecss.2011.02.006

Maggs, J. Q., Mann, B. Q., & Cowley, P. D. (2013). Reef fish display station-keeping and ranging behaviour in the Pondoland Marine Protected Area on the east coast of South Africa. African Journal of Marine Science, 35(2), 183–193. doi:10.2989/1814232x.2013.798152

Nillos Kleiven, P. J., Espeland, S. H., Olsen, E. M., Abesamis, R. A., Moland, E., & Kleiven, A. R. (2019). Fishing pressure impacts the abundance gradient of European lobsters across the borders of a newly established marine protected area. Proceedings. Biological Sciences, 286(1894), 20182455. doi:10.1098/rspb.2018.2455

O'Dea RE, Lagisz M, Jennions MD, Koricheva J, Noble DWA, Parker TH, et al. (2021) Preferred reporting items for systematic reviews and meta-analysis in ecology and evolutionary biology: a PRISMA extension. Biological Reviews 96: 1695–1722. https://doi.org/10.1111/brv.12721

Parsons, D. M., Morrison, M. A., & Slater, M. J. (2010). Responses to marine reserves: Decreased dispersion of the sparid Pagrus auratus (snapper). Biological Conservation, 143(9), 2039–2048. doi:10.1016/j.biocon.2010.05.009

Pelc, R. A., Baskett, M. L., Tanci, T., Gaines, S. D., & Warner, R. R. (2009). Quantifying larval export from South African marine reserves. Marine Ecology Progress Series, 394, 65–78. doi:10.3354/meps08326

Pinillos, F., & Riera, R. (2022). The influence of boundary habitat continuity on spillover from a Mediterranean marine protected area. Thalassas : Revista de Ciencias Del Mar, 38(1), 687–696. doi:10.1007/s41208-022-00396-7

Sala-Coromina, J., García, J. A., Martín, P., Fernandez-Arcaya, U., & Recasens, L. (2021). European hake (Merluccius merluccius, Linnaeus 1758) spillover analysis using VMS and landings data in a no-take zone in the northern Catalan coast (NW Mediterranean). Fisheries Research, 237(105870), 105870. doi:10.1016/j.fishres.2020.105870

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Stobart, B., Warwick, R., González, C., Mallol, S., Díaz, D., Reñones, O., & Goñi, R. (2009). Long-term and spillover effects of a marine protected area on an exploited fish community. Marine Ecology Progress Series, 384, 47–60. doi:10.3354/meps08007

Thorbjørnsen, S. H., Moland, E., Huserbråten, M. B. O., Knutsen, J. A., Knutsen, H., & Olsen, E. M. (2018). Replicated marine protected areas (MPAs) support movement of larger, but not more, European lobsters to neighbouring fished areas. Marine Ecology Progress Series, 595, 123–133. doi:10.3354/meps12546

Tilney, R. L., Nelson, G., Radloff, S. E., & Buxton, C. D. (1996). Ichthyoplankton distribution and dispersal in the Tsitsikamma National Park marine reserve, South Africa. South African Journal of Marine Science/Suid-Afrikaanse Tydskrif Vir Seewetenskap, 17(1), 1–14. doi:10.2989/025776196784158482

Vigo, M., Navarro, J., Masmitja, I., Aguzzi, J., García, J. A., Rotllant, G., … JB Company. (2021). Spatial ecology of Norway lobster Nephrops norvegicus in Mediterranean deep-water environments: implications for designing no-take marine reserves. Marine Ecology Progress Series, 674, 173–188. doi:10.3354/meps13799

Villegas-Ríos, D., Claudet, J., Freitas, C., Moland, E., Thorbjørnsen, S. H., Alonso-Fernández, A., & Olsen, E. M. (2021). Time at risk: Individual spatial behaviour drives effectiveness of marine protected areas and fitness. Biological Conservation, 263(109333), 109333. doi:10.1016/j.biocon.2021.109333

Willis, T. J., Millar, R. B., & Babcock, R. C. (2003). Protection of exploited fish in temperate regions: high density and biomass of snapper Pagrus auratus (Sparidae) in northern New Zealand marine reserves. The Journal of Applied Ecology, 40(2), 214–227. doi:10.1046/j.1365-2664.2003.00775.x

## ANNEX 3: TEST, VALIDATION AND FEEDBACK OF SPILLEST TOOL

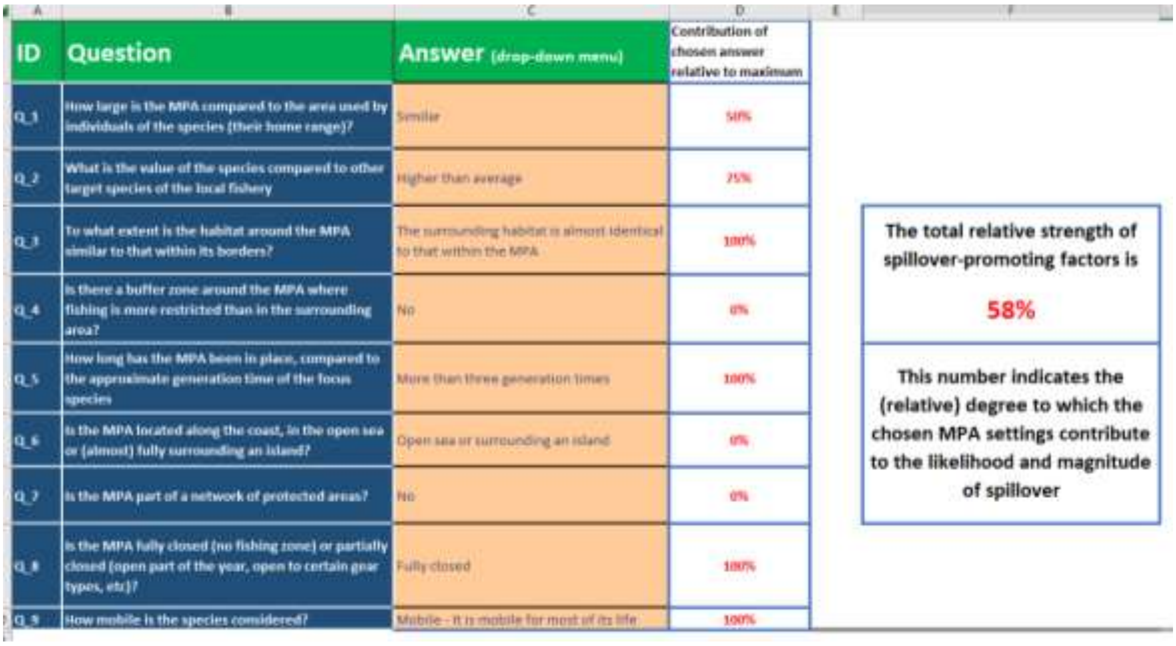
This annex summarizes the responses of the case study leaders to a request to fill in the SPILLEST tool as appropriate for their case study and reflect on the process and the results obtained.

There is a slight difference between the version sent out to the case study leaders and the version presented in the main report (Section 4). In the version used for the validation, question 10, about reproductive strategies was not yet implemented because the results of the species traits contributing to spillover (Section 2.3.2) were not available at the time.

**Gotska Sandön Marine Protected Area, Sweden**

The case study leader found the outcome of the tool to generally match with what was expected. They remarked that this particular no-take zone produces a lot of spillover of flatfish larvae to the island of Gotland, much more than you would expect from geography (two islands situated 100 km apart). This is due to the fact that there is a strong directional current from the no-take zone towards Gotland, whereby a large proportion of the larvae according to a hydrodynamic model ends up in the area of Gotland where the species are fished both commercially and recreationally. These circumstances are of course something that is difficult to pick up with a simple classification scheme.

They mentioned that the tool does not take into account that the no-take zone is an important spawning area for both target species, turbot and Baltic flounder, either. A suggestion was made to perhaps incorporate a question regarding this aspect in the tool, as it appears to be an important element determining the level of spillover from areas closed to fishing.



| ID | Question | Answer (drop-down menu) | Contribution of chosen answer relative to maximum |
|---|---|---|---|
| Q_1 | How large is the MPA compared to the area used by individuals of the species (their home range)? | Similar | 50% |
| Q_2 | What is the value of the species compared to other target species of the local fishery | Higher than average | 75% |
| Q_3 | To what extent is the habitat around the MPA similar to that within its borders? | The surrounding habitat is almost identical to that within the MPA | 100% |
| Q_4 | Is there a buffer zone around the MPA where fishing is more restricted than in the surrounding area? | No | 0% |
| Q_5 | How long has the MPA been in place, compared to the approximate generation time of the focus species | More than three generation times | 100% |
| Q_6 | Is the MPA located along the coast, in the open sea or (almost) fully surrounding an island? | Open sea or surrounding an island | 0% |
| Q_7 | Is the MPA part of a network of protected areas? | No | 0% |
| Q_8 | Is the MPA fully closed (no fishing zone) or partially closed (open part of the year, open to certain gear types, etc)? | Fully closed | 100% |
| Q_9 | How mobile is the species considered? | Mobile - It is mobile for most of its life | 100% |

The total relative strength of spillover-promoting factors is

58%

This number indicates the (relative) degree to which the chosen MPA settings contribute to the likelihood and magnitude of spillover

**Figure 45. Screenshot of SPILLEST for Gotska Sandön Marine Protected Area (Sweden).**

### Tvedestrand Marine Protected Area, Norway

The case study leader is not sure if the predicted outcome matches their situation, but remarks that it is an interesting metric to have. They remark that although there have quantitative data from all areas (inside, border and outside the MPA), the results of their assessment of spillover are confounded by the increasing fishing pressure that is happening outside the border. Since there is no data on how this fishing pressure is developing, it is difficult to see on how this affects the spillover (to a small extent) that is observed right outside the MPA.

| ID | Question | Answer (drop-down menu) | Contribution of chosen answer relative to maximum |
|---|---|---|---|
| Q_1 | How large is the MPA compared to the area used by individuals of the species (their home range)? | Much larger | 0 % |
| Q_2 | What is the value of the species compared to other target species of the local fishery | Among the highest | 100 % |
| Q_3 | To what extent is the habitat around the MPA similar to that within its borders? | The surrounding habitat is almost identical to that within the MPA | 100 % |
| Q_4 | Is there a buffer zone around the MPA where fishing is more restricted than in the surrounding area? | No | 0 % |
| Q_5 | How long has the MPA been in place, compared to the approximate generation time of the focus species | Less then one generation time | 0 % |
| Q_6 | Is the MPA located along the coast, in the open sea or (almost) fully surrounding an island? | Along the coast | 100 % |
| Q_7 | Is the MPA part of a network of protected areas? | No | 0 % |
| Q_8 | Is the MPA fully closed (no fishing zone) or partially closed (open part of the year, open to certain gear types, etc)? | Partially closed | 0 % |
| Q_9 | How mobile is the species considered? | Partly - it is (nearly) sessile a substantial part of its life | 50 % |

The total relative strength of spillover-promoting factors is

**39 %**

This number indicates the (relative) degree to which the chosen MPA settings contribute to the likelihood and magnitude of spillover

**Figure 46. Screenshot of SPILLEST for Tvedestrand MPA (Norway).**

### Belgian offshore wind farm zone, Belgium

The case study leader remarked that filling in the tool worked well and that experimenting with other settings led to results in agreement with their expectations. They mention that they have filled out the tool with flatfish (plaice, sole) in mind, which are relevant commercially exploited species in the area.

