A4.1 Deliverable - Maps showing important areas based on ecological connectivity

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Introduction

This deliverable is part of the BIODIVERSEA Action 4: Analysing the sufficiency of the marine protected area network and presents results of sub-action 4.1. Analysing the ecological sufficiency of the present MPA network (ecological connectivity). The deliverable results are detailed in a recent publication (Miettunen et al. 2026) and outlined briefly below.

Ecological connectivity is a fundamental concept in spatial ecology. Connectivity can broadly be described as spatial linkages between two populations or habitat patches, maintained through flows of energy or materials, realized through movement or dispersal of organisms. In marine protected area design and planning, connectivity should be accounted for, not only between MPAs, but also outside MPAs, as to get a broad overview where conservation (or restoration) efforts may be effective (or futile) in the future.

In marine systems with variable current patterns, a key challenge remains how to quantify connectivity in ecologically meaningful way (e.g. Virtanen et al. 2020). We evaluated ecological connectivity of benthic habitats in the Archipelago Sea by using the Lagrangian particle tracking model OpenDrift (Dagestad et al. 2018) together with current velocity data from a high-resolution (500 m) 3D hydrodynamic model, informed by detailed species distribution models. Using data on benthic habitats enabled us to focus the investigation on areas with high habitat quality, instead of concentrating only on MPAs.

Data and methods

The study area covers the Archipelago Sea and the adjacent Åland Sea in the southwestern part of Finland (Fig. 1). The Archipelago Sea has more than 50,000 small islands and skerries, which is why resolving connectivity patterns within these areas needs as input high-resolution current velocity and biological data. The area has steep bathymetry gradients, with several channels exceeding 100 m in depth, while the mean depth is only 19 m. The Åland Sea is much more open and deeper, consisting of two deep basins reaching a maximum depth of approximately 300 m.

We used 3D current velocity fields from a high-resolution NEMO model covering the Åland Sea-Archipelago Sea with ~460 m horizontal resolution. The model has 200 vertical layers, with ~1 m spacing in the upper 120 m and up to 8 m in deeper areas (~280 m). Output consisted of 6-hourly averages for 2013–2017, forced by ERA5 atmospheric data and CMEMS reanalysis at the open boundaries (~3.7 km resolution). Details of the configuration and validation are provided in Westerlund et al. (2021) and Miettunen et al. (2024).

We simulated connectivity between selected sites in the Archipelago Sea and Åland Sea using the OpenDrift Lagrangian particle-tracking model (Dagestad et al., 2018), applying its passive drift module and offline forcing from precalculated currents. Simulations used a second-order Runge-Kutta scheme with a 5-min time step. Horizontal diffusion and vertical turbulent mixing were represented with random-walk parameterizations: we applied $K_h = 1.0$ m²/s for horizontal diffusion and $K_v = 0.002$ m²/s for vertical mixing, the latter based on average values estimated from NEMO output. Vertical mixing used a 5-s internal timestep. Random-walk diffusion mainly influences trajectories in open-sea areas, whereas flow in most of the study region is constrained by coastline and bathymetry.

