A7 Deliverable - Pressure maps for the whole coast of Finland based on models

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Introduction

This deliverable is part of the BIODIVERSEA Action 7: *Identifying pressures affecting marine environment and actions that mitigate those pressures* and presents results for the deliverable *Pressure maps for the whole coast of Finland based on models.* The deliverable results are detailed in a recent publication (Virtanen et al. 2026) and outlined briefly below.

Human activities strongly impact shallow coastal marine ecosystems, particularly benthic habitats that underpin biodiversity, food webs, and ecosystem resilience. Although cumulative effect assessments (CEAs) are widely used to evaluate combined human pressures, they often suffer from scale- and data-related limitations that can obscure localized impacts in complex coastal seascapes. To address these gaps, we applied a high-resolution, spatially explicit framework to identify clusters of co-occurring human pressures, assess their overlap with eutrophication, and quantify their relative impacts on benthic ecosystems using detailed species distribution models. Our approach aims to improve ecological condition assessments and support targeted conservation and restoration actions aligned with global biodiversity goals.

Data and methods

The study area covers the Finnish marine area, encompassing approximately 81,500 km² of shallow coastal waters characterized by strong environmental gradients in salinity, depth, and geomorphology, as well as high eutrophication and seasonal ice disturbance. The region includes exposed sandy coasts in the north and a highly fragmented archipelago system in the south, supporting diverse but relatively species-poor benthic communities adapted to low salinity and harsh conditions.

We compiled high-resolution spatial data on a wide range of human activities affecting benthic habitats, including coastal infrastructure, dredging, dumping, shipping and boating routes, aquaculture, sand and mineral extraction, and other marine uses. Data were sourced from national registers, reported activity datasets, and interpretation of aerial imagery to capture both large- and small-scale activities. The temporal scope of the analysis corresponds to the availability of these datasets and aligns with the period of biological surveys. Most of the activities were concentrated in the inner archipelago and close to shore, with the majority related to recreation (Fig. 1).

Based on these human activity layers, we modelled human pressures potentially affecting the seafloor by distinguishing between direct footprints and diffuse pressures. Direct footprints represent permanent habitat loss caused by structures or activities and were quantified as fractional coverage within a 20 m grid. Diffuse pressures represent ongoing or recurrent disturbances, such as sedimentation and turbidity, extending beyond activity footprints. These were modelled using distance-decay functions parameterized using scientific literature, available regional guidelines (e.g. MSFD), and expert judgement. Separate models were developed for maritime traffic, incorporating distance to shipping lanes, shoreline proximity, and water depth to reflect spatial variation in seafloor disturbance.