They find that the tool confirms that there is spillover possible, and remark that this is in line with expectations, and that the tool also predicts the magnitude would not to be very large, because the contribution to the stock is probably minimal.

They remarked that it was not clear how to interpret the term 'home range' and if this includes migration or not. Plaice, for example, has a very limited home range during spring, summer and autumn, but migrates over hundreds of kilometers during their winter migrations. They asked if such migration should be taken into account or not.


**Figure 47. Screenshot of SPILLEST for the Belgian offshore wind farm zone (Belgium).**

### Lyme Bay Marine Protected Area, UK

The case study leader mentioned that for this case study, there was no single focal species, but crab and lobster are important commercial species targeted by the local fishery, so they based their answers on these species. They find that the output of 58% is quite accurate as many stakeholders believed there was a likelihood of spillover occurring but could not conclusively confirm it. This is largely due to the recovery of the rocky reef habitat and exclusion of mobile fishing gear. They remarked that it might be useful to consider how the recovery of the benthic habitat might also drive the recovery of associated species leading to a greater likelihood and magnitude of spillover. In other words, to what extent has the benthic habitat recovered since the MPA has been in place?

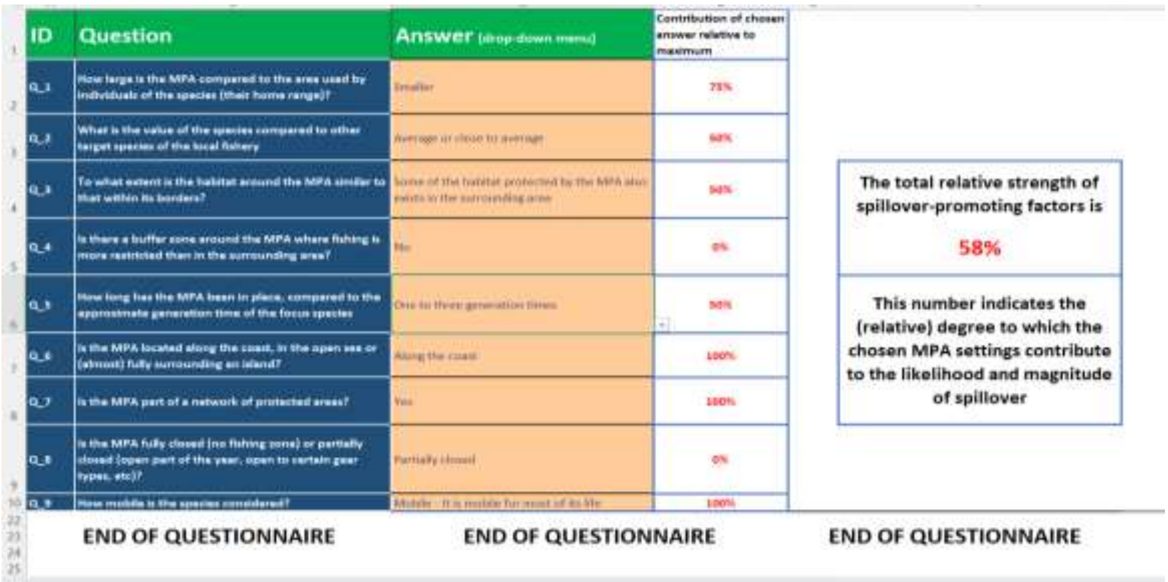



**Figure 48. Screenshot of SPILLEST for Lyme Bay Marine Protected Area (UK).**

### Flamanville Protected Area, France

The case study lead remarked that the tool matched their expectations, and that the selection of answers available from the drop-down menus were applicable to the Flamanville Protected Area. They mentioned that the only real target species of this MPA was the European lobster (*Homarus gammarus*), so it is difficult to compare the value to other species which are non-target and typically have little commercial value. They also had difficulty answering the question on the similarity of the habitat around the protected area, because it requires knowledge of the surrounding ecological environment. The outcome (relative strength) overall matched the expectation of the case study lead. Their report indicated evidence for spillover of lobsters.

| ID | Question | Answer (drop-down menu) | Contribution of chosen answer relative to |
|---|---|---|---|
| | How large is the MPA compared to the area used by individuals of the species (their home range)? | Similar | 50% |
| | What is the value of the species compared to other target species of the local fishery | Among the highest | 100% |
| | To what extent is the habitat around the MPA similar to that within its borders? | Some of the habitat protected by the MPA also exists in the surrounding area | 50% |
| | Is there a buffer zone around the MPA where fishing is more restricted than in the surrounding area? | No | 0% |
| | How long has the MPA been in place, compared to the approximate generation time of the focus species | One to three generation times | 50% |
| Q_6 | Is the MPA located along the coast, in the open sea or (almost) fully surrounding an island? | Along the coast | 100% |
| | Is the MPA part of a network of protected areas? | Yes | 100% |
| | Is the MPA fully closed (no fishing zone) or partially closed (open part of the year, open to certain gear types, etc)? | Partially closed | 0% |
| Q_9 | bile is the species considered? | Partly - it is (nearly) sessile a substantial part of its life | 50% |

The total relative strength of spillover-promoting factors is

56%

This number indicates the (relative) degree to which the chosen MPA settings contribute to the likelihood and magnitude of spillover

**Figure 49. Screenshot of SPILLEST for the Flamanville Protected Area (France).**

### The Écréhous and the Minquiers, Jersey

The case study lead remarked that the estimation of 33% is likely to be optimistic for the crustacean species which are partially fished within the MPAs. They report that stakeholders were sceptical that there was any spillover for species other than scallops, so 33% seems like a high number.

| ID | Question | Answer (drop-down menu) | Contribution of chosen answer relative to maximum |
|---|---|---|---|
| Q_1 | How large is the MPA compared to the area used by individuals of the species (their home range)? | Similar | 50% |
| Q_2 | What is the value of the species compared to other target species of the local fishery | Among the highest | 100% |
| Q_3 | To what extent is the habitat around the MPA similar to that within its borders? | Some of the habitat protected by the MPA also exists in the surrounding area | 50% |
| Q_4 | Is there a buffer zone around the MPA where fishing is more restricted than in the surrounding area? | No | 0% |
| Q_5 | How long has the MPA been in place, compared to the approximate generation time of the focus species | One to three generation times | 50% |
| Q_6 | Is the MPA located along the coast, in the open sea or (almost) fully surrounding an island? | Open sea or surrounding an island | 0% |
| Q_7 | Is the MPA part of a network of protected areas? | No | 0% |
| Q_8 | Is the MPA fully closed (no fishing zone) or partially closed (open part of the year, open to certain gear types, etc)? | Partially closed | 0% |
| Q_9 | How mobile is the species considered? | Partly - it is (nearly) sessile a substantial part of its life | 50% |

The total relative strength of spillover-promoting factors is

33%

This number indicates the (relative) degree to which the chosen MPA settings contribute to the likelihood and magnitude of spillover

**Figure 50. Screenshot of SPILLEST for the Écréhous and the Minquiers, Jersey.**

### Lamlash Bay and South Arran, UK

The case study leader remarked that the tool worked well and they had no issues filling it out. Also, it met their expectations for the No-Take Zone they applied it to. They ask the question how to deal with a situation where there are multiple dominant target species. The screenshot of SPILLEST was not received.

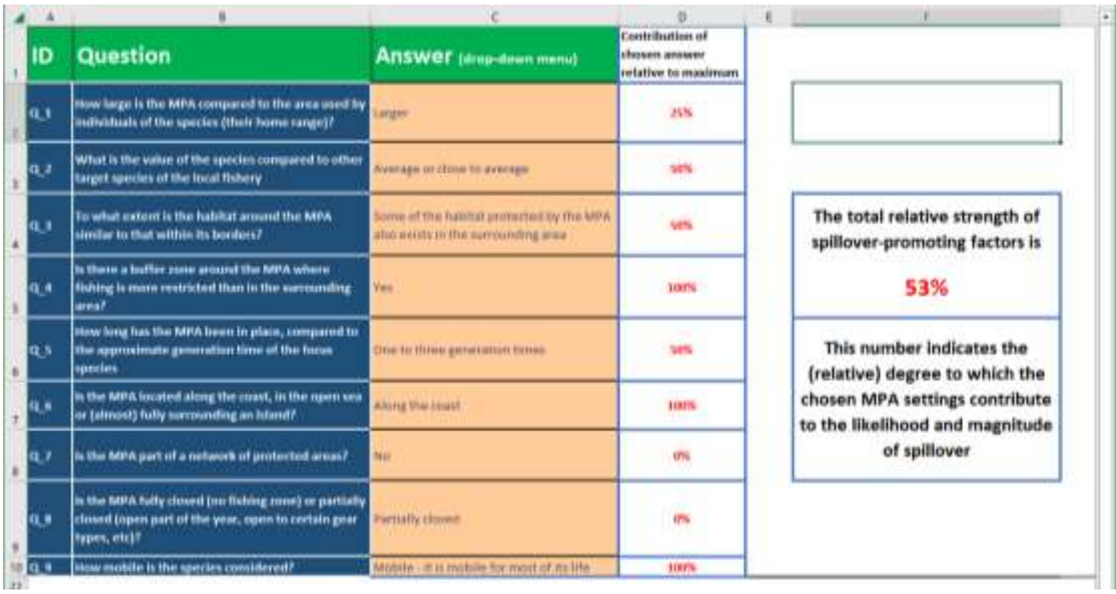
### Professor Luiz Saldanha Marine Park, Formigas Marine Protected Area and Selvagens Islands Marine Protected Area, Portugal

The case study lead of these three case studies remarked that they had some difficulty in filing out the tool, as it was unclear how to treat references to 'the species' in the questions. They report that they have filled in the answers keeping in mind the most relevant target species for their case study area.

A conclusion from the **Professor Luiz Saldanha Marine Park** case study was that "*although some scientific evidence has been identified on spillover in the literature, future research is necessary in order to gain a comprehensive understanding of the spillover effects of the Professor Luiz Saldanha Marine Park.*" (Annex 6). A result of 53% of likelihood (**Figure 51**) conforms with this conclusion.

In the **Formigas Marine Protected Area** case study, there is a lack of studies focusing on spillover from this specific MPA. From MPAs in the same Azores region, however, there is evidence of spillover for at least one finfish species. Because of a limited number of stakeholders' responses to the questionnaire, it is not possible to draw firm conclusions about stakeholder perceptions on spillover from the MPA. A result of 31% of likelihood (**Figure 52**) seems to match the uncertainty of the outcomes of this case study.

