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Coastal habitats and sea level rise in Finland — vulnerability and adaptation

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Coastal meadows and sandy beaches in the Gulf of Finland are important habitats for a wide variety of species, but they are under threat from rising sea levels. In this study, we used sea level rise projections and spatial data to analyse the extent of habitat loss and the migration potential of these habitats along the northern coast of the Gulf of Finland. Our results show that 10–92% of the current coastal meadow area and 14–65% of sandy beaches will become submerged by 2100, depending on the sea level rise scenario. The likelihood of coastal habitat survival decreases with higher magnitudes of sea level rise due to extensive losses and limited migration potential. Increased coastal management, restoration, and land use planning are needed to preserve the current extent of coastal habitats in the future.

Introduction

Coastal habitats and low-lying ecosystems are facing the impacts of sea level rise (SLR). Adverse consequences of SLR include habitat submersion and degradation, coastal erosion, and biodiversity loss. When sea levels rise and habitat migration is blocked by physical barriers such as roads, buildings, topography, or unsuitable soil, habitats become confined within a shrinking space between a fixed barrier and the rising sea (Fig. 1; Pontee 2013, Silva *et al.* 2020, Agulles 2021). This phenomenon, called coastal squeeze, can limit adaptation opportunities and eventually lead to habitat loss. Steep topography and man-made infrastructure are the main limiting factors identified in the literature (e.g. Torio and Chmura 2013, Borchert *et al.* 2018).

Several studies have established that migration can effectively mitigate the loss of various coastal habitats (e.g., Sims *et al.* 2013, Linhoss *et al.* 2015, Thorne *et al.* 2018), although adaptation depends on local conditions (Borchert *et al.* 2018, Smith 2020). If suitable low-lying open space exists adjacent to current ecosystems, migration can occur naturally. Habitat migration can be supported through coastal planning, such as building regulations, or by securing sufficient inland space and migration corridors for habitat relocation (Leo *et al.* 2019, Spidalieri 2020). Existing coastal habitats can also be protected or restored to enhance their resilience to rising sea levels (Spidalieri 2020).

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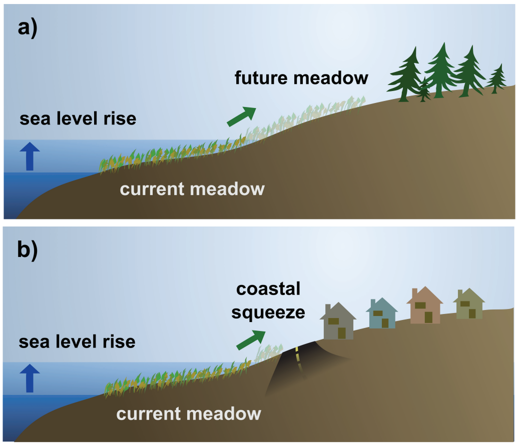

Fig 1. Illustration of coastal squeeze. **a**) The coastal meadow submerged by the rising sea can migrate inland. **b**) The migration is prevented by coastal infrastructure.

In this study, we examine the impacts of SLR on coastal ecosystems along the northern coast of the Gulf of Finland (GoF), Baltic Sea. This region experiences the strongest impacts of SLR in Finland, as post-glacial land uplift is weaker here than along other parts of the Finnish coast (Pellikka *et al.* 2023). We focus on two types of coastal habitats: coastal meadows and sandy beaches (Fig. 2). Despite their relatively small size, these habitats support a significant number of species and are among the most biodiverse habitat types on the coasts of Finland. According to the Finnish Red Data Book of species, 85 taxa (25%) out of the 335 assessed species primarily inhabiting coastal meadows are considered threatened or near threatened (Hyvärinen *et al.* 2019). On sandy beaches, the proportion of threatened or near threatened species is even higher: 161 taxa (42%) out of 384 assessed species.

Coastal meadows encompass various open habitats characterised by perennial vegetation. This habitat type is highly diverse and rich in flora, remaining open either through grazing or natural forces such as sea ice and waves, which prevent tree growth. In Finland, six seashore meadow types have been identified which depend on traditional land practices such as cattle grazing and mowing. Each of these meadow types is classified as Critically Endangered (Lehtomaa *et al.* 2019). Coastal stony meadows, which are maintained by natural forces rather than grazing, are classified as Near Threatened in the national assessment of habitat types (Kontula and Raunio 2019, Reinikainen *et al.* 2019). This type of meadow is typical and widespread along the entire GoF coast, although individual sites are generally small and narrow (Reinikainen *et al.* 2019).

In Finland, coastal habitats and species are threatened by both direct and indirect human impact. The main threat arises from the eutrophication of the Baltic Sea, which leads to excessive vegetation growth, further exacerbated by the reduction or cessation of traditional grazing and mowing practices in many areas (Reinikainen *et al*. 2019). Coastal sandy beaches and their diverse flora and fauna are also at risk from activities such as trampling, construction, and the spread of invasive species, including the rugosa rose (*Rosa rugosa;* Reinikainen *et al.* 2019). Sea level rise adds further pressure to these already vulnerable habitats (Ryttäri *et al*. 2023).