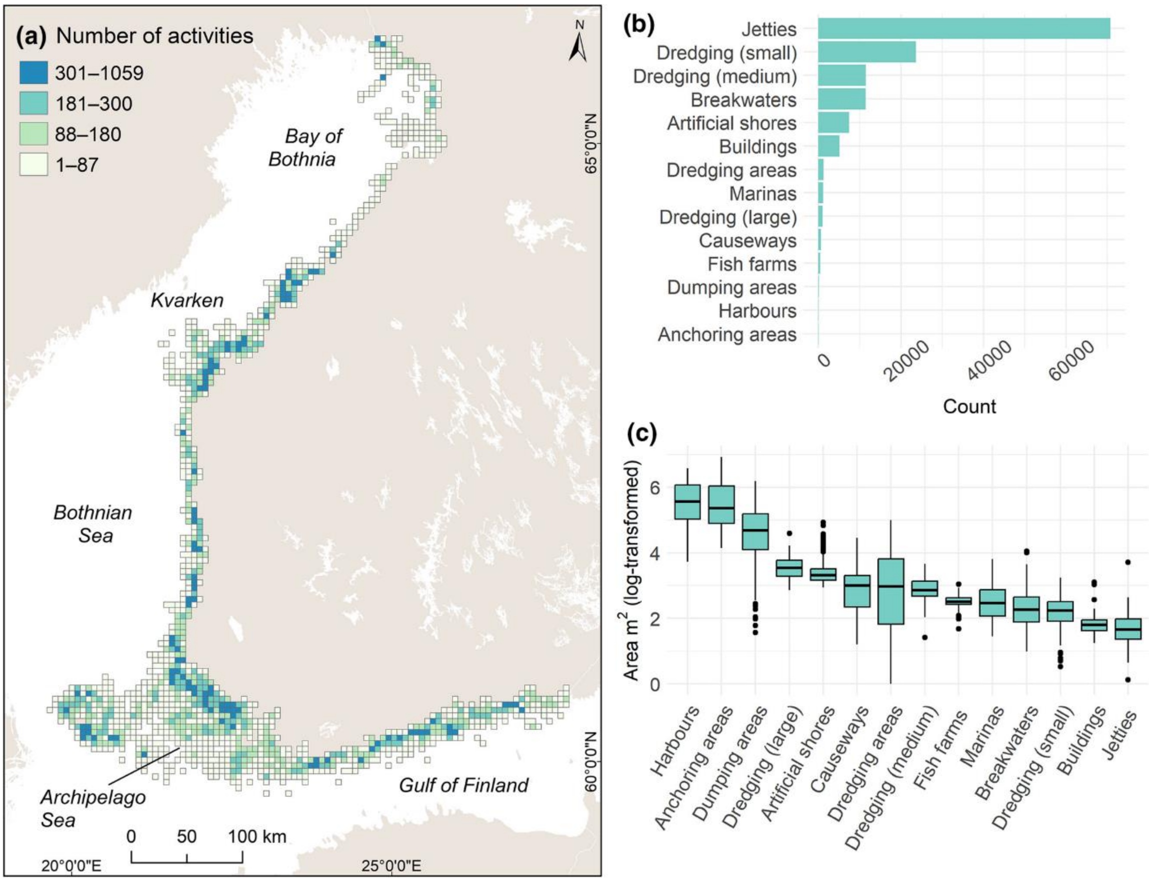

Figure 1. *Map showing the number of activities within 5 × 5 km grids visualized with quantiles (a), the number of individual activities (b), and their spatial footprints (c). Line-type activities are excluded from the figure (marine cables, boating fairways, shipping lanes).*

We then analysed the co-occurrence of pressures by identifying spatial clusters of areas with similar pressure profiles. Using spatial pressure signatures calculated within a 2-km neighbourhood, we quantified similarity among areas using Jensen–Shannon divergence and applied hierarchical clustering to delineate distinct pressure complexes. Cluster robustness and separability were evaluated using statistical stopping rules and spatial homogeneity metrics.

To assess how pressure complexes interact with eutrophication, we characterised the eutrophication profile of each cluster using spatial datasets on nutrient concentrations, hypoxia frequency, and particulate accumulated matter. These indicators represent long-term growing-season conditions derived from monitoring data and modelling. We compared eutrophication levels in pressure clusters with reference areas lacking mapped human activities and tested for differences among clusters using nonparametric statistical analyses.

Finally, we evaluated the ecological impacts of pressures on benthic ecosystems using species distribution models (SDMs) developed from extensive underwater survey data collected through the Finnish inventory programme for underwater marine diversity (Velmu). SDMs for 112 benthic species were grouped into 31 habitat types and used to estimate potential habitat distributions at 20 m resolution. For each habitat type, we quantified the proportion of area affected by different pressures by combining predicted habitat occurrence with pressures. As the SDMs were developed independently of the mapped human activities, they represent potential distributions under prevailing environmental conditions, allowing us to estimate the relative contribution of different human pressures that impacts benthic biodiversity.