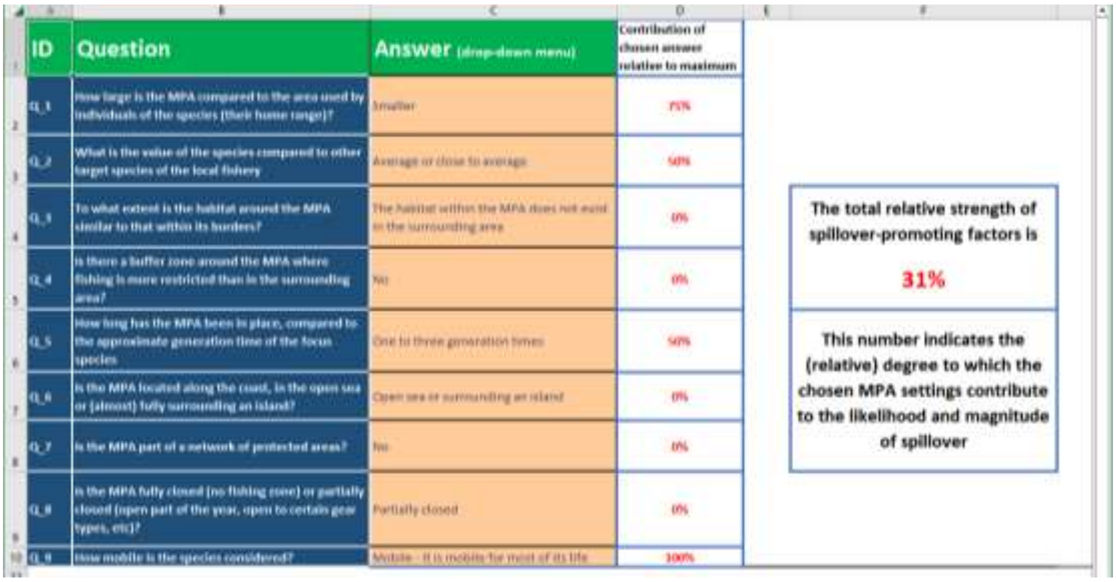
For the **Selvagens Islands Marine Protected Area** there is no available literature on spillover and the engagement of stakeholders was limited. The two respondents who filled out the questionnaire had contradicting responses on the likelihood of spillover effects. An outcome of 31% of likelihood of spillover (**Figure 53**) therefore seems to match the results of the case study.



| ID | Question | Answer (drop-down menu) | Contribution of chosen answer relative to maximum |
|---|---|---|---|
| Q_1 | How large is the MPA compared to the area used by individuals of the species (their home range)? | Larger | 25% |
| Q_2 | What is the value of the species compared to other target species of the local fishery | Average or close to average | 50% |
| Q_3 | To what extent is the habitat around the MPA similar to that within its borders? | Some of the habitat protected by the MPA also exists in the surrounding area | 50% |
| Q_4 | Is there a buffer zone around the MPA where fishing is more restricted than in the surrounding area? | Yes | 100% |
| Q_5 | How long has the MPA been in place, compared to the approximate generation time of the focus species | One to three generation times | 50% |
| Q_6 | Is the MPA located along the coast, in the open sea or (almost) fully surrounding an island? | Along the coast | 100% |
| Q_7 | Is the MPA part of a network of protected areas? | No | 0% |
| Q_8 | Is the MPA fully closed (no fishing zone) or partially closed (open part of the year, open to certain gear types, etc)? | Partially closed | 0% |
| Q_9 | How mobile is the species considered? | Mobile - it is mobile for most of its life | 100% |



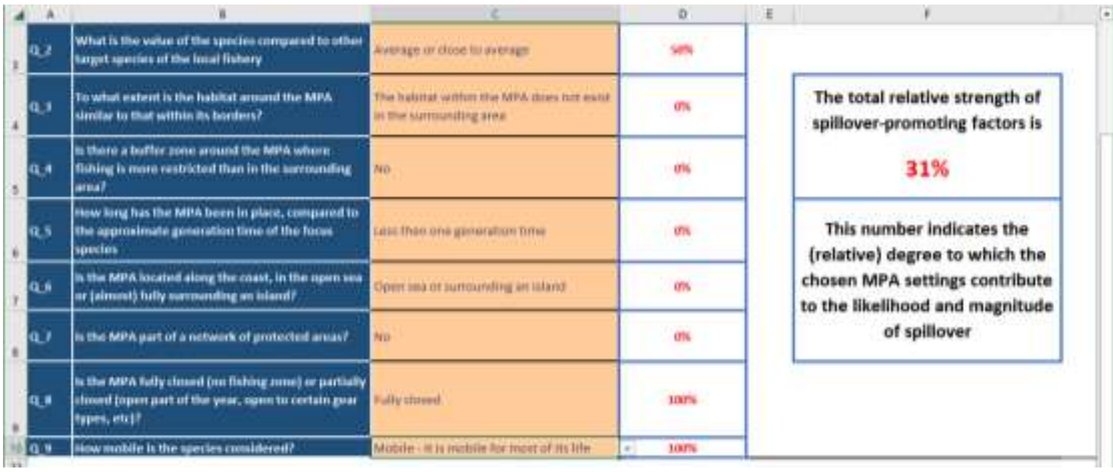
**Figure 51. Screenshot of SPILLEST for Professor Luiz Saldanha Marine Park (Portugal).**



| ID | Question | Answer (drop-down menu) | Contribution of chosen answer relative to maximum |
|---|---|---|---|
| Q_1 | How large is the MPA compared to the area used by individuals of the species (their home range)? | Smaller | 75% |
| Q_2 | What is the value of the species compared to other target species of the local fishery | Average or close to average | 50% |
| Q_3 | To what extent is the habitat around the MPA similar to that within its borders? | The habitat within the MPA does not exist in the surrounding area | 0% |
| Q_4 | Is there a buffer zone around the MPA where fishing is more restricted than in the surrounding area? | No | 0% |
| Q_5 | How long has the MPA been in place, compared to the approximate generation time of the focus species | One to three generation times | 50% |
| Q_6 | Is the MPA located along the coast, in the open sea or (almost) fully surrounding an island? | Open sea or surrounding an island | 0% |
| Q_7 | Is the MPA part of a network of protected areas? | No | 0% |
| Q_8 | Is the MPA fully closed (no fishing zone) or partially closed (open part of the year, open to certain gear types, etc)? | Partially closed | 0% |
| Q_9 | How mobile is the species considered? | Mobile - it is mobile for most of its life | 100% |



**Figure 52. Screenshot of SPILLEST for the Formigas Marine Protected Area (Portugal).**



| | | | |
|---|---|---|---|
| Q_2 | What is the value of the species compared to other target species of the local fishery | Average or close to average | 50% |
| Q_3 | To what extent is the habitat around the MPA similar to that within its borders? | The habitat within the MPA does not exist in the surrounding area | 0% |
| Q_4 | Is there a buffer zone around the MPA where fishing is more restricted than in the surrounding area? | No | 0% |
| Q_5 | How long has the MPA been in place, compared to the approximate generation time of the focus species | Less than one generation time | 0% |
| Q_6 | Is the MPA located along the coast, in the open sea or (almost) fully surrounding an island? | Open sea or surrounding an island | 0% |
| Q_7 | Is the MPA part of a network of protected areas? | No | 0% |
| Q_8 | Is the MPA fully closed (no fishing zone) or partially closed (open part of the year, open to certain gear types, etc)? | Fully closed | 100% |
| Q_9 | How mobile is the species considered? | Mobile - it is mobile for most of its life | 100% |

The total relative strength of spillover-promoting factors is

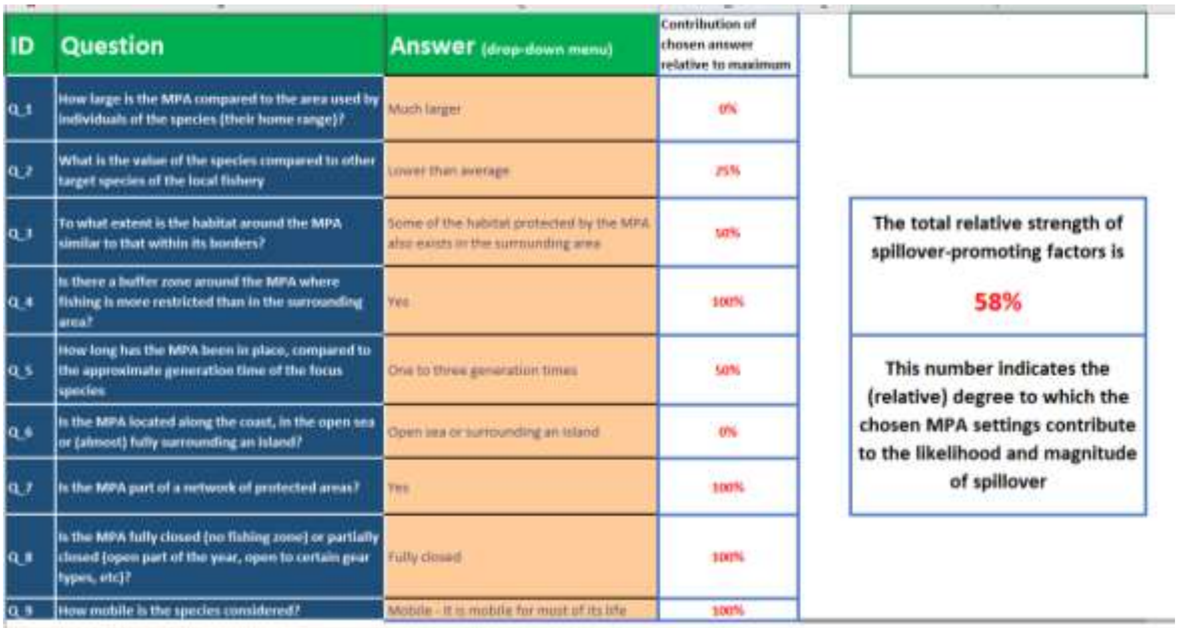
31%

This number indicates the (relative) degree to which the chosen MPA settings contribute to the likelihood and magnitude of spillover

**Figure 53. Screenshot of SPILLEST for the Selvagens Islands Marine Protected Area (Portugal).**

## La Graciosa Marine Protected Area, Canary Islands, Spain

The case study lead asked to which species the tool referred in the questions that mention 'the species'. The case study shows that: "*To answer the question of whether spillover could be occurring at the La Graciosa MPA, is not a straightforward question. There is evidence to suggest spillover effects are occurring for both the indicator species Serranus atricauda and Sparisoma cretense based on indicators of increased biomass and abundance*" (Annex 6). On the other hand, limitations of the methodology applied resulted in some cautiousness in interpretation of the results. The 58% of likelihood of spillover (Figure 54) seems to be appropriate.



| ID | Question | Answer (drop-down menu) | Contribution of chosen answer relative to maximum |
|---|---|---|---|
| Q_1 | How large is the MPA compared to the area used by individuals of the species (their home range)? | Much larger | 0% |
| Q_2 | What is the value of the species compared to other target species of the local fishery | Lower than average | 25% |
| Q_3 | To what extent is the habitat around the MPA similar to that within its borders? | Some of the habitat protected by the MPA also exists in the surrounding area | 50% |
| Q_4 | Is there a buffer zone around the MPA where fishing is more restricted than in the surrounding area? | Yes | 100% |
| Q_5 | How long has the MPA been in place, compared to the approximate generation time of the focus species | One to three generation times | 50% |
| Q_6 | Is the MPA located along the coast, in the open sea or (almost) fully surrounding an island? | Open sea or surrounding an island | 0% |
| Q_7 | Is the MPA part of a network of protected areas? | Yes | 100% |
| Q_8 | Is the MPA fully closed (no fishing zone) or partially closed (open part of the year, open to certain gear types, etc)? | Fully closed | 100% |
| Q_9 | How mobile is the species considered? | Mobile - it is mobile for most of its life | 100% |

The total relative strength of spillover-promoting factors is

58%

This number indicates the (relative) degree to which the chosen MPA settings contribute to the likelihood and magnitude of spillover

**Figure 54. Screenshot of SPILLEST for La Graciosa Marine Protected Area, Canary Islands (Spain).**

## ANNEX 4: STAKEHOLDER QUESTIONNAIRE

We developed a questionnaire to assess the perceptions of key stakeholders on the potential spillover effects in their nearby MPAs (Section 5). A letter was sent to the key stakeholders with background information, regarding the aim of the study and interviews, the consortium, privacy and contact information.