The coastline of Finland is rugged and predominantly composed of bedrock and moraine, which together account for 84% of the shoreline (Granö *et al.* 1999). Approximately 5% consists of sandy and gravelly areas, while 10% is made up of finer materials such as clay and silt, which provide suitable soil conditions for coastal meadows. The northern GoF coast is characterised by an irregular coastline with a vast number of islands and a high level of coastal development. The shore is typically steep and rocky, with narrow vegetation zones (Reinikainen *et al.* 2019), making coastal habitats particularly vulnerable to SLR.

This study examines whether valuable coastal ecosystems are under threat from future SLR in the GoF. In addition, we investigate the migration opportunities of coastal meadows and sandy beaches. To our knowledge, this is the first study of this topic focusing on the Finnish coastal areas. We aim to answer the following research questions:

1) To what extent will the current coastal meadows and sandy beaches be submerged under different scenarios of future SLR by 2100?
2) What is the theoretical migration space available for coastal meadow and sandy beach ecosystems in the study area?

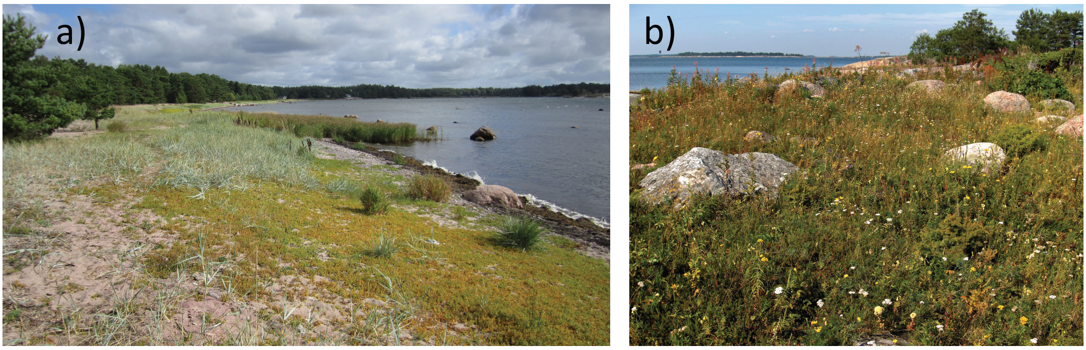

Fig 2. a) A sandy beach on the Hanko Peninsula with typical vegetation. **b)** A small patch of coastal meadow in Kirkkonummi, Gulf of Finland.

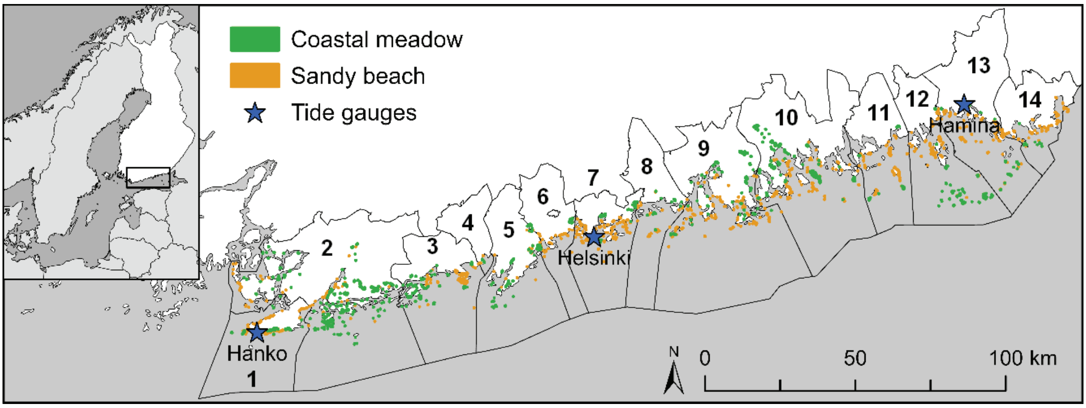

Fig 3. Coastal meadows, sandy beaches, and the locations of tide gauges in the study area along the northern coast of the Gulf of Finland. The polygon boundaries of coastal habitats are emphasised to make the features visible on the map. Black lines mark the municipality boundaries. The municipalities are numbered as follows: 1) Hanko, 2) Raasepori, 3) Inkoo, 4) Siuntio, 5) Kirkkonummi, 6) Espoo, 7) Helsinki, 8) Sipoo, 9) Porvoo, 10) Loviisa, 11) Pyhtää, 12) Kotka, 13) Hamina, 14) Virolahti.