Results

We identified generally positive but weak spatial associations among most diffuse pressures, indicating that many human activities tend to co-occur but only to a limited extent. The strongest spatial association was observed between dredging areas and shipping lanes, while weaker links were found among recreational land use, coastal infrastructure, harbours, and boating fairways. Using clustering analysis, we delineated three distinct pressure complexes across Finnish marine waters: a nearshore "Recreation cluster" dominated by recreational land use, coastal infrastructure, and boating activities; an "Industry cluster" associated primarily with commercial harbours and anchoring areas; and a "Maritime traffic cluster" characterized mainly by shipping lanes (Fig. 2). Industrial and maritime traffic clusters were spatially more homogeneous, whereas recreational pressure complexes were highly heterogeneous, particularly within the inner and middle archipelago where multiple recreational activities frequently overlapped.

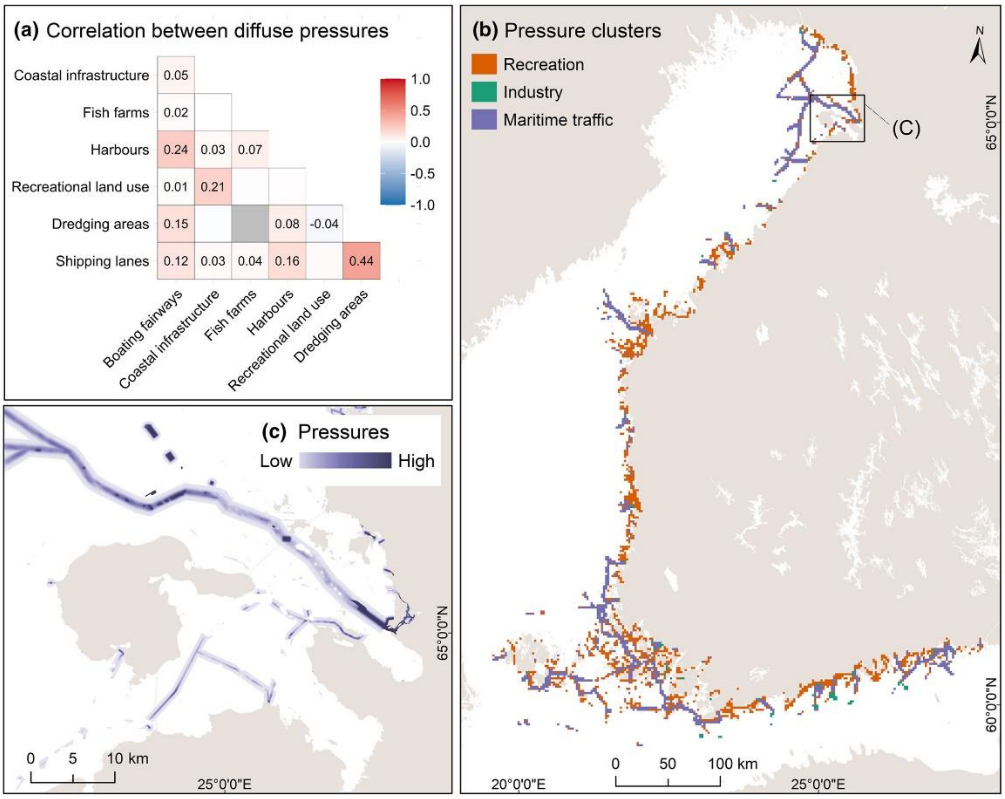

Figure 2. *Pairwise correlation between diffuse pressures with statistically significant associations indicated by numbers and grey indicating no overlap (a), results of cluster analysis showing the three identified impact signatures (b), and an example area of pressures exerted (mainly related to cluster 'Maritime traffic') (c).*

All identified pressure clusters were associated with elevated eutrophication levels compared to reference areas without mapped human activities. Nutrient concentrations and particulate accumulated matter were higher across all clusters, with the strongest accumulation observed in recreational areas. The industrial cluster showed the highest likelihood of hypoxia occurrence. Statistically significant differences in eutrophication conditions were detected among all pressure clusters, indicating that different pressure complexes are associated with distinct eutrophication profiles (Fig. 3).