### Survey questions

Identification [Your personal details (name and e-mail) may be used to contact you regarding this survey, in particular to check that the summary of the outcome of the survey reflects your views].

Recording [we would like to record this interview to help us cross-check the notes afterwards. The recording will be kept confidential and deleted once the notes are finalised].

a) Your name ….
b) Your email address ……
c) Your organisation ……
d) Name of MPA …….
e) Do you consent to the Project Team using your response for the purpose of this study? [Yes/No]
f) What type of stakeholder category are you? [National authority; Scientist; Fisheries sector; NGO; Other (please specify)]

The rest of the questionnaire was directed into three sets, depending on the type of stakeholder: (i) fishery sector; (ii) management authorities; and (iii) scientists/NGOs.

### SET 1: Questionnaire fishery sector

**Table 15. A. Background - our goal here is to understand more about the respondent and their use of the MPA.**

| Question | | Method of answering | Options |
|---|---|---|---|
| 1 | Where do you land the majority of your fish? | Open | |
| 2 | What primary fishing gear(s) do you use? | Open | |
| 3 | What is your main target specie(s)? | Open | |
| 4 | Do you know when the MPA was established? | Closed | [Yes; No] |
| 5 | How aware are you of the regulations and management measures of the (*name of MPA*)? | Open | |
| 6 | Where do you regularly fish? | Closed | [Inside the MPA; outside the MPA; at the MPA border; inside and outside the MPA] |
| 7 | Is this the same place you regularly fished before the MPA was established? If no, please explain where you fished before. | Closed | [Yes; No] |
| 8 | i. How frequently do you fish inside the MPA? | Likert scale, with comments. | [Never; Once a week; 2-3 fishing trips per week; |

| Question | | Method of answering | Options |
|---|---|---|---|
| | ii. How frequently do you fish adjacent to the MPA?<br>iii. How frequently do you fish outside the MPA?<br>iv. How frequently do you fish in both? | | every fishing trip]<br>Specific comments… |

**Table 16. B. Fishery impacts - our goal here is to understand the respondent's perceptions of the socio-economic impacts of spillover from the MPA.**

| Question | | Method of answering | Options |
|---|---|---|---|
| 9 | Since the establishment of the MPA, are you experiencing changes in your catch? If so, what are these changes? | Open | |
| 10 | *[Only ask if fishing is permitted within MPA*] In comparison to areas outside the MPA, are catches from inside the MPA higher? | Likert Scale | (1) Definitely; (2) Probably; (3) Probably not; (4) Definitely not<br>Specific comments …. |
| 11 | Are there specific species that have become more abundant inside the MPA or adjacent to the fishing grounds since establishment of the MPA? | Yes/No<br>With comments | |
| 12 | To what extent do you believe spillover from (insert name of MPA) has contributed to the recovery of overexploited fish populations in adjacent fisheries? | Likert scale, with comments | [Extremely; To a large extent; Moderately; To a small extent; Not at all]<br>Specific comments… |
| 13 | Fishers' catches in this area are higher now than before the MPA was established. | Open | Strongly agree; Agree; Neutral; Disagree; Strongly Disagree]<br>Specific comments… |
| 14 | Fisheries in this area benefit economically by having the MPA | Closed, with comment | Strongly agree; Agree; Neutral; Disagree; Strongly Disagree]<br>Specific comments… |
| 15 | The designation of an MPA / area where fishing is limited in this area has led to an increase in revenues for fishers | Likert scale, with comments | [Strongly agree; Agree; Neutral; Disagree; Strongly Disagree]<br>Specific comments… |
| 16 | The fishing community in this area feel their fisheries livelihoods are more secure after the MPA was established | Likert scale, with comments | [Strongly agree; Agree; Neutral; Disagree; Strongly Disagree]<br>Specific comments… |
| 17 | In your opinion, are there more fishers in this (*case study)* than before the MPA was established? | Yes/No<br>Please explain | |

**Table 17. C. Management tool – our goal here is to understand the respondent's perceptions on whether MPAs are conservation or fisheries management tools.**

| Question | | Method of answering | Options |
|---|---|---|---|
| 18 | In your opinion, is the MPA acting as a conservation tool, a fisheries management tool or both? | Open Please explain | |
| 19 | Rate the level of agreement with the statement: "In order to develop commercial fisheries, certain areas of the MPA should be permanently closed to fishing." | Likert scale, with comments | [Strongly agree; Agree; Neutral; Disagree; Strongly Disagree] Specific comments... |
| 20 | Based on your observations and experiences, do you agree that the establishment of MPAs is an effective conservation strategy to support fish populations and commercial fisheries in this area? | Likert scale, with comments | Strongly agree; Agree; Neutral; Disagree; Strongly Disagree] Specific comments... |
| 21 | In your opinion, is there spillover of either fish or larvae from your MPA that is helping fisheries? | Open | |
| 22 | If yes, what is the magnitude at which spillover effects are detectable? | Likert scale, with comments | [At the MPA border; a few kilometres from MPA border; several kilometres from MPA border] |
| 23 | If yes, what factors are contributing to spillover effects? | Choose all factors that apply | [Size of MPA; years since MPA was established; protection level; dominant habitat; other, please specify] |
| 24 | Is the MPA helping to protect and improve biodiversity or does it benefit fisheries and the fishing communities? Or both? Please explain. | Open | |

## SET 2: Questionnaire management authorities.

**Table 18. A. Background - our goal here is to understand more about the respondent and their use of the MPA.**

| Question | | Method of answering | Options |
|---|---|---|---|
| 1 | Which MPA do you manage and what type of MPA is it? | Open | |
| 2 | How long have you been managing this MPA? | Open | |
| 3 | Does your MPA have a management plan? If so,<br>a. How long has it been in place?<br>b. Is 'spillover' included in the conservation objectives?<br>c. To what extent is fishing allowed in the MPA? | Open | |

| Question | | Method of answering | Options |
|---|---|---|---|
| 4 | Where does fishing regularly occur? | Likert scale, with comments | [Inside the MPA; outside the MPA; at the MPA border; inside and outside the MPA] |

**Table 19. B. Fishery impacts - our goal here is to understand the respondent's perceptions of the socio-economic impacts of spillover from the MPA.**

| Question | | Method of answering | Options |
|---|---|---|---|
| 5 | Since the establishment of the MPA, have you observed any changes in fish abundance, biomass, or species composition i) within the MPA; ii) outside (adjacent) to the MPA? If so, what are these changes? | Yes/ No Please explain | |
| 6 | Since the establishment of the MPA, have you noticed fishers experiencing changes in catch? If so, what are these changes? | Yes/ No Please explain | |
| 7 | **[Only ask if fishing is permitted within MPA]** In comparison to areas outside the MPA, have you noticed fishers experiencing changes in catch within the MPA? If so, what are these changes? | Open | |
| 8 | To what extent do you believe the spillover from (insert name of MPA) has contributed to the recovery of overexploited fish populations in adjacent fisheries? | Likert scale, with comments | [Extremely; To a large extent; Moderately; To a small extent; Not at all] Specific comments… |
| 9 | Fishers' catches in this area are higher now than before the MPA was established. | Open | Strongly agree; Agree; Neutral; Disagree; Strongly Disagree] Specific comments… |
| 10 | Fisheries in this area benefit economically by having the MPA | Closed, with comment | Strongly agree; Agree; Neutral; Disagree; Strongly Disagree] Specific comments… |
| 11 | The designation of an MPA / area where fishing is limited in this area has led to an increase in revenues for fishers | Likert scale, with comments | [Strongly agree; Agree; Neutral; Disagree; Strongly Disagree] Specific comments… |
| 12 | The fishing community in this area feel their fisheries livelihoods are more secure after the MPA was established | Likert scale, with comments | [Strongly agree; Agree; Neutral; Disagree; Strongly Disagree] Specific comments… |

| Question | | Method of answering | Options |
|---|---|---|---|
| 13 | In your opinion, are there more fishers in this (*case study)* than before the MPA was established? | Open | |

**Table 20. C. Management tool – our goal here is to understand the respondent's perceptions on whether MPAs are conservation or fisheries management tools.**

| Question | | Method of answering | Options |
|---|---|---|---|
| 14 | In your opinion, is the MPA acting as a conservation tool, a fisheries management tool or both? | Open Please explain | |
| 15 | In your opinion, what are the most effective management or policy measures to promote spillover from MPAs on adjacent fisheries? | Open | |
| 16 | Rate the level of agreement with the statement: "In order to develop commercial fisheries, certain areas of the MPA should be permanently closed to fishing." | Likert scale, with comments | [Strongly agree; Agree; Neutral; Disagree; Strongly Disagree] Specific comments… |
| 17 | To what extent do you believe collaborative initiatives between research groups, local fishing communities, and fisheries management authorities have been in understanding and managing the impacts of spillover from MPAs on adjacent fisheries? | Likert scale, with comments | [Not successful at all; Slightly successful; Moderately successful; Highly successful; Extremely successful] Specific comments… |
| | a. Have such collaborative initiatives this been helpful for the acceptance of the MPA by local stakeholders? | Closed | [Yes; No] |
| | b. has this helped with compliance and enforcement of the regulations? | Closed | [Yes; No] |
| | c. has this led to more beneficial outcomes of the MPA? Please explain your answer. | Closed, with comment | [Yes; No] Specific comment… |
| 18 | In your opinion, is there spillover of either fish or larvae from your MPA that is helping fisheries? | Open | |
| 19 | If yes, what is the magnitude at which spillover effects are detectable? | Likert scale, with comments | [At the MPA border; a few kilometres from MPA border; several kilometres from MPA border] |
| 20 | If yes, what factors are contributing to spillover effects? | Choose all factors that apply | [Size of MPA; years since MPA was established; protection level; dominant habitat; other, please specify] |
| 21 | Is the MPA helping to protect and improve biodiversity or does it benefit fisheries and the fishing communities? Or both? Please explain. | Open | |

## SET 3: Questionnaire scientists and NGOs.

**Table 21. A. Background - our goal here is to understand more about the respondent and their use of the MPA.**

| Question | | Method of answering | Options |
|---|---|---|---|
| 1 | What is the name and size of the MPA you are currently researching or researched? | Open | |
| 2 | What are the regulations and management measures of the MPA? | Open | |
| 3 | How long have you been researching the MPA? | Open | |
| 4 | What specific data collection methods or approaches have you employed to study the impacts of the MPA on local biodiversity and the potential for spillover to adjacent fisheries? | Open | |
| 5 | Is spillover among the priority topics to be considered in future research? | Open | |