Materials and methods

Sea level rise projections

Our study area covers the northern (Finnish) coast of the GoF, extending from the Hanko Peninsula in the west to Virolahti in the east (Fig. 3). In this region, the two main opposing factors affecting long-term sea level are global sea level rise and postglacial land uplift. Land uplift proceeds at a constant rate on a century timescale, ranging from 4.2 mm yr^{-1} in the west to 3.0 mm yr^{-1} in the east (Pellikka *et al.* 2023). By comparison, the rate of global SLR is accelerating and averaged 3.7 mm yr^{-1} between 2006 and 2018 (Fox-Kemper *et al.* 2021). At present, land uplift and global SLR approximately counterbalance each other in the study area. However, as global SLR accelerates, it will surpass land uplift, reversing the historically declining mean sea level trend in the region.

Future SLR remains highly uncertain. The primary drivers of global SLR are the thermal expansion of seawater and the melting of glaciers and ice sheets. Various methods exist for projecting future SLR, leading to considerable variation in the projections published in scientific literature (Garner *et al.* 2018). Additionally, regional deviations from the global mean are significant. In this study, we use the local SLR projections from Pellikka *et al.* (2023). Rather than relying on a single global SLR projection, these projections are based on ten studies published between 2012 and 2021, including the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Fox-Kemper *et al.* 2021). In addition to global factors, the projections by Pellikka *et al.* (2023) account for regional anomalies in SLR rates, postglacial land uplift, and changes in wind climate, which may influence mean sea level within the semi-enclosed Baltic Sea basin (Johansson 2014).

The rate of future SLR depends on the trajectory of anthropogenic greenhouse gas emissions. The SLR projections used in this study are based on three different emission pathways, known as Shared Socioeconomic Pathways (SSPs). The lowest scenario, SSP1-2.6, represents ambitious climate change mitigation: rapid and immediate emission reductions keep global warming below 2°C (Chen *et al.* 2021). In the intermediate scenario, SSP2-4.5, emissions peak around mid-century, with global warming estimated to remain below 3°C. In the high-emission scenario, SSP5-8.5, emissions continue to rise throughout the century, potentially leading to warming exceeding 4°C. Current policies suggest that the intermediate scenario is more likely to be realised than the low or high scenario (Hausfather and Peters 2020, den Elzen *et al.* 2022).

Pellikka *et al.* (2023) provide full probability distributions of the expected sea level in 2100 at the Finnish tide gauge locations under the three emission scenarios. To assess the impact of SLR on coastal habitats, we selected five projections to represent different possible future pathways for local sea level (Table 1):

1) Low: The median projection under the low-emission scenario (SSP1-2.6)
2) Medium: The median projection under the intermediate scenario (SSP2-4.5)
3) High: The median projection under the high-emission scenario (SSP5-8.5)
4) Very high: The 95th percentile under the intermediate scenario (SSP2-4.5)
5) Extreme: The 99th percentile under the intermediate scenario (SSP2-4.5)

The two low-probability projections, "very high" and "extreme", were included to account for the high uncertainty in future SLR projections. Most of this uncertainty stems from the potential instability of marine ice sheets, particularly the West Antarctic ice sheet (DeConto *et al.* 2021, Fox-Kemper *et al.* 2021, Morlighem *et al.* 2024). Even greater SLR cannot be ruled out if emissions follow the highest emission scenario, but such a rise is extremely unlikely.

To illustrate the different projections used, we present them alongside observed annual mean sea levels in the study area over the 20th century (Fig. 4). Tide gauge data from the Finnish Meteorological Institute's database were used to calculate the historical time series, and a simple second-order fit was applied to create a time series extending from the present to the projected mean sea level in 2100.

Pellikka *et al.* (2023) provide projections for the Finnish tide gauge locations, three of which are in the study area: Hanko, Helsinki, and Hamina (Fig. 3). We interpolated the SLR projections into a continuous surface along the GoF coast using Triangulated Irregular Network (TIN) interpolation. A Digital Elevation Model

Table 1. Local sea level rise projections used in this study (Pellikka *et al.* 2023): change over the 21st century (from the 1995–2014 baseline to 2100) and the mean sea level in 2100 in the Finnish national N2000 height system. All values are in cm.

Scenario	Hanko		Helsinki		Hamina	
	1995–2014 to 2100	2100 (N2000)	1995–2014 to 2100	2100 (N2000)	1995–2014 to 2100	2100 (N2000)
Low	4	23	9	29	16	37
Medium	20	39	25	45	31	53
High	49	68	54	74	61	82
Very high	72	90	76	96	83	105
Extreme	113	132	118	138	125	146

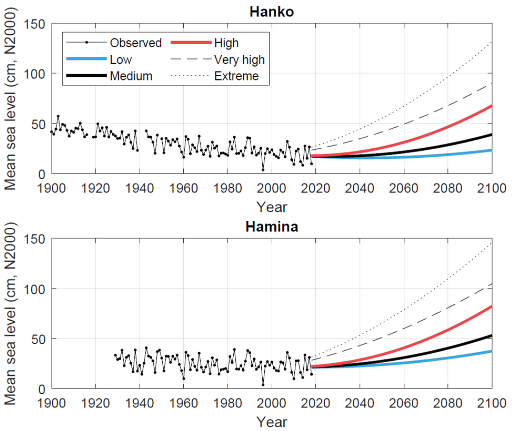

Fig 4. Sea level rise projections used in this study, shown for two locations: Hanko in the western part of the study area and Hamina in the east (see Fig. 3). Observed annual mean sea levels are also plotted for comparison.