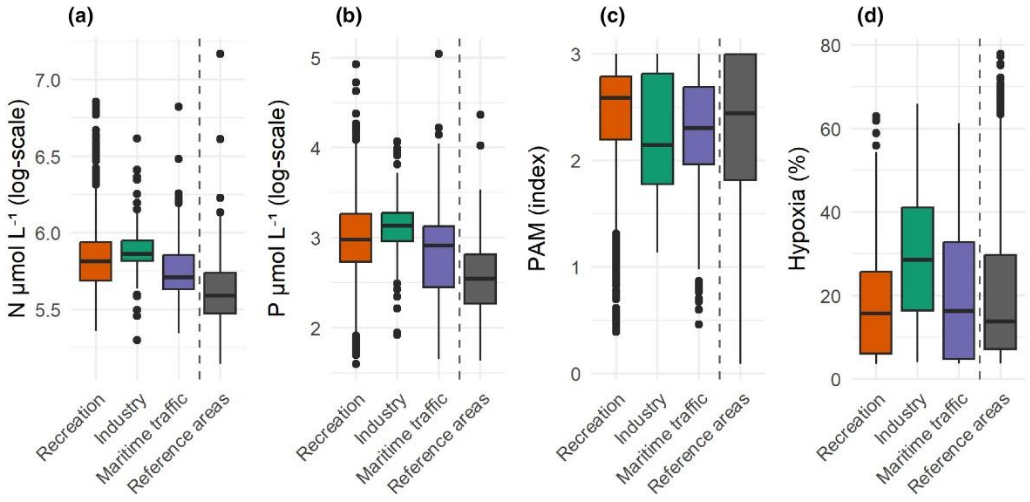

Figure 3. *Eutrophication profiles of pressure clusters and reference areas, based on total nitrogen (µmol L^{-1}) (a), total phosphorus (µmol L^{-1}) (values log-transformed) (b), particulate accumulated matter (PAM), where the index values represent the amount of accumulated matter: 0 = none, 1 = small amount, 2 = intermediate amount and 3 = substantial amount (c), and probability (%) of hypoxia occurrence (d). Reference areas ('pristine groups') are areas without considerable human activities and were not associated with any of the pressure clusters identified.*

Direct impacts on benthic habitats were dominated by dredging, which caused the greatest habitat loss, particularly in shallow vegetated habitats such as mare's-tail meadows, floating-leaf plant communities, spiny naiad, and charophyte-dominated lagoons. Coastal infrastructure was the second most damaging activity and affected largely the same habitat types. Although dredging and coastal infrastructure covered a very small proportion of the total sea area, they accounted for a disproportionate share of total habitat loss, which nevertheless remained below 3% per habitat type when summed across all activities. In contrast, indirect impacts from diffuse pressures were much more extensive. When combined across activities, indirect impacts exceeded 40% of the potential distribution for many habitat types. Boating fairways caused the largest indirect impacts, followed by shipping lanes, recreational land use, and coastal infrastructure. Boating activities primarily affected mussel- and clam-dominated habitats, while shipping lanes disproportionately disturbed deeper benthic habitats characterized by amphipods, polychaetes, and Baltic clams. Shallow coastal habitats were most strongly affected by recreational activities.

When accounting for both spatial extent and impact magnitude, dredging, harbours, and coastal infrastructure caused greater habitat loss than expected based on their limited geographic coverage. Conversely, indirect impacts from most activities, particularly recreational land use, coastal infrastructure, and boating fairways, were substantially larger than expected, highlighting the dominant role of widespread, diffuse pressures in shaping benthic habitat condition (Fig. 4).