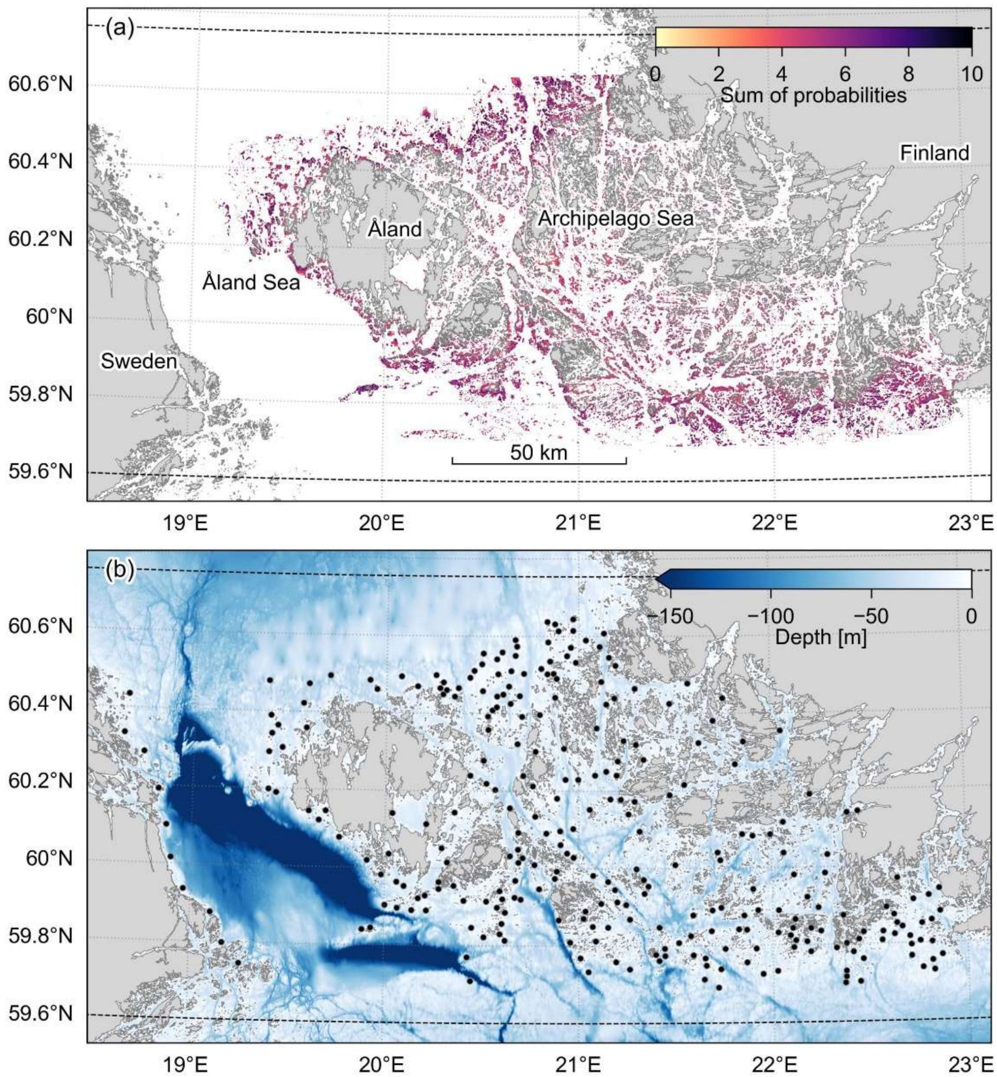

***Figure 1**. (a) Key habitat areas for hard substrate species within Finnish waters in our study area. (b) Bathymetry in the Åland Sea and Archipelago Sea region indicated with a blue colour scale and the seeding locations of the propagules indicated with black dots. Dashed black lines show the southern and northern borders of the model domain. Bathymetry and coastline data from EMODnet Bathymetry Consortium, 2022. Image courtesy: Miettunen et al. (2026).*

To simplify ecological connectivity modelling, we identified key habitat areas using 46 species distribution models (SDMs) at 20 m resolution (Virtanen et al. 2024), based on environmental variables such as bathymetry, substrate, and salinity. We summed the SDM probability maps, cropped them to the hydrodynamic model domain, and applied the 0.80 quantile threshold to delineate high-biodiversity habitat areas. The focus was on hard-bottom benthic species (e.g. macroalgae and invertebrates), mainly found in outer-archipelago reef areas, as inner-archipelago habitats have declined due to eutrophication.

To keep particle-tracking simulations computationally feasible, we selected 275 random seeding locations within the identified habitat areas in the Archipelago Sea, spaced at least 1.5 km apart to match the model resolution (see Figure 1). We also added 10 evenly spaced locations along the Swedish coast to assess potential connectivity with Finnish habitats, as Swedish SDM data was lacking.

In the trajectory simulations, particles represented neutrally buoyant propagules (e.g., spores, seeds, planktonic stages) and were modelled as passive Lagrangian particles without swimming, settling, or mortality, mostly due to limited information available. Dispersal traits were approximated by defining the seeding and drift periods: propagules were released during May-August, reflecting peak reproduction, and tracked for a maximum pelagic duration (PD) of 30 days. Although true PDs likely vary among species, this upper limit allowed us to compare relative connectivity patterns across the study area.