(DEM) with two-metre resolution was used to create layers representing the future extent of the sea for each SLR scenario. Areas where the elevation (DEM value) was lower than the interpolated local sea level were considered to become submerged in the future.

Datasets

The geospatial data used in this study consist of several open-access datasets, listed below. These datasets are subject to regular updates: the analysis presented in this paper is based on data obtained from the databases between Nov 2022 and Jun 2023.

1) Digital Elevation Model (DEM) in two-metre spatial resolution (National Land Survey of Finland 2020, available at https://www.maanmittauslaitos.fi/en/maps-and-spatial-data/expert-users/product-descriptions/elevation-model-2-m)
2) Coastal meadows
   a) Biotope data of state-owned protected areas (Metsähallitus 2019, available at https://www.paikkatietohakemisto.fi/geonetwork/srv/fin/catalog.search#/metadata/e3aa7b2a-e6e2-45dc-a29a-b64bcf2aba9f)
   b) Meadows from the Topographic database of the National Land Survey of Finland (NLS 2022, available at https://www.maanmittauslaitos.fi/kartat-ja-paikkatieto/asiantuntevalle-kayttajalle/tuotekuvaukset/maastotietokanta-0)
3) Sandy beaches: features of sandy beaches (Finnish Environment Institute 2022, available at https://ckan.ymparisto.fi/dataset/%7B42D70E21-6B65-4FDF-BEF8-CAA4466B09F9%7D)
4) Migration space analysis
   a) Corine land cover dataset in 20-metre resolution (Finnish Environment Institute 2018, available at https://ckan.ymparisto.fi/dataset/corine-maanpeite-2018): built areas, forests
   b) Topographic database of the National Land Survey of Finland (NLS 2022): roads, sandy areas, rocky terrain
   c) Forest stand data (Finnish Forest Centre 2021, available at https://www.metsakeskus.fi/fi/avoin-metsa-ja-luontotieto/metsatietoaineistot/metsavaratiedot)
5) Municipality boundaries 1:10 000 (NLS 2023, available at https://www.maanmittauslaitos.fi/en/maps-and-spatial-data/professionals/product-descriptions/division-administrative-areas-vector)

Current extent and submersion of coastal habitats

The different geospatial datasets cover varying areas and classify habitat types or land use using different methods, some of which are more accurate than others. For example, to study the current extent of coastal meadows, we combined data from the Metsähallitus biotope dataset and meadows from the NLS topographic database. The biotope dataset includes coastal meadows in state-owned protected areas that have been predominantly verified on-site: we included coastal meadow, heath, fresh meadow, moist meadow, leaf meadow, and salt marsh classes. The topographic database, which is primarily based on remote sensing, includes a meadow class con-

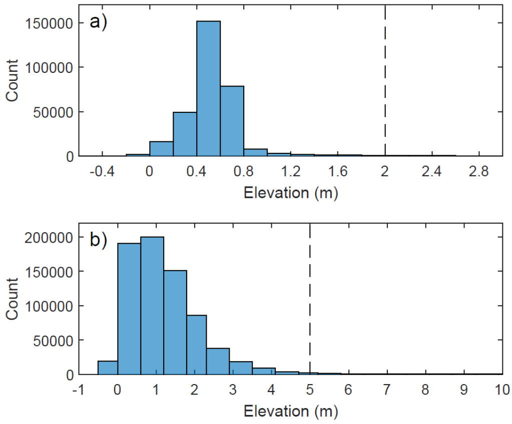

Fig 5. Distribution of **a)** coastal meadow and **b)** sandy beach elevations in the study area. The data consist of DEM values in two-m cells. Dashed lines mark the thresholds applied to include only coastal habitats.

taining all natural areas larger than 0.5 hectares covered by grasses and herbs.

To limit the analysis to the coast, we needed to apply elevation thresholds to the data. However, defining and determining the extent of the coastal zone is not straightforward. For the analysis of meadows, we clipped the habitat data using a two-metre elevation threshold and intersected it with a 100-metre distance from the coastline to exclude inland meadows. The two-metre elevation limit was determined by examining the elevations of current coastal meadows (Fig. 5a). Using the DEM, we calculated the distribution of cell elevation values within the boundaries of meadows classified as "Boreal Baltic coastal meadows" (habitat code 1630) in the Natura 2000 classification. This habitat class best corresponds to the definition of coastal meadows, which is why it was used to determine the elevation limit that can be applied to other datasets with wider coverage. We found that these meadows are low-lying, predominantly located within the two-metre threshold. This is reasonable, as many coastal meadows are highly dependent on coastal forces, such as waves and the movement of sea ice, which keep them open (Reinikainen *et al.* 2019). Two metres roughly corresponds to the recorded maximum flood height in the study area (Pellikka *et al.* 2018) and therefore marks the area directly influenced by waves and sea level variations.