**Table 22. B. Fisheries impacts- our goal here is to understand the respondent's perceptions of the socio-economic impacts of spillover from the MPA.**

| Question | | Method of answering | Options |
|---|---|---|---|
| 6 | Since the establishment of the MPA, have you observed any changes in fish abundance, biomass, or species composition i) within the MPA; ii) outside (adjacent) to the MPA? If so, what are these changes? | Yes/no Please explain | |
| 7 | The changes you referred to in Q7, how do these compare with areas outside the MPA? | Open | |
| 8 | Since the establishment of the MPA, have you observed any changes in fish abundance, biomass, species composition or body size of fishes in the MPA? If so, what are these changes? | Open | |
| 9 | In comparison to areas outside the MPA, have you observed increases in fish abundance, biomass, or species composition within the MPA? | Open | |
| 10 | Have you noticed any changes in fish movement behaviour since the implementation of the MPA? If so, what are these changes? | Open | |
| 11 | What is the likelihood that spillover is occurring:<br>(i) from the fully protected areas?<br>(ii) from the partially protected areas? | Likert scale, with comments | [Highly likely; likely; Neutral; Unlikely; Very Unlikely] Specific comments… |
| 12 | To what extent do you believe the spillover from MPAs has influenced the catch composition in adjacent fishing grounds? | Likert scale, with comments | [Not at all; To a small extent; Moderately; To a large extent; Extremely] Specific comments… |
| 13 | Fishers' catches in this area are higher now than before the MPA was established. | Likert Scale | Strongly agree; Agree; Neutral; Disagree; Strongly Disagree] Specific comments… |

| Question | | Method of answering | Options |
|---|---|---|---|
| 14 | Fisheries in this area benefit economically by having the MPA | Likert scale | [Strongly agree; Agree; Neutral; Disagree; Strongly Disagree] Specific comments… |
| 15 | The designation of a MPA / area where fishing is limited in this area has led to an increase in revenues for fishers | Likert scale, with comments | [Strongly agree; Agree; Neutral; Disagree; Strongly Disagree] Specific comments… |
| 16 | The fishing community in this area feel their fisheries livelihoods are more secure after the MPA was established | Likert scale, with comments | [Strongly agree; Agree; Neutral; Disagree; Strongly Disagree] Specific comments… |
| 17 | In your opinion, are there more fishers in this (*case study)* than before the MPA was established? | Open | |

**Table 23. C. Management tool – our goal here is to understand the respondent's perceptions on whether MPAs are conservation or fisheries management tools.**

| Question | | Method of answering | Options |
|---|---|---|---|
| 18 | In your opinion, is the MPA acting as a conservation tool, a fisheries management tool or both? | Open Please explain | |
| 19 | To what extent is investigating spillover a research priority? | Likert scale, with comments | [High priority; Low priority; Not a priority] |
| 20 | To what extent do you believe collaborative initiatives between research groups, local fishing communities, and fisheries management authorities have been in understanding and managing the impacts of spillover from MPAs on adjacent fisheries? | Likert scale, with comments | [Not successful at all; Slightly successful; Moderately successful; Highly successful; Extremely successful] Specific comments… |
| | a. Have such collaborative initiatives been helpful for the acceptance of the MPA by local stakeholders? | Closed | [Yes; No] |
| | b. has this helped with compliance and enforcement of the regulations? | Closed | [Yes; No] |
| | c. has this led to more beneficial outcomes of the MPA? Please explain your answer. | Closed, with comment | [Yes; No] Specific comment… |

| Question | | Method of answering | Options |
|---|---|---|---|
| 21 | Rate the level of agreement with the statement: “In order to develop commercial fisheries, certain areas of the MPA should be permanently closed to fishing.” | Likert scale, with comments | [Strongly agree; Agree; Neutral; Disagree; Strongly Disagree] Specific comments… |
| 22 | In your opinion, is there spillover of either fish or larvae from your MPA that is helping fisheries? | Closed | [Yes; No] |
| 23 | If yes, what is the magnitude at which spillover effects are detectable? | Likert scale, with comments | [At the MPA border; a few kilometres from MPA border; several kilometres from MPA border] |
| 24 | If yes, what factors are contributing to spillover effects? | Choose all factors that apply | [Size of MPA; years since MPA was established; protection level; dominant habitat; other, please specify] |
| 25 | Is the MPA helping to protect and improve biodiversity or does it benefit fisheries and the fishing communities? Or both? Please explain. | Open | |

# ANNEX 5: SPILLOVER ASSESSMENT ADVISORY PROTOCOL

**Preparation of the advisory protocol**

The document was drafted by Tamara Vallina (Wageningen Marine Research, WMR) based on various scientific papers, with the primary sources of information from works of van Kooten et al. (2015), Di Lorenzo et al. (2020), and Ovando et al. (2020). Additional contributions to the text were made by Dr. Tobias van Kooten (WMR), and was reviewed by Lennert van der Pol (WMR).

**The advisory protocol can be read independently or as a supplement to the full report. While it stands alone as a practical resource, for a more comprehensive understanding of spillover, it is recommended to read it in addition to this report or other relevant sources. Its primary goal is to guide readers to make well-informed decisions when designing their spillover analysis.**

**Pocket-Guide: Goals when studying spillover (a summary)**

1. Determine the type of spillover to be analyzed: ecological spillover (i.e. outward net emigration of juveniles, subadults and/or adults from the MPA driven by density-dependent processes) or fishery spillover (i.e. the proportion of this biomass that can be fished and that directly benefits fishery yields and revenue). Another process to be analysed could be the passive export of eggs and larvae outwards from the MPA.
2. Recognize potential challenges of observing and analyzing spillover by considering factors such as the duration since the establishment of the marine protected area (MPA), the ecological relevance of the MPA (low versus high fish abundance), characteristics of the focal species (like exploitation history, mobility, and reproductive mechanism), potential population-level effects, and fisheries response.
3. Evaluate the available data for your case study, considering spatial and temporal ranges and the number of observations, and assess the suitability of the data for spillover analysis (see table 27).
4. When data from multiple sites are available, select appropriate control sites: Not too far from the MPA to keep similar environmental conditions to the MPA, and similar in size to the MPA to avoid comparing dynamics of a different spatial scale. When possible, choose multiple reference sites at varying distances from the MPA. Carefully choose before and after moments: There should be a sufficient time gap between the pre-and post-establishment observations. If possible, choose multiple moments post-establishment with increasing time since establishment. Lastly, identify a suitable focal species: Studying multiple (groups of) species can be extra insightful. If possible, choose both an exploited and non-exploited species, preferably with medium movement ranges, and important for local communities.
5. Design the analysis by examining changes in relative fish abundance (or other relevant indicators such as total biomass or species diversity) in detail, being mindful of potential challenges in comparing over time (e.g. fisher efficiency, non-linear population growth, confounding variables like seasonality). See the list of potential variables for assessing spillover effects (table 29). Ensure the robustness of the analysis.

## Contents of the advisory protocol

# Introduction

## General considerations

Analyzing spillover is important for understanding ecological processes, evaluating the effectiveness of MPAs, maximizing economic benefits, and promoting sustainable fisheries and conservation. There is a need to ensure that any statistical analysis of data to effectively quantify patterns of spillover is both statistically rigorous and replicable. This document aims to design an advisory protocol with the assistance of case studies. By utilizing the specific analysis and methodologies from the case studies of this work, we seek to evaluate and refine recommendations for research strategies to assess spillover effects from MPAs to adjacent waters.

First, this document provides an overview of the biological concept of spillover based on the findings in scientific literature. Furthermore, it discusses distinct types of spillover, variables that influence spillover, and reasons why spillover may not occur or be difficult to detect. Then, this document provides case study partners with the statistical procedures necessary to analyze spillover effects by developing an overview of the biological concept of spillover and outlining the different methods and tools available for analyzing spillover effects. The case studies that were selected within this study report different data sources for potential spillover monitoring. Therefore, it is impractical to provide a specific approach for each case study, as we recognize and value the unique ideas and advancements of each analysis. Instead, a general approach is presented here and discusses important aspects of spillover that should be considered during any spillover analysis.

The reader should consider this protocol as a guide open for use by all. However, as you are the expert on your data, use a methodology you deem most appropriate. It is a dynamic document that welcomes recommendations, corrections, and contributions from anyone interested. If you have suggestions or wish to propose changes, please do not hesitate to share them, and contact the lead author.

## What is spillover?

Fisheries are an essential part of the economy and food security for communities worldwide. However, overfishing and unsustainable fishing practices can lead to the depletion of fish stocks and the degradation of marine ecosystems. MPAs that eliminate fishing pressure enable the restoration of fish populations and biomass in that region through growth and reproduction. Eventually, this might lead to the overflow of biomass from the MPA into the surrounding areas, which is referred to as spillover (Polacheck 1990). In theory, spillover might benefit fisheries through increased or stabilized yields, making up for the lost fishing grounds caused by the creation of the MPA (Sanchirico 2006, Grüss et al., 2011).

Fish populations within MPAs contribute to the harvestable stock through two primary mechanisms. Firstly, there is fishery spillover, which is the migration of harvestable individuals from the MPA into the adjacent areas, further augmenting the harvestable stock in those areas (Rowley, 1994). Secondly, there is larval spillover, which is the movement of larvae or eggs from the MPA to the surrounding areas where they grow up to exploitable sizes (Gell and Roberts, 2003). An MPA with strong larval or egg export can protect a harvested stock from reaching critically low levels where recruitment becomes insufficient, disabling the stock's ability to replenish itself. The available evidence regarding larval export from MPAs contributing to fishery benefits beyond their boundaries is limited. This is primarily attributed to the complexity associated with studying the origin of larvae (Van Kooten et al., 2015).

**Why spillover might not be happening or cannot be detected?**

Observing or analyzing spillover can present significant challenges. If spillover cannot be observed, several possibilities should be considered. First, it may be due to the actual absence of spillover occurring. Second, the total effects on fish populations both within the MPA and in surrounding areas can be small and exceptionally difficult to detect (Ovando et al., 2021). Ocean dynamics are complex, and rather than only serving as protection, the establishment of MPAs can influence many factors that change the dynamics of the fish populations within and around it. Lastly, it could be attributed to the methodologies by which spillover was analyzed. This section will primarily focus on discussing the reasons why spillover might not occur.

1. Time since the establishment of the MPA

Ecological effects resulting from MPAs are dependent on the duration since their establishment (e.g. Friedlander et al., 2017). It may take longer before rules are adhered to or for enforcement to take place. It is important to recognize that additional time may be necessary for populations to replenish or develop to a level where spillover effects become noticeable. The probability of spillover increases with the age of the protected area, as older MPAs tend to harbour higher abundances of adult individuals: Older and larger females often produce disproportionally more and higher quality eggs (Weigel et al., 2014). Long-lived or slow-reproducing species may take a long time to accumulate in protected areas, and population growth may follow more complex patterns (Babcock et al., 2010).

2. Ecological relevance of the MPA

If the area designated for the MPA had limited ecological value prior to its establishment, for example when fish abundance is low due to non-anthropogenic factors, the designation of the MPA may not result in the desired conservation benefits. If closing these areas does not significantly impact fishing intensity or spatial distribution, it is unlikely that any fishery benefits can be anticipated from the MPA. It could also be that a specific ecological habitat is protected. When the closed area is surrounded by an unsuitable habitat for the focal species, the likelihood of movement out of the boundaries of the closed area is low (Di Lorenzo et al., 2020).