From each location, 100 particles were released twice daily throughout May-August, yielding 6000–6200 particles per site per month. Particles were seeded randomly within 250 m of each site and evenly across the upper 11 m of the water column (or the full depth if shallower), matching observed habitat depths of hard-bottom species (i.e. Forsblom et al. 2024). Each propagule was tracked for 30 days, with individuals deactivated upon reaching the domain boundary; those encountering coastline remained stationary until currents allowed them to continue. Outputs were recorded hourly, including particle status, position, depth, and age.

We estimated ecological connectivity as *potential connectivity*, defined as the probability that propagules travel between habitat sites. For each pair of seeding locations, potential connectivity was calculated as the percentage of particles released from one site that passed within 500 m of the other during a given pelagic duration (PD). No pre-competence period, settlement rules, or depth constraints were applied, so any particle passing a site counted as a connection, representing the maximum possible passive dispersal range. Connectivity was evaluated for PDs of 5, 15, and 30 days.

Results

We averaged potential connectivity across all simulated summers (2013–2017) to obtain mean connectivity patterns for the region. These results are shown as connectivity matrices (Figure 2), illustrating the probability of transport between each of the 285 seeding locations for pelagic durations of 5 and 30 days.

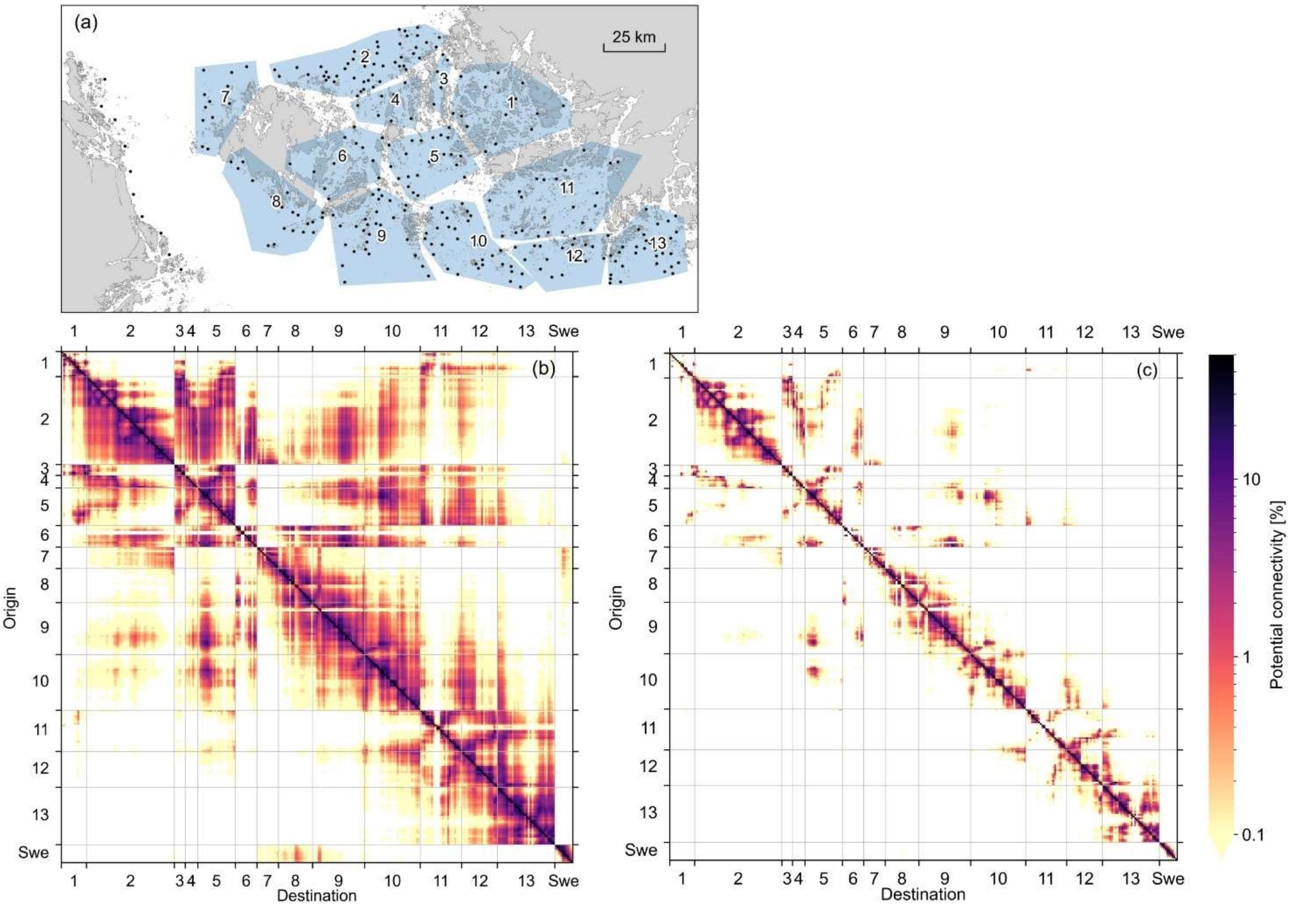

Figure 2*. (a) Grouping of habitat locations based on occurrence intensity of habitats and archipelago characteristics (e.g., geography, bathymetry). Mean potential connectivity (%) between all 285 locations for pelagic durations of 30 days (b) and 5 days (c). Values <0.01% are omitted. Axis numbers correspond to the groups shown in panel (a), where, for example, group 1 contains 14 inner-archipelago sites and group 2 includes 49 northern open-sea sites.“Swe” indicates the 10 Swedish coastal locations. Coastline data: EMODnet Bathymetry 2022. Image from (Miettunen et al. 2026).*

Potential connectivity during the summer season is higher from north to south than vice versa, as the prevailing current directions in the surface layer are not favorable for northward transport from the southern parts of the Archipelago Sea (Figure 3). With a 30-day pelagic duration propagules from the northern outer archipelago disperse southward to the central outer archipelago (groups 4–6), the southern outer archipelago, and the Åland Islands. Southern outer-archipelago habitats (groups 10–12) show moderate connectivity to central groups (4–5) but only weak links northward. Central outer-archipelago sites (groups 3–5) connect in both directions, with generally stronger southward transport.