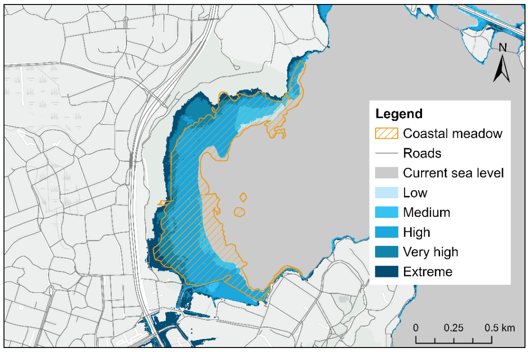

Fig 6. Example of coastal meadow submersion under different future SLR scenarios in Laajalahti, Espoo. In this case, roads and other urban infrastructure effectively block any migration opportunities inland.

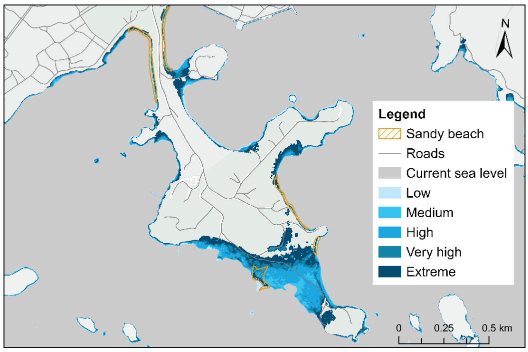

Fig 7. The Kallahti Peninsula in Helsinki is known for its high natural and recreational value. The sandy beaches are already at risk of submersion under the medium scenario.

We performed a similar analysis to study the elevation distribution of current sandy beaches (Fig. 5b). Based on this, we applied a five-metre elevation threshold to the beach dataset to exclude areas far from the coast. After determining the current extent of the habitat types under investigation, we quantified the proportional area loss caused by SLR. This was done through overlay analysis to calculate how much of the current area falls within the submerged regions of each SLR scenario. Examples of two individual sites are shown (Figs. 6 and 7).

Migration opportunities

We analysed the migration opportunities of coastal meadows and sandy beaches based on land use and topography. To define the potential migration area, we added two metres (meadows) or five metres (beaches) to the projected extent of each future SLR scenario. In other words, we assumed that the future elevation range of coastal habitats would remain similar to current conditions. We limited the migration area to dry land, meaning that sea and future submerged areas, lakes, rivers, and wetlands were considered unavailable for habitat formation. Additionally, individual patches of habitat unaffected by SLR were considered to remain in place, and for these, we did not calculate the potential migration area.

From the topographically feasible migration area, we excluded unsuitable habitats and obstructing features based on the Corine land cover dataset and the NLS topographic database. For meadows, these included built areas (except for parks and golf courses), coniferous and mixed forests, rocky and sandy terrain, and all roads apart from small paths. Migration opportunities depend on soil type, as coastal meadows form on fine clay and silt soils (Reinikainen *et al.* 2019). However, due to the lack of sufficiently precise soil data, this factor was not included in the analysis. Instead, we used forest type as a proxy: deciduous forests were considered suitable future locations, while coniferous and mixed forests were excluded from the potential migration area, as they tend to grow on coarse sand and moraine, which are unsuitable for coastal meadow formation.

After removing unsuitable habitats and obstructions, we separated the remaining polygons into individual parts and discarded areas that were spatially disconnected from the current meadows, making them inaccessible for direct migration. This step ensured the exclusion of areas disconnected from existing meadows by barriers such as roads or stretches of unsuitable habitat. Finally, for coastal meadows, we classified the suitable migration area into three categories based on land cover: fields (agricultural areas), other open areas, and deciduous forest.

Next, we conducted a similar analysis for sandy beaches. The migration of sandy beaches is obstructed by human infrastructure as well as natural factors such as rocky areas, clayey soils, or humus-rich soils. For instance, agricultural land is unsuitable for sandy beach migration. The soil type in the potential migration area is critical: there must be sand. Areas classified as fine-grained soil are the most clearly suitable, but moraine- or gravel-dominated areas may also be viable if sufficient sandy patches are present among the coarser material. We considered two clearly potential migration environments: transitional woodland/shrub (Corine land cover type 3242) and pine forests on fine sandy soils (soil types 20–22: fine-grained soil, fine-grained till, fine-grained graded soil). Additionally, we analysed one suboptimal habitat type: pine forests on coarser soils, such as moraine (soil types 10–12: medium-grained or coarse soil, coarse till, coarse graded soil). Only areas directly connected to existing sandy beaches were included.

For both coastal meadows and sandy beaches, the results were summarised for the entire study area, distinguishing between the continental coast and islands. This distinction allowed us to assess potential differences in susceptibility between island and mainland habitats. Additionally, we calculated the results within the boundaries of the coastal municipalities.