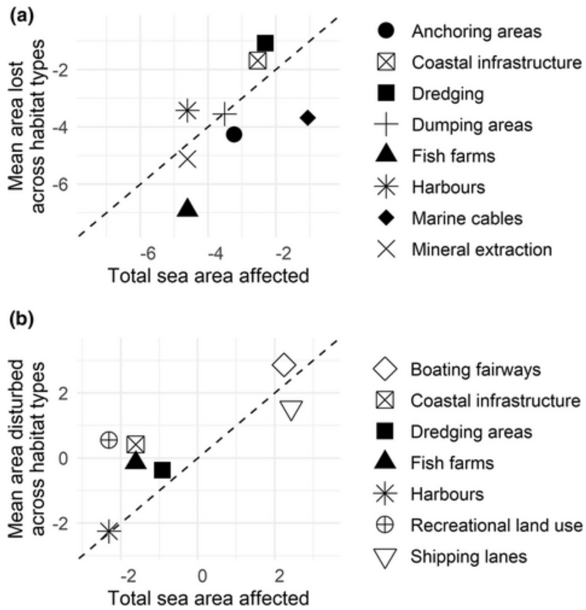

Figure 4. *Relative severity of the impact of activities based on their geographic extent (% of the sea area), calculated as the mean habitat loss (a) and disturbance (b) across habitat types. Both axes are shown on a logarithmic scale. The diagonal line shows the line at which impacts are expected 1:1 relative to their size. The impact of activities on habitat types is larger than expected if the symbols are above the line and lower if under the line.*

Discussion

We show that diffuse pressures from human activities exert far greater and more widespread impacts on benthic habitats than direct habitat loss, despite many activities being geographically confined. When analysed at high spatial resolution, human activities form distinct diffuse pressure complexes, clusters of co-occurring pressures that collectively affect a wide range of habitat types. These complexes were most pronounced in the inner and middle archipelago, where they overlap with eutrophication pressure from land-based sources, potentially amplifying their ecological effects.

Indirect disturbance from diffuse pressures was one to two orders of magnitude greater than direct habitat loss. Recreational boating emerged as a particularly influential driver of benthic disturbance, affecting numerous habitat types. These impacts are likely amplified by the seasonal coincidence of peak boating activity with the growing season of aquatic vegetation and by the accessibility of shallow, sheltered areas with limited water exchange. In contrast, industrial uses such as shipping lanes and harbours showed relatively limited estimated impacts, likely because they are located in deeper waters. However, this contrast raises important questions about pressure detectability and causality, including whether some impacts are already embedded in environmental predictors used in species distribution models or whether exposure does not necessarily translate into ecological harm. These uncertainties highlight the need for more empirical studies, including before–after control–impact designs, to better resolve cause–effect relationships between specific pressures and ecological responses.

All identified pressure complexes were associated with elevated nutrient levels compared to reference (“pristine”) areas, suggesting strong interactions between diffuse pressures and eutrophication. Decades of nutrient enrichment have reduced ecosystem resilience in the Baltic Sea, potentially making benthic communities more vulnerable to additional human pressures. The distinct eutrophication profiles of pressure complexes further indicate that ecological sensitivities vary spatially, underscoring that uniform management approaches are unlikely to be effective. Instead, mitigation measures must be tailored to specific pressure complexes and coordinated across sectors and spatial scales.

From a management perspective, our findings emphasize the need to address numerous small-scale activities that collectively drive substantial ecosystem degradation but often fall below regulatory thresholds. Targeted measures such as stricter regulation of small-scale dredging, spatial restrictions or speed limits for recreational boating in sensitive areas, and ecosystem-based coastal development guidelines are likely to yield disproportionate conservation benefits. In a heavily eutrophicated system, identifying and safeguarding areas that remain in relatively good condition is particularly important, as these areas may also offer the greatest potential for cost-effective restoration.

Reference

Virtanen, E. A., L. Forsblom, L. Kaikkonen, N. Kallio, S. Korpinen, A. Takolander, T. Wärri, and M. Viitasalo. 2026. Impacts of diffuse pressure complexes complicate conservation and management of benthic marine habitats. Journal of Applied Ecology **n/a**:e70247.