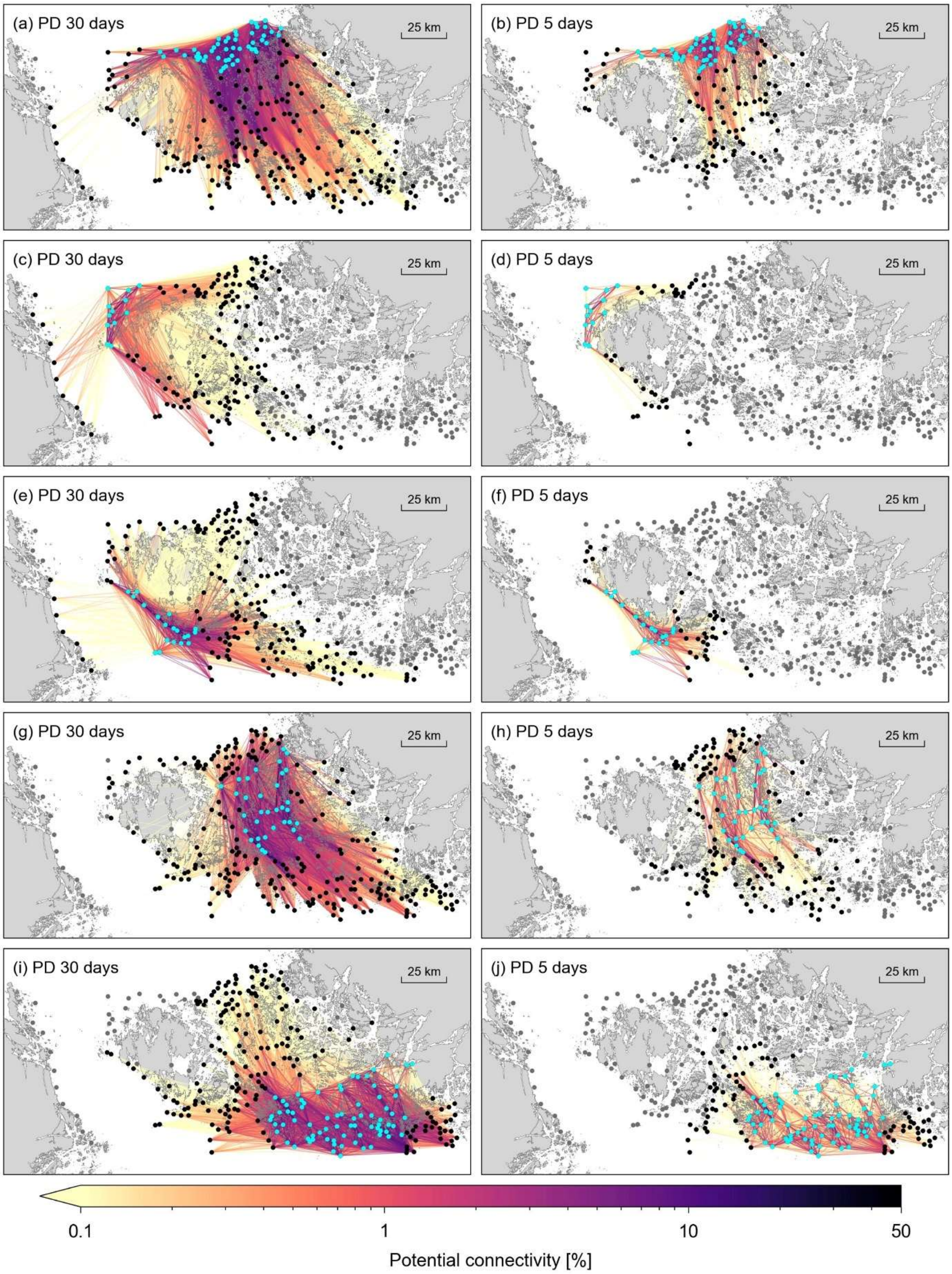

***Figure 3**. Mean potential connectivity (visualised with coloured lines) from selected seeding locations (points highlighted with cyan) when pelagic propagule duration (PD) is 30 days (left panels) and 5 days (right panels). Black dots show locations to which there is at least some connection from the selected locations and grey dots show the rest of the modelled seeding locations.*

With a 5-day PD, dispersal is much more restricted. Northern sites connect only as far as the central archipelago, while southern sites mostly connect within their own region. Central outer-archipelago locations retain limited two-way connectivity, mainly northward from groups 3–4 and southward from group 5.

We also identified several habitat areas with limited dispersal potential. Sheltered inner-archipelago habitats (group 1) are especially isolated from the rest of the Archipelago Sea. With a 30-day PD, propagules arriving there originate mainly from the northern and central outer archipelago (groups 2, 3, 5), while those leaving disperse mostly toward central and southern outer-archipelago habitats (groups 3, 5, 11, 12). With a 5-day PD, both incoming and outgoing connections are sparse and occur only among a few nearby sites. Habitats along the western Åland island coast (groups 7, 8) are likewise largely isolated. With a 30-day PD, they show some links to northern and southern outer-archipelago sites, but with a 5-day PD they connect only with nearby locations. We also examined connectivity with Swedish coastal habitats. With a 30-day PD, some links exist between Sweden and the western Åland island sites, and a few weak connections appear with a 15-day PD.

We further evaluated annual and monthly variability in connectivity and found some differences in patterns for a 30-day PD, driven mainly by changes in prevailing surface currents. Dispersal probabilities for propagules released in May-July were generally consistent across 2013–2017 (Fig. 4). In late summer, however, northward currents become more common. Therefore, propagules released in August and drifting into September show increased northward transport and reduced southward transport. As a result, connectivity slightly increases from southern to northern sites and decreases from north to south compared to earlier months.