Results

Depending on the scenario, SLR threatens to submerge 10–92% of coastal meadows and 14–65% of sandy beaches in the study area by 2100 (Table 2). Under the medium scenario, which is considered the most likely, coastal meadows are expected to decline by 23% and sandy beaches by 22%. The loss of coastal meadows greatly increases under higher scenarios, which is expected given that their typical elevations range from 0.4 to 0.8 metres above the current sea level (Fig. 5a). The relative loss of sandy beaches is greater than that of coastal meadows under the low SLR scenario but increases more gradually in the more extreme scenarios. As sandy beaches can extend up to five metres in elevation, a larger proportion of their area remains unaffected by SLR compared to coastal meadows. However, even sandy beaches risk losing up to 65% of

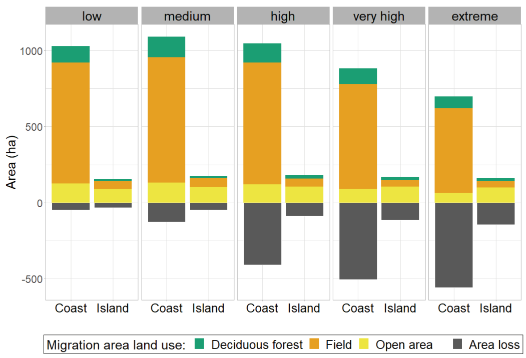

Fig 8. Coastal meadow area loss and potential migration area, classified by land use, in each SLR scenario.

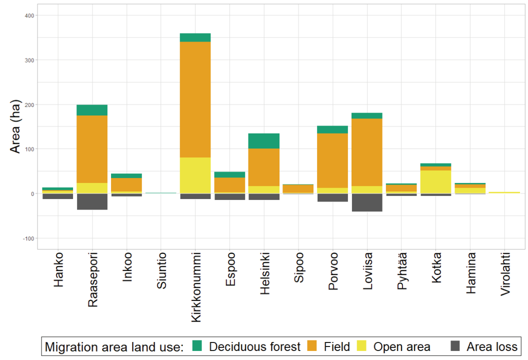

Fig 9. Municipality-level coastal meadow loss and migration opportunities under the medium SLR scenario by 2100.

their current area under the most extreme SLR scenario.

Our analysis suggests that, in theory, migration opportunities for coastal meadows exceed habitat loss estimates across all scenarios (Fig. 8). Sufficient migration space appears to be available to support habitat migration and mitigate coastal meadow loss, although these opportunities decrease considerably under high SLR scenarios. A sharp reduction in migration space relative to habitat loss indicates that under high SLR scenarios, coastal meadows have fewer opportunities for natural adaptation and are less likely to persist through migration. In contrast, under lower sea level rise, inland migration is more feasible, as the available migration space is several times larger than the estimated meadow loss.

For meadows, the migration space consists mostly of agricultural areas (fields) on the coast and other types of open area on the islands. Only a small portion of the area is classified as deciduous forest (Fig. 8).

The municipality-level analysis revealed considerable regional variation in meadow loss and migration opportunities (Fig. 9). Migration opportunities depend on the current meadow area, meaning that fewer existing meadows also correspond to fewer migration opportunities. While most municipalities have sufficient migration space under the medium SLR scenario, the largest surplus of migration area is found in certain municipalities (e.g. Kirkkonummi, Kotka). In contrast, meadows in Hanko have the poorest migration opportunities.

Regarding the migration potential of sandy beaches, our analysis painted a different picture from that of coastal meadows. In higher scenarios, the loss of sandy beach area exceeded the possible migration area, unless pine forests on coarse soil were also considered as suitable migration space (Fig. 10). Under the low and medium SLR scenarios, the possible migration area was equal to or slightly larger than the area lost. Including pine forests on coarse soil in the analysis would indicate ample migration space, but in practice, this category is largely unsuitable: only the sandy patches within this land cover class could have potential for migration. As with coastal meadows, there were regional differences between municipalities (Fig. 11). Along the northern GoF coast, the best opportunities to compensate for sandy beach loss are in Hanko, a sandy peninsula in the western part of the gulf, while the poorest are in Inkoo.

Table 2. The estimated submerged area (in hectares, with the percentage of the total area in parentheses) of two coastal habitat types under five different SLR scenarios by 2100.

Scenario	Sand beaches	Coastal meadows
Low	41.0 (14.1 %)	79.5 (10.4 %)
Medium	64.3 (22.2 %)	175.0 (23.0 %)
High	106.8 (36.8 %)	498.3 (65.4 %)
Very high	138.4 (47.7 %)	620.5 (81.4 %)
Extreme	187.7 (64.7 %)	703.2 (92.3 %)

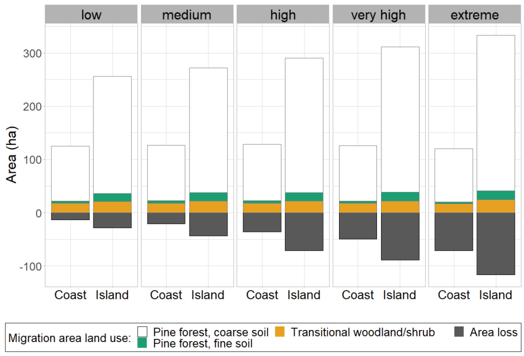

Fig 10. Sandy beach area loss and potential migration area, classified by land use, in each SLR scenario. Pine forest on coarse soil represents a land cover class that may have some migration potential but is largely unsuitable in practice.