3. Species-dependent responses to the MPA

Spillover effects can vary depending on the species studied. Murawski et al. (2004) observed spillover in specific stocks, including haddock, yellowtail flounder, and winter flounder, which significantly contributed to the overall increase in average catches near closed areas. However, the other ten species of the thirteen examined did not exhibit such spillover. The effectiveness of closing areas to fisheries is largely influenced by the ecological characteristics unique to each species, which will be further explored below.

a. *The focal species was not exploited*
   The impact of a MPA is expected to be more significant and rapid for heavily fished species. Species that are heavily targeted by fishing activities are more susceptible to depletion outside of protected areas compared to less targeted species. Consequently, the abundance difference between protected and non-protected areas is expected to be more pronounced for high-value species, increasing the likelihood of detecting spillover if it occurs (Di Lorenzo et al., 2020).

b. *Species mobility in relation to the size of the MPA*
   Generally, larger MPAs tend to have greater conservation benefits compared to smaller ones. They provide more habitat protection and support larger

populations of species. They also offer more space for species to grow, reproduce, and migrate, enhancing their long-term viability. Additionally, larger MPAs are often better equipped to buffer against threats, such as pollution, overfishing, and habitat destruction (Di Lorenzo et al., 2020)

The chances of fishery spillover benefits in relation to the MPA size are species-specific. For spillover to happen, the size and location of MPAs have to be adapted to the home range, mobility and movement patterns of juveniles and adults (Botsford et al., 2009). MPA networks that cover 30% or less of a population's range are unlikely to have significant population-level effects, unless the fished populations are severely overexploited (Ovando et al., 2021).

Sessile species, which are unable to move, are unlikely to cross MPA boundaries (Le Quesne and Codling 2009). Fish with very low movement rates tend to remain within the MPA and do not contribute to spillover effects. Although there might be significant differences in biomass in- and outside of MPAs, the actual impact of the protection on the population may be smaller. Species with intermediate movement rates relative to the size of the MPA have the highest potential for benefiting from the establishment of MPAs through spillover effects (Botsford et al., 2003).

However, many fish species undertake extensive migrations, covering distances ranging from tens to thousands of kilometres. Fish with very high movement rates compared to the size of the MPA spend a significant amount of time outside the protected area, where they are susceptible to fishing mortality. For these fish the relative protective effects of MPAs are small (Gerber et al., 2005). In cases of high movement, it can be challenging to detect differences between the inside and outside of MPAs, despite the potential of substantial effects on the population (Ovando et al., 2021).

c. *Dispersal of eggs or larvae*

Depending on the MPA size and current strength, detecting increased fish stocks due to larval export may be difficult without an exceptionally large production of eggs or larvae by the studied species (Pelc et al., 2010). Commonly, The proportional increase in recruitment at sites outside reserves is small, particularly for species with long-distance larval dispersal distances, making it very difficult to detect in field studies. Enhanced recruitment due to larval export might be detected by sampling several sites at varying distances from reserves, and specifically only down current for species with directional dispersal.

4. Population-level effects

Population-level effects in the context of MPAs and fisheries management here refers to the collective broader impact of the establishment of MPAs on fish populations. The most relevant topics in population-level effects will be further explored below.

a. *Density dependence*

Fishery benefits are more likely to occur when MPAs focus on protecting under-sized or under-aged individuals of harvested species. However, the presence of density-dependent effects can complicate or even reverse this relationship (Hastings and Botsford, 1999). Density-dependent growth occurs when individuals grow at a slower rate in high-density populations, resulting in smaller individuals within the protected population. As a result, any spillover is likely to be limited to smaller individuals.

b. *Community shifts*
   The establishment of MPAs can lead to significant shifts in community dynamics. If all species are allowed to recover, the species composition may (temporarily) shift towards those that were previously more susceptible to fishing (Stobart et al., 2009), or towards the species that reproduce the fastest. It can also promote the presence of species that are specialists in the MPA habitat type. By protecting key species at higher trophic levels, such as predators or keystone species, MPAs can indirectly influence the abundance and distribution of other species within the community. These shifts might prevent the expected conservation benefits for the focal species (Micheli et al., 2004).

5. Fishery response

Apart from the ecology of the fish, the response of the fishery is another important determinant of the success of an MPA demonstrating spillover effects. The fishers that used to work in the waters where the MPA was established might reallocate to waters outside the MPA, where fishing effort subsequently increases. Increased fishing effort along the boundaries of the MPA, so-called 'fishing the line' (Kellner et al., 2007) could lead to the appearance of a reduced catch per unit effort (CPUE), as there is more competition. CPUE should therefore always be compared to total biomass caught. Fishing the line in turn may reduce the capacity of the MPA to replenish larval, juvenile, or adult fish in surrounding unprotected waters. Therefore, considering the fishery response and the potential effects of fishing the line are essential for understanding the full picture of MPA performance and its implications for spillover effects.

## The protocol

Having gained an understanding of the potential outcomes of MPAs, the next question is how to effectively detect and measure these effects. After evaluating multiple methodological approaches for assessing spillover, it becomes clear that there are notable similarities among them. The differences primarily lie in the type of data that is available, and the temporal and spatial scale at which it was collected. In table 24, the main data categories and their most common sources are listed. Only quantitative data sources are discussed, so anecdotal/non-scientific observations, as well as theoretical modelling data, will be ignored. There are several main types of fishery data, with the most common ones being indicators of fish abundance and biomass. Since this data type is the most prevalent, it will be the further focus of this protocol.

**Table 24. Overview of main data types from which spillover effects could potentially be analysed, followed by the variety of sampling methods (based on initial literature assessment; see Section 3.3 in 'Methodological approaches to assess spillover') with which these can be collected.**

| Fishery data type | Sampling methods |
|---|---|
| Fish abundance / biomass | AIS/VMS data and/or logbook data<br>Small-scale fisheries logbook data<br>Visual censuses (stationary point count / by transect)<br>Capture-Recapture / Mark-Recapture<br>Marine biological surveys<br>(Light) traps |
| Larval biomass | Plankton samples |
| Fish size, weight, and age | Market sampling<br>Marine sampling (surveys) |

| Fishery data type | Sampling methods |
|---|---|
| Fish movement | Acoustic telemetry network<br>Tagging |

**The comparative approach**

In an ideal scenario, evaluating the effectiveness of an MPA for fisheries management would involve testing whether the MPA directly leads to an increase in an indicator of fish biomass. To assess MPA functionality, the most common approach is a comparison between samples taken within and outside of the MPA (impact and control) and can be further studied by comparing observations before and after MPA establishment (Before After Control Impact (BACI) design). Comparing measurements before and after inside and outside MPAs can be useful as it allows to differentiate the MPA effects from the differences between control and impact sites, but unless carefully designed might not be informative about the population-level effects of MPAs (see below).

BACI approach for spillover assessment

Although the classic BACI approach might be insightful for the functioning of MPAs, it might not be very suitable for detecting potential spillover effects. Imagine having data of biomass in the MPA and in a reference site, once before the establishment of the MPA and once after. When comparing biomass after to before (Δ biomass), seventeen qualitatively different outcomes are possible (table 25). Out of these, only three indicate potential spillover, and it is difficult to differentiate between an effect of the Impact (the MPA) or natural fluctuations in the population. Conclusions on biomass can be made by comparing biomass before and after (Δ biomass) in MPA and reference site before and after MPA establishment. Protective functioning of the MPA can be concluded if Δ biomass is greater in the MPA than in the reference site. Spillover is consistent with a positive Δ biomass in both the MPA and reference area, but this outcome can also be the result of an autonomous increase. As will be demonstrated in a later example, it might be more informative to look at multiple reference sites outside the MPA.

**Table 25. This table provides an overview of the conclusions that can be drawn from the classic MPA BACI approach in assessing spillover. The examples presented are theoretical. The first two columns describe the difference in biomass before and after establishment of the MPA in the MPA site (Δ MPA) and in the reference site (Δ Ref). The potential combinations of changes in biomass were named in the column scenario name. The last three columns indicate whether a conclusion can be drawn from each scenario regarding the total biomass of the MPA and reference site, whether the MPA provides protection benefits, and whether the results indicate spillover.**

| Δ MPA | Δ Ref | Scenario name | Biomass? | Protection? | Spillover? |
|---|---|---|---|---|---|
| 0% | 0% | Stable | Consistent | No | No |
| 0% | 10% | Ref. site increased | Increase | No | No |
| 10% | 0% | MPA increased | Increase | Yes | No |
| 10% | 5% | Both increased, but MPA stronger | Increase | Yes | Potentially |
| 5% | 10% | Both increased, but ref. site stronger | Increase | No | Potentially |
| 10% | 10% | Mutually increased | Increase | Potentially | Potentially |
| -10% | 0% | MPA decreased | Decrease | No | No |
| -10% | 5% | Ref. site increased, but MPA decreased stronger | Decrease | No | No |

| Δ MPA | Δ Ref | Scenario name | Biomass? | Protection? | Spillover? |
|---|---|---|---|---|---|
| -5% | 10% | MPA decreased, but ref. site increased stronger | Increase | No | No |
| -10% | 10% | MPA decreased as strong as ref. site increased | Consistent | No | No |
| 0% | -10% | Ref. site decreased | Decrease | Yes | No |
| -10% | -5% | Both decreased, but MPA stronger | Decrease | No | No |
| -5% | -10% | Both decreased, but ref. site stronger | Decrease | Yes | No |
| -10% | -10% | Mutually decreased | Decrease | No | No |
| 10% | -5% | Ref. site decreased, but MPA increased stronger | Increase | Yes | No |
| 5% | -10% | MPA increased, but ref. site decreased stronger | Decrease | Yes | No |
| 10% | -10% | MPA increased as strong as ref. site decreased | Consistent | Yes | No |

<u>BACI approach for spillover assessment with data from only outside the MPA</u>

For spillover to occur, it is crucial that the biomass or abundance of fish within the closed area is higher than outside it. While increases in biomass or abundance within both the MPA and the reference area can indicate successful protection of the target species by the MPA, such evidence alone is insufficient to conclude that these effects are solely due to spillover. Density-related spillover is characterized by a gradient of biomass or abundance that starts at the boundary and decreases with increasing distance from the boundary of the MPA (McClanahan and Mangi 2000; Abesamis & Russ, 2005).

Repeated assessments before and after enforcement in multiple sites around the MPA, preferably with increasing distance from the MPA, provide an estimate of the spatial variability between the Control and Impact sites in the absence of the MPA's effect. By comparing the changes in biomass (or other response indicator) between the reference sites before and after the establishment of the MPA, potential spillover effects can be assessed.

The negative relationship between the chosen response indicator and distance from a closed area boundary can serve as an indication of spillover, but only if this pattern has emerged or become stronger since the establishment of the MPA. However, even interpreting density gradients as evidence for spillover must be done cautiously (Murawski et al., 2005). Table 26 provides a summary of conclusions that can be drawn, focusing solely on spillover effects. Detection of spillover effects relies on comparing biomass between the reference site near the MPA and the reference site further away. However, no statements can be made about the effects within the MPA itself.