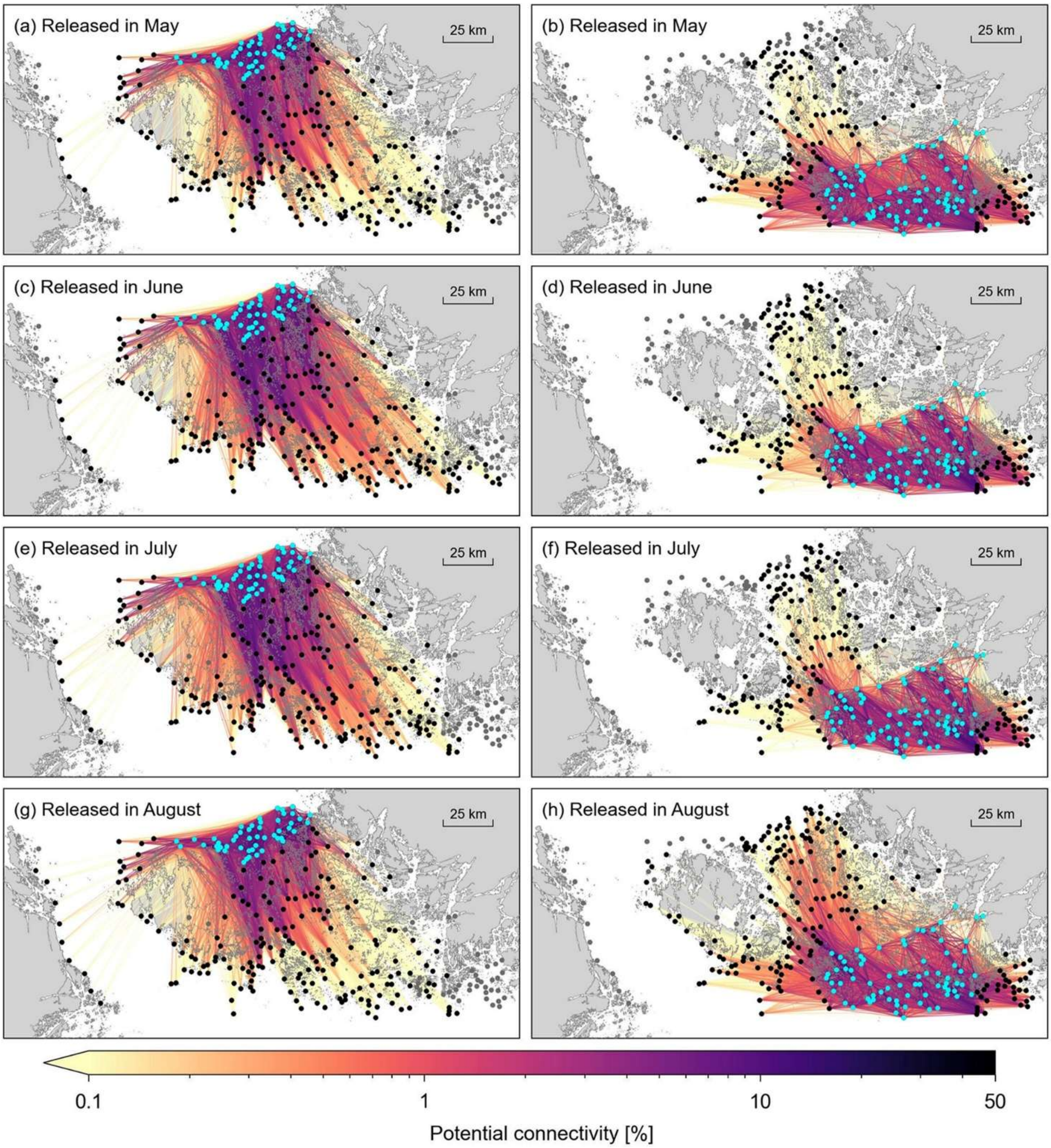

Figure 4. *Monthly mean potential connectivity (visualised with coloured lines) from selected seeding locations (points highlighted with cyan) when pelagic propagule duration (PD) is 30 days. Left panels show connectivity from the northern habitats and right panels from the southern habitats. First row shows the probability of dispersal for propagules that are seeded in May and are drifting during May–June, the second row the propagules seeded in June and drifting during June–July, etc. Black dots show locations to which there is at least some connection from the selected locations and grey dots show the rest of the modelled seeding locations.*

Discussion

Overall, our results show that ecological connectivity was generally low and strongly distance-dependent in the area, driven by variable surface currents. Despite the rather low connectivity between different habitats in the area, we identified several key areas that may play an important role in sustaining gene flow across broader regions. Our results suggest that habitats in the northern part of the Archipelago Sea are particularly important for maintaining ecological connections to habitats further south. This has one important implication: maintaining northern habitats in good ecological condition is crucial, meaning that activities that may result in ecological deterioration of habitats should be avoided or impacts minimized. We also identified effectively isolated habitats, mainly in the inner archipelago, which also are in poor ecological condition due to eutrophication and other sea uses. Therefore, recovery of key species within the area may be difficult even with considerable efforts to mitigate eutrophication due to poor ecological connectivity with other areas.

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