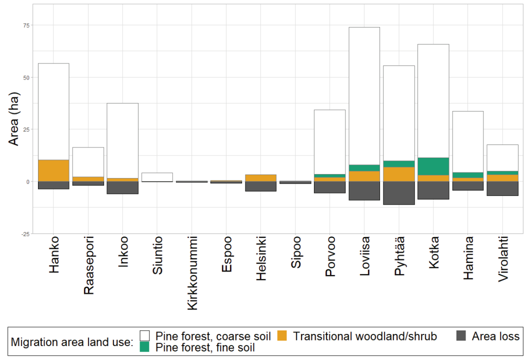

Fig 11. Municipality-level sandy beach loss and migration opportunities under the medium SLR scenario by 2100. Pine forest on coarse soil represents a land cover class that may have some migration potential but is largely unsuitable in practice.

Discussion

Rising sea levels threaten valuable, species-rich coastal habitats, increasing the need for coastal land use planning, management, and restoration measures. Our results show that a sizeable portion of these ecosystems is at risk of submersion by 2100 along the northern GoF coast. Since coastal meadows and sandy beaches are already endangered due to various human activities, sea level rise could severely impact the stability of these ecologically important ecosystems and their species.

In the future, coastal habitats will experience varying degrees of area loss depending on local conditions. Notably, small low-lying habitat patches may become entirely submerged, whereas larger patches might only lose part of their area, with the remaining upper sections potentially sustaining enough habitat for their fauna and flora. The loss of multiple small habitat patches weakens the habitat network, affecting the metapopulation dynamics of species and increasing their risk of extinction (e.g. Hanski and Ovaskainen 2000, van Nouhuys 2016).

The submersion of current habitats may be offset by migration to new areas, though the possibilities for this vary regionally due to factors such as topography, soil type, and man-made infrastructure. Even if migration space at a broader scale exceeds habitat loss, the adaptation opportunities for individual meadows or sandy beaches vary. Therefore, habitat loss may occur even under lower SLR scenarios if local adaptation opportunities are limited.

Island habitats are particularly vulnerable, especially on smaller islands, as the area of islands will irreversibly decrease and adaptation opportunities may be limited due to restricted inland space. The formation of new islands is also possible as low-lying islands are split and peninsulas are separated by rising sea level. While this could create new space for coastal habitats, it is not guaranteed that these newly formed areas would serve as potential migration space for habitats lost elsewhere.

The available datasets and their quality imposed restrictions on the analysis:

1) The DEM has a vertical elevation accuracy of 0.3 metres on average, which brings some uncertainty to the creation of submersion surfaces and the estimation of habitat loss. The error varies spatially, however, and open environments, such as coastal areas, likely have better accuracy than forested regions. The accuracy also reflects small-scale deviations, which do not introduce systematic bias on a broader scale.
2) There was a lack of conclusive data on habitat types, particularly regarding the numerous small habitat patches in the study area. Automated processes may misclassify target areas, with small

patches being grouped with larger, dominant neighbouring habitats. For most areas, the data has not been verified in the field.

3) Since no datasets accurately and comprehensively specify coastal habitats, we had to establish elevation thresholds to exclude somewhat similar inland habitats, which inevitably added some ambiguity to the analysis.
4) The available soil data lacked the precision needed for this study, even though soil type is a crucial factor in determining the suitability of areas for the migration of coastal meadows and sandy beaches.

All in all, the results may present an overly optimistic view of adaptation opportunities. Since exact migration requirements or dispersal models were not applied, and only limited soil data was available, our results include all areas where migration is theoretically supported by suitable land use and topography. Due to various constraints, it is highly unlikely that all of this area would be accessible for migration. For example, it remains uncertain whether coastal meadows and their perennial vegetation can successfully establish on land previously used as agricultural fields. Additionally, Kont *et al.* (2003) suggest that even if migration occurs, biodiversity loss may still happen, as rare species may be unable to adapt to suboptimal conditions. Further research of migration capacities and the suitability of environments would be needed to determine the potential migration space more accurately.

The availability of land is also a challenge for habitat migration. We assumed that any open space, regardless of ownership or current use, allows the inland movement of habitats. For sandy beaches, the most suitable migration area is pine forest on fine soil, while for coastal meadows, it is agricultural land, i.e. cultivated fields. However, it is uncertain whether arable lands and forest management areas, especially those under private ownership, will be available for migration, as this raises the question of financial losses for landowners. Since fields hold economic value for society, efforts will likely be made to maintain them for agricultural use through flood control measures.