**Table 26. This table provides an overview of the conclusions that can be drawn from the BACI approach comparing reference sites nearer and further away from an MPA to assess spillover. The examples presented are theoretical. The first two columns describe the difference in biomass in before and after establishment of the MPA in the reference site near the MPA (Δ Ref near MPA) and in the reference site further from the MPA (Δ Ref further from MPA). The potential combinations of changes in biomass were named in the column scenario name. The last column indicates whether the results indicate spillover.**

| Δ Ref near MPA | Δ Ref further from MPA | Scenario name | Spillover? |
|---|---|---|---|
| 0% | 0% | Stable | No |
| 0% | 10% | Only further increased | No |

| Δ Ref near MPA | Δ Ref further from MPA | Scenario name | Spillover? |
|---|---|---|---|
| 10% | 0% | Only nearer increased | Potentially |
| 10% | 5% | Both increased, but nearer increased more | Potentially |
| 5% | 10% | Both increased, but further increased more | No |
| 10% | 10% | Both increased | No |
| -10% | 0% | Only near decreased | No |
| -10% | 5% | Further increased, but near decreased stronger | No |
| -5% | 10% | near decreased, but further increased stronger | No |
| -10% | 10% | near decreased as strong as far increased | No |
| 0% | -10% | Only further decreased | Potentially |
| -10% | -5% | Both decreased, but nearer decreased more | No |
| -5% | -10% | Both decreased, but further decreased more | Potentially |
| -10% | -10% | Both decreased | No |
| 10% | -5% | Further decreased, but near increased stronger | Potentially |
| 5% | -10% | Near increased, but further decreased stronger | Potentially |
| 10% | -10% | Near increased as strong as far decreased | Potentially |

<u>Other comparative approaches for spillover assessment</u>

An assessment of the occurrence of spillover requires sufficient data quantity and quality. In particular, a combination of spatial and temporal data is required. Spatially, the main requirement is the presence of observations within and outside the MPA, and a high enough number of sites outside the MPA where data is collected. Temporally, the main requirement is that there are observations both before and after the establishment of the MPA, and that data was collected a sufficient number of times after MPA establishment. Table 27 presents the suitability of different combinations of spatial and temporal data. The limitations of certain datasets in drawing conclusions on spillover are highlighted, along with the necessary indicators for detecting spillover.

Having only observations before the MPA was established can of course never be telling for the effects of an MPA. Only one observation after establishment of the MPA is not helpful either, as the chances of it reflecting natural variation in population densities are very high. It can only be insightful if there are multiple reference sites, and there is a negative effect from distance to MPA on biomass. If there are multiple data points after the establishment of the MPA, spillover can be detected if there is a positive effect of the time since MPA establishment on biomass in and out of the MPA (referred to as after-control/impact (ACI) or beyond-BACI design).

Having observations outside the MPA only is common, as baseline observations are often not invested in (Willis et al., 2003). Looking at data before and after MPA establishment in a reference site only is referred to as before/after-control (BAC) design. Having multiple control/reference sites is always preferable as it reduces the possibility of attributing spillover to preexisting spatial patterns that coincidentally look like spillover (Thiault et al., 2017). Additionally, observing a decreasing effect of distance in biomass from the MPA border is a strong indicator of spillover, for which multiple observations with increasing distance from the MPA are necessary. Having multiple observations post-establishment also enhances the reliability of spillover detection, as it helps distinguish true spillover from temporal fluctuations in population densities.

Having observations in the MPA alone, even many observations over time, is never enough to conclude anything about the occurrence of spillover. Having just one reference site is also not informative, as it could reflect normal spatio-temporal variations. An increasing biomass time trend over multiple spatial observations after the establishment of the MPA can be an indication of spillover. **The undisputed best way to study the presence of spillover is to have multiple reference sites and multiple observation moments both before and after MPA establishment**. The strongest signal of spillover is when there is a negative effect of distance to the border of the MPA on biomass, which gets stronger with time since establishment of the MPA.

**Table 27. Overview of suitability temporal and spatial data combinations for spillover analysis. The columns show different spatial options (MPA and/or reference site), while rows show temporal options (before and/or after MPA establishment), both ranging in number of observations. Cell colors indicates suitability for analysis, with letters indicating the reason(s) for rejection, and numbers indicating what would indicate spillover. Blank cells have insufficient data for analysis.**

| | | | **Spatial focus** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | *MPA* | | *ref* | | *MPA + ref* | | | |
| | | observations | n=1 | n>1 | n=1 | n>1 | $n_{both}$=1 | $n_{MPA}$>1, $n_{ref}$=1 | $n_{MPA}$=1, $n_{ref}$>1 | $n_{both}$>1 |
| **Temporal focus** | *before* | n=1 | | | | | | | | |
| | | n>1 | | | | | | | | |
| | *after* | n=1 | | | | c, 1 | c | c | 1 | 1 |
| | | n>1 | | | b | 3 | c | c | 3 | 3 |
| | *before + after* | $n_{both}$=1 | a, b | a, b | b | 1 | a, b, c | a, b, c | 1 | 3 |
| | | $n_{before}$>1, $n_{after}$=1 | a, b | a, b | b | 1 | a, b, c | a, b, c | 1 | 1 |
| | | $n_{before}$=1, $n_{after}$>1 | a, b | a, b | b, 2 | 3 | 2 | 2 | 3 | 3 |
| | | $n_{both}$>1 | a | a | b, 2 | 3 | 2 | 2 | 3 | 3 |

**Suitability for spillover assessment**
- Not suitable
- Debatable
- Suitable

**Reason for rejection**
a) An indication of MPA functionality only
b) Could reflect normal temporal variation
c) Could reflect normal spatial variation

**What would indicate spillover?**
1) An effect of distance to MPA
2) An effect of time since MPA establishment
3) An effect of distance to MPA and it gets stronger over time (or after MPA establishment)

## Choosing appropriate references

Choosing control/reference site(s)

When selecting a reference area or site to study spillover effects around an MPA, several factors should be considered. Often, reference site selection is limited by data availability. There should be sufficient observations in the reference site to be able to make a logical comparison to assess spillover effects (table 27). As discussed above, it is always better to have multiple reference sites. The selection of the reference site should be guided by scientific expertise and take into account the specific biological traits of the species to be studied. It should be made sure that the reference site is not subject to significantly more or less fishing pressure or other anthropogenic activities since the establishment of the MPA that could confound the assessment of spillover effects. Other key considerations for choosing an appropriate reference site are proximity to the MPA and size.

The reference sites should be located not too far from the MPA to ensure ecological similarity/representativeness in terms of habitat type(s), species composition, and environmental conditions. However, it should be taken into consideration that the comparison sites nearby can be directly influenced by the MPA by displaced fishing effort, resulting in increased fishing pressure compared to before establishment of the MPA. If possible, choose multiple reference sites at varying distances from the MPA. The reference site should be of sufficient size and spatial extent to capture potential spillover effects. It should be bigger for more mobile species and should cover a suitable range of habitats and incorporate relevant ecological features that are comparable to those within the MPA.

**BOX 1. Example of choosing control and reference sites**

Medoff et al. (2022) conducted a study on potential spillover for tuna species in the Papahānaumokuākea Marine National Monument, Hawaii, providing a tangible example. The methodology used distance from the border of the protected area to test changes in CPUE before and after establishment of the protected area. They focused on two highly mobile species, bigeye tuna and yellowfin tuna, known for their extensive migrations and ability to cover vast distances in search of food and suitable environmental conditions.

To select reference sites, different buffer distances around the MPA were tested, with the "far" reference site located at twice the distance from the MPA compared to the "near" site. Distances of 100, 200, and 300 nautical miles (nmi) from the protected border were used, corresponding to 0.25, 0.5, and 0.75 times the mean diameter of the MPA, respectively. The analysis revealed that catch rates (CPUE) increased more significantly in the near region compared to the far region for both tuna species in all scenarios. The spillover effect was particularly pronounced for yellowfin tuna in the 100- and 200-nmi region radii, while differences in catch rates for bigeye tuna became more apparent with the 300-nmi radius. Additionally, rather than a binary indicator for proximity to the MPA, they explored a continuous distance measure with observations until 600 nmi from the MPA. By interacting distance with the period before or after MPA establishment, the researchers found a positive effect for both bigeye and yellowfin tuna of being closer to the MPA on CPUE after the establishment of the protected area.

Mossler (2023) highlighted a flaw in the analysis conducted by Medoff et al. (2022), which assessed changes in CPUE using absolute numbers without accounting for the non-uniform spatial abundance of tuna. It was observed that prior to the implementation of the MPA, there were already more tuna near the designated protected area, likely due to favorable habitat conditions. Moreover, during the study period, yellowfin tuna populations exhibited a general increase throughout the western Pacific. A general population increase would automatically result in a higher number of new individuals near the MPA compared to farther locations, as there were already more individuals to reproduce. To accurately assess spillover the appropriate approach would be to examine relative increases, which did not reveal significant evidence of spillover in this case. Nonetheless, the spatial design employed by Medoff et al. (2022) can still serve as a valuable example of choosing control and reference sites.

Choosing before and after moment(s)

When choosing the moments in time to study differences before and after MPA establishment, it is important to consider a number of factors (limited by data availability). When pre-establishment baseline observations are available, this baseline should capture the conditions and dynamics of the ecosystem and fish populations prior to any potential effects of the MPA. There should be a sufficient time gap between the pre- and post-establishment periods to capture any potential changes resulting from the MPA. The duration of this gap may vary depending on the specific ecological processes, life cycles of target species, and the expected time frame for spillover effects to manifest. If multiple observations are available post-establishment, incorporating the time since establishment as predicting variable can improve the analysis. It is important to take into account natural temporal variability (e.g. seasons) in the ecosystem and fish populations when selecting the time periods. This helps distinguish between natural fluctuations and changes attributed to the MPA, enhancing the reliability of the analysis. It is important to strike a balance between capturing meaningful changes resulting from the MPA and accounting for natural temporal variability in the ecosystem. As an example, Medoff et al. (2022) focused on yearly means for CPUE trends over time and on total means for statistical comparisons of CPUE before and after MPA establishment in 2016 using data for the years from 2010 to 2019.

Choosing the focal species

Often, MPAs are established with the aim of protecting specific species and their habitats. When regulations are set in place to protect an area, it leads to the indirect protection of other species and their habitats as well. The analysis of spillover effects may therefore focus on multiple different species. The choice of focal species may depend on the specific goals and objectives of your study, as well as the characteristics of the MPA and its surrounding ecosystem. Below are guidelines to make an informed decision.

- Evaluate the availability and quality of data for different species. Choose species for which sufficient data are available, ensuring robust and reliable analysis. If there is only data for reference sites nearby the MPA, focus on species with limited mobility or relatively small home ranges. These species are more likely to show localized spillover effects.
- Consider the interests and concerns of various stakeholders, including local communities, resource users, conservation organizations, fisheries and managing agencies. Engaging stakeholders in the selection process can enhance the relevance and acceptance of the study's findings. If the MPA was established primarily for the conservation of a specific species, or for a habitat that is very suitable for specific species, it makes sense to include those species in the analysis as a focal point, as they may exhibit the most noticeable spillover effects from MPAs.
- When there is no preference for a particular species by stakeholders, it is a first step to assess the ecological role and significance of different species in the ecosystem. Focus on species that play crucial roles as keystone species, habitat-formers, or indicators of ecosystem health. When there is a particular interest in conservation, prioritize species that are of conservation concern or listed as endangered, threatened, or vulnerable. If the focus is primarily on fisheries, the focus should be on species that have a high commercial or recreational value.
- Studying multiple (groups of) species might be extra insightful to understand potential spillover dynamics. Analyzing spillover effects for species that are connected to the target species or occupy adjacent trophic levels in the food web can shed light on the cascading effects of MPAs on trophic dynamics and ecosystem functioning. It can also serve a controlling function. Ovando et al. (2021) assessed two groups of species: those targeted by fishing, and those not targeted by fishing. They argued that since targeted species have much higher mortality rates due to fishing, the non-targeted species serve as a control for other changes in the ecosystem, such as warming events.

## Designing the analysis: things to consider

Catch, effort and CPUE

1. Looking at both catch and effort

When comparing biomass before and after establishment of an MPA, it is essential to consider both total catches and effort together, rather than looking at them individually (Table 28). Focusing solely on catch or effort can lead to incomplete and misleading conclusions. Catch represents the outcome of fishing activities and provides insights into the abundance and availability of target species, while effort reflects the intensity and investment of fishing activities. Both catch and effort are influenced by various factors, including environmental conditions, and fishing strategies. Changes in catch alone may not accurately reflect the impact of the MPA if effort levels have also changed. For example, a decrease in catch could be attributed to reduced effort rather than a decline in fish abundance. On the other hand, an increase in total catch might be the result of higher fishing effort rather than spillover from the MPA.

In addition to consider catch and effort together, it is also important to recognize the limitations of relying solely on catch per unit effort (CPUE) when assessing the functionality of an MPA before and after its establishment. CPUE, which represents the amount of catch obtained per unit of fishing effort, is commonly used as a proxy for fish abundance or biomass. However, it should be noted that changes in CPUE can be influenced by factors other than fish biomass alone. Increased competition among fishers can lead to lower CPUE even if fish biomass remains stable or even increases. Intense fishing pressure outside the MPA boundaries, resulting from fishers reallocating their effort, can result in greater competition and reduced CPUE. Therefore, a decrease in CPUE alone does not necessarily indicate a decline in fish biomass.

**Table 28. This table provides an overview of the conclusions that can be drawn about total fishable biomass in the studies area from comparing catch statistics (total catch or CPUE) in relation to effort, which is a key step in assessing spillover. "Increase," "Stable," and "Decrease" say something about the fishing effort, total catches in the area, or CPUE. "Less," "constant" or "more" say something about the change in biomass in the studied area. These conclusions may benefit from further examination and discussion within the scientific community before accepting them as definitive.**

| | | **Total Catch** | | | **CPUE** | | |
|---|---|---|---|---|---|---|---|
| | | Increase | Stable | Decrease | Increase | Stable | Decrease |
| **Effort (not efficiency)** | Increase | constant | less | less | more | constant/more | constant/less |
| | Stable | more | constant | less | more | constant | less |
| | Decrease | more | more | constant | more/constant | constant | less |

Comparisons over time

1. Account for improved efficiency

Furthermore, when examining CPUE as an indicator of MPA functionality, it is essential to consider the potential influence of changing fishing practices, advancements in fishing technology, and improvements in fishermen's skills (Medoff et al., 2022). Over time, fishers may become more experienced and employ more specialized gear, which can lead to higher catch rates and potentially inflate CPUE values. While an increase in CPUE might suggest a positive outcome for the MPA, it is crucial to differentiate between genuine increases in fish biomass and improvements in fishing efficiency. This is particularly important when only post-establishment data is used, as the efficiency outside the MPA could be temporarily reduced because fishers are forced to operate in new and relatively unknown locations. Such a temporary decline could mask spillover which may be occurring. By examining catch, effort and CPUE concurrently, it becomes possible to differentiate between changes driven by MPA effects and those influenced by other factors. Assessing the effect of variation in effort and skill can be tackled by incorporating covariates that represent them: To rule out an increased CPUE due to increased fishing efficiency, control for consistency in the fleet operating in the area of investigation. Increased fishing efficiency include technical improvements of vessels and gear (vessel length, horsepower), and improvements in fishing skills (number of crew). To check for increased competition, control for the number of vessels (or fishing time) fishing in the zone.

2. Non-linear relations

Adherence to restrictions that come with MPA establishment or active enforcement may be slow. Additionally, it can take some time before changes in the fish populations start to appear, especially for long-lived species. In these situations, the buildup of individuals does not grow linearly from the establishment of the MPA (Babcock et al., 2010). Complicating things even further, changing fishing pressure also changes population effects. The relation between taking out fish and the population capacity to replenish itself is not linear (fishery production function exponent is not equal to 1), although this is often assumed.

Smith et al. (2006) clarified that unless fishing effort before MPA establishment was the same, analyzing CPUE is equivalent to restricting all of the fishery production function exponents to 1. If the true fishery production function exponent is below 1, then a decrease in effort post-reserve will produce an increase in CPUE, even if the MPA is not generating any harvest benefits. They illustrated this by an effort decline of 46% over a certain amount of time and an 50 % increase in CPUE over the same period. If the fishery production function exponent is 0.5 over that period of time, then this effort decline would translate into a 36% increase in CPUE even if fishable biomass did not change (Smith et al., 2006).

There are new ways of accounting for these non-linear population growth patterns in comparative analyses. A recent approach called Progressive-Change BACIPS offers more flexibility by allowing the measurement of different types of temporal change (e.g. exponential, and logistic relations) in addition to the linear change (Thiault et al., 2017). While the use of BACIPS studies is increasing, such studies remain relatively uncommon (Thiault et al., 2019). When non-linear population growth dynamics are expected, one can also analyze these by fitting generalized linear models (GLMs) or generalized additive models (GAMs) with appropriate distributions for the response variable, determining the shape of the relation.

3. Seasonality

Aside from the effect of age of the MPA, there can also be a temporal effect of seasonality. CPUE studies can address this by always making before-after comparisons at the same time of year, but (if enough data is available) modeling seasonality directly allows for use of all observations rather than excluding before (after) observations that cannot be matched with after (before) observations in the same period of the year. More complex interactions can also be present. For example, Smith et al. (2006) considered an interaction between gear type and month, which accounts for particular gear types having higher catchability than others when spawning aggregations occur.

**Robustness**

Robustness checks are a fundamental principle in spillover analysis. They serve as a critical step to validate and strengthen the reliability of your findings. The idea behind robustness checks is to assess the consistency and stability of your results under different conditions or scenarios.

These checks involve applying the same methodology, which you used for your primary analysis, to a subset of the data or a specific context where no spillover effect is anticipated (Medoff et al., 2022). The goal is to ensure that your conclusions hold true across various situations and that they are not overly influenced by specific data points or assumptions.

Robustness checks provide valuable insights into the generalizability of your findings and help mitigate the risk of drawing unwarranted conclusions based on isolated observations. By conducting these checks, you demonstrate the rigor of your analysis and enhance the overall credibility of your spillover assessment.

### Variables to consider for assessing spillover effects

Below is a preliminary list containing variables to consider for the analysis of spillover effects (Table 29). This list is not exhaustive and can be expanded as necessary for specific studies to incorporate variables deemed crucial for a comprehensive analysis of spillover effects. Specific variables of interest may vary depending on the study system and the species under investigation. These variables can be used as predictors in statistical models to assess their influence on fish biomass or other spillover indicators.

**Table 29. List with potential variables in the assessment of spillover effects.**

| Variables |
|---|
| • Distance from the protected area: The proximity of sampling sites to the boundaries of the protected area. |
| • Time since establishment: The time that has elapsed since the establishment of the protected area. |
| • Habitat characteristics: Factors such as substrate type, depth, and complexity that may influence species distribution and abundance. |
| • Fishing effort: The intensity of fishing activity in the surrounding areas, both inside and outside the protected area. |
| • Species mobility: The movement patterns and migratory behavior of the target species. |
| • Exploitation of target species: The exploitation status of the species; heavily exploited species are likely to exhibit stronger MPA spillover effects. |
| • Pre-existing population dynamics: The initial population levels and trends of the species before the establishment of the protected area. |
| • Environmental variables: Factors such as temperature, salinity, and primary productivity that can impact species distribution and abundance. |
| • Size and design of the protected area: The extent, shape, and effectiveness of the protected area in conserving and promoting target species. |

| Variables |
| --- |
| • Connectivity with adjacent habitats: The degree of connectivity between the protected area and surrounding habitats, allowing for potential spillover. |
| • Fishing regulations: The presence and enforcement of specific fishing regulations within and outside the protected area. |

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# ANNEX 6: CASE STUDY REPORTS

Fifteen case studies in the Baltic Sea, North Sea, EU Atlantic Western Waters and some outermost regions (focusing on the Azores, Madeira and Canary Islands) were selected to gather insights into potential spillover effects of different types of marine protected areas (MPAs). The majority of the case studies (11) is located in the European Union (EU) waters (Belgium, France, The Netherlands, Poland, Portugal, Spain and Sweden); four case studies are located in non-EU waters (Norway and the United Kingdom).

In this case study work, besides studying typical MPAs, 'other effective area-based conservation measures' (OECMs), including offshore wind farms (OWFs) were also investigated, as they might be as relevant in the study of spillover effects. OECMs represent geographically defined areas outside formal protected areas which contribute to positive and sustained long-term outcomes for the in situ conservation of biodiversity.

The selection of case studies was made mainly based on geographical coverage and data availability to assess potential spillover effects. The case studies are well-spread in the different sea basins, cover an array of Member States and nations, but also vary in the type of species (e.g. fish, crustacea, bivalves) and type of data that are available (e.g. fishery data, trap data, tagging data, capture-recapture data). In the case studies, the spillover effects are analysed based on qualitative and/or quantitative analytical approaches, using available data and/or a stakeholder survey.

**Case studies on the assessment of potential spillover effects** published in a separate volume (doi:10.2926/384994)

| Nr | Case Studies | Country | Regional Sea |
|---|---|---|---|
| 1 | Gotska Sandön Marine Protected Area | Sweden | Baltic Sea |
| 2 | Słowiński and Woliński National Parks | Poland | Baltic Sea |
| 3 | Tvedestrand Marine Protected Area | Norway | Skagerrak |
| 4 | North Sea Coastal Zone | The Netherlands | North Sea |
| 5 | Borssele offshore wind farm zone | The Netherlands | North Sea |
| 6 | Belgian offshore wind farm | Belgium | North Sea |
| 7 | Lyme Bay Marine Protected Area | United Kingdom | English Channel |
| 8 | Flamanville Protected Area | France | English Channel |
| 9 | The Écréhous and the Minquiers | Jersey | English Channel |
| 10 | Lamlash Bay and South Arran | United Kingdom | Celtic Sea |
| 11 | Atlantic Islands National Park of Galicia | Spain | Iberian Coast |
| 12 | Professor Luiz Saldanha Marine Park | Portugal | Iberian Coast |
| 13 | Formigas Marine Protected Area | Portugal | Macaronesia |
| 14 | Selvagens Islands Marine Protected Area | Portugal | Macaronesia |
| 15 | La Graciosa Marine Protected Area | Spain | Macaronesia |

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