On the other hand, some migration space may not be captured in our analysis, as we assumed that migration is possible only to areas adjacent to existing habitat patches. Since plant seeds can disperse over greater distances, the formation of new habitat patches farther from current ones remains a theoretical possibility. Long-distance migration of plants depends on various dispersal agents, such as wind, water, or animals (Howe and Smallwood 1982). Floating seeds, capsules, or rhizomes facilitate migration along shorelines, whereas seeds that drop near the parent fail to contribute to migration. The decline of suitable habitats poses a particular threat to rare plants, which often have small populations and more specific habitat requirements than common species. Poor mobility and dispersal barriers may prevent their migration to new areas (Corlett and Westcott 2013). This aspect requires further study, including consideration of assisted migration as a conservation tool (Hällfors *et al.* 2016). In any case, our analysis is more likely to overestimate rather than underestimate the actual availability of migration space.

Our results show a clear difference in the potential migration area between the examined habitat types: for sandy beaches, the migration space relative to the lost area is much more limited than for coastal meadows. While this partly reflects the narrower requirements of sandy beaches for suitable migration space, it may also be influenced by methodological choices made in the analysis. For coastal meadows, we excluded certain unsuitable land types and obstructions and considered all remaining areas as potential migration space. In contrast, for sandy beaches, we included only two to three potentially suitable land cover classes. As a result, the analysis may have overestimated the migration space of coastal meadows by incorporating unsuitable areas, whereas for sandy beaches, the lack of soil type data may have led to an underestimation of available migration space.

Changes in wave and wind conditions, expected with rising sea levels and a changing climate, will influence the formation of sandy beaches — an aspect not considered in this study. A global, satellite-derived analysis of sandy beaches indicates that 24% of the world's sandy beaches are eroding, 28% are accreting, and 48% remain stable (Luijendijk *et al*. 2018). According to the same data, sandy beaches are eroding along the southern coast of the Baltic Sea, accreting in the Bothnian Sea, and remaining stable on the northern GoF coast (a detailed map in Weisse *et al.* 2021). Due to the very small tidal range in the Baltic Sea, the main factors influencing beach profiles are storm surges, wave set-up, the presence or absence of sea ice, and long-period wave energy (Weisse *et al.* 2021). On sedimentary shores, coastline changes are highly sensitive to even small variations in these driving forces. The effect of an individual storm on beach processes and sediment transport can vary considerably depending on wind and wave characteristics. In the eastern GoF, the most extreme erosion events and sand losses are caused by long-lasting westerly or southwesterly storms, which generate high waves and water levels, coupled with an absence of stable sea ice during such events (Ryabchuk *et al.* 2021).

The adaptation opportunities of coastal habitats can be enhanced through conservation measures, such as protecting and restoring areas to create suitable conditions for migration. This requires careful land use planning to identify the most promising locations. Conservation and restoration efforts can be incentivised through financial benefits, and land can be specifically acquired for conservation purposes or protected through agreements restricting coastal development (Leo *et al.* 2019). Proactive coastal planning is essential to prevent future habitat loss and mitigate coastal squeeze. Early intervention is particularly important in forested areas, as migration into these environments is slow and dense tree cover can effectively block habitats from keeping pace with sea level rise. For sandy beaches, potential habitat could be created relatively easily through restoration measures, such as logging trees and removing the organic soil layer in areas with sandy soil. Here, once more, arises the question of human economy and priorities: is it acceptable to convert land into ecologically valuable but economically unproductive terrain, rather than maintaining it as woodlands or fields?

In this study, we did not explore habitats that might benefit from future sea level rise. Examples of these include different types of alluvial habitats, such as coastal lagoons (Hérivaux *et al.* 2018) and alluvial forests. These habitats warrant further research. Additionally, there is a need for research on whether it is possible for coastal meadows to form on former fields and how this transition could be facilitated and supported. This could already be tested in fields subject to regular flooding.

Conclusions

The key findings of this study can be summarized as follows:

- In the Gulf of Finland, a remarkable amount of species-rich coastal habitats face the risk of shrinking or disappearing due to projected sea level rise. Depending on the climate change scenario, 10–92% of the current coastal meadow area and 14–65% of existing sandy beaches will be lost by 2100.
- Habitat migration may help mitigate the losses. For coastal meadows, the area identified as potential for migration exceeds the area that will submerge. On the mainland coast, this consists mainly of agricultural land. Continued agricultural use could make this land unavailable for migration. For sandy beaches, there may not be enough space to preserve the current habitat area.
- Proactive conservation and restoration measures are needed to ensure sufficient migration space for these habitats and to protect coastal nature.

This study is the first attempt to quantify the impact of sea level rise and coastal squeeze on coastal habitats on the Finnish coast. The analysis could be refined if there was more information on the exact migration requirements of coastal habitats, as well as improved geospatial data on habitat types, land use, and soil quality. Modelling methods could also provide further insight into the migration of habitats facing sea level rise.

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