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Assessing and forecasting the effects of submersion on biodiversity. A method to implement an ecological-quality indicator in a context of coastal realignment and rising sea levels

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ABSTRACT

In the context of climate change and sea-level rise, coastal realignment consists in reopening polders to marine waters to favor 'nature-based' mitigation measures. Such operations have consequences on biodiversity, which vary depending on the parameters studied and site features. In this study, a multimetric indicator aiming to evaluate and predict the potential ecological quality of sites undergoing a realignment operation was developed. This indicator is based on the combination of two tools, (i) a biological-capacity matrix to assess the importance of different habitats of a defined typology for taxonomical, patrimonial and functional parameters; (ii) habitat maps obtained by photointerpretation for past habitats, by machine learning using space-borne imagery for present habitats and by forecasting using submersion models for future habitats. The indicator is presented in the form of a radar chart, with each axis corresponding to one parameter of the biological-capacity matrix and highlighting its different values for different coastal-realignment scenarios or different time horizons.

1. Introduction

Land reclamation, i.e. the draining of marshes on low-lying coasts and estuary shores to make them suitable for agriculture, is an ancient phenomenon. In Western Europe, an area of approximately 15000 square kilometers (km^2) is the product of the land-reclamation process (Goeldner-Gianella, 2007). The largest areas reclaimed are in the Netherlands and Germany (6000 km^2 in the two countries). In France, land reclamation took place on the Channel and Atlantic coasts, where large areas were reclaimed, for example in Authie Bay along the Picardy coast.

The abandonment of the land-reclamation policy has been gradual since the end of the 20th century, after an initial phase of abandonment of certain agricultural polders. In parallel, a process of coastal realignment has been observed for the past forty years, which aims to reopen polders to marine intrusions. The emergence of this new trend, though still limited in terms of surface area to date (it concerns approximately 1 % of the land initially reclaimed from the sea), is not negligible, as the number of realignment projects tripled from the 1980s to the 2000s (Goeldner-Gianella, 2007). Realignments have been undertaken for several reasons, including environmental (development of the patrimonial saltmarsh habitats) and economic (the financial viability of dike maintenance is questioned) reasons, especially in the context of rising sea levels (Goeldner-Gianella and Verger, 2009). Such an intervention leads to the submersion of lands by salt water, which impacts biodiversity at different levels (taxonomical, functional, patrimonial) (e.g. Boorman and Hazelden, 2017; Roman et al., 2002). According to the systematic review by Debue et al. (2022), the plant species richness usually decreases in realigned areas due to the replacement of glycophyte species by halophyte ones, while the abundance of fishes and shorebirds increase thanks to the development of saltmarshes, mudflats and open-water areas.

"Adapto" is a five-year European Life project (https://www.lifeadapto.eu) currently underway on ten pilot sites in France that explores an array of solutions to counter the effects of climate change on the French coastline from an ecological, economic and social point of view. Some sites are involved in dune restoration, however several others were selected to experiment coastal realignment, taking into account expected changes in the environment due to dike breaches and sea-level rise. In order to assess the impact of coastal-realignment interventions on biodiversity, an ecological-quality indicator adapted to coastal environments was developed, based on six sites of the Adapto

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project concerned by coastal realignment.

Over the last decade, multimetric indicators have become essential tools for public policy (Coates et al., 2007; Mondy et al., 2012). The advantages of multimetric indicators are multiple, including the fact that they provide additional information on the biological compartment studied. Here, a multimetric and habitat-based approach was selected because it can account for all the potential biodiversity present on each site, for both current and future scenarios of submersion. Different metrics were evaluated for a set of habitats: taxonomical, estimating their species richness for different taxonomic groups; patrimonial, corresponding to their potential in patrimonial habitats; and functional, assessing their importance in the realization of various ecological functions.

2. Material and methods

2.1. Study sites

Six sites on the French Channel and Atlantic coasts were selected for this study (Fig. 1).

Two of these sites have already been partially realigned:

- the Mortagne-sur-Gironde polder (950 ha (ha)): approximately 190 ha have been realigned since storm Martin in 1999,
- Île Nouvelle (420 ha): approximately 140 ha have been realigned since storm Xynthia in 2010 (Z1) and 30 ha were realigned three years later (Z2),

and realignment projects are planned in the near future for the other four sites:

- Authie Bay (3000 ha): two scenarios are studied, corresponding to a coastal realignment of approximately 115 ha (S1: realignment of Z1) or 145 ha (S2: realignment of Z1 + Z2),
- Orne Estuary (1300 ha): two scenarios are studied, corresponding to a coastal realignment of approximately 110 ha (S1: Z1) or 140 ha (S2: Z1 + Z2),
- Lancieux Bay (450 ha): one scenario is studied, corresponding to a coastal realignment of approximately 140 ha,
- Leyre Delta (1200 ha): the realignment project is studied in two steps, first 45 ha realigned by 2030 (Z1) and an additional 110 ha by 2050 (Z2).

These last four sites have a similar structure, with a dike, in some cases extended by a dune barrier, separating water, tidal flats and saltmarshes on the ocean side from areas dominated by mesophile grasslands (with more or less large areas occupied by woodlands and thickets) on the inland side. The Leyre Delta, formerly a saltpond and fish-farming area, has water basins on the landside of the dike. The two realigned sites are both situated in the Gironde Estuary. At Mortagne, the dike separates saltmarshes and reedbeds from mesophile grasslands and crops. Île Nouvelle is dominated by reedbeds, with large areas covered by water, wet woodlands and thickets.

2.2. Methods

The ecological-quality indicator is based on four steps (Fig. 2), (i) a habitat typology is defined; (ii) habitat maps are made at different times (past and present if realignment has already occurred, present and future otherwise); (iii) a biological-capacity matrix is defined; (iv) the indicator is calculated based on the habitat areas and the matrix for each cartographic model. Steps 1 and 3 are for indicator construction: once created, the typology and the matrix can be reused when applying the indicator at other habitat-compatible realignment-concerned sites. Steps 2 and 4 are for indicator utilization: they are proper to a site.

2.2.1. Definition of a habitat typology

A habitat typology was defined, based on a preliminary field phase as well as on existing habitat maps available for the six sites (Table 1). The typology was designed taking into account several requirements, (i) a hierarchical structure, simple to use in the field for site managers; (ii) as complete as possible, with all the major habitats (area > 1 ha on each site) present on the six sites linked to a single entry of the typology; and (iii) a well-identified individual spectral response in order to limit confusion among habitats during the modeling phase (see below).

2.2.2. Modeling of habitat maps.

2.2.2.1. Predictive mapping of current habitats by remote sensing. In some cases, the initial habitat maps available prior to our work covered only a small part of the site (e.g. 12 % for the site on Authie Bay) and were based on heterogeneous habitat-classification typologies. In order to obtain recent, precise and comparable habitat maps covering the whole area of each site, a modeling procedure, combining both the use of the existing material and complementary field sampling, was applied. This procedure was designed to be applicable to any site composed of the same habitats, as long as the sites had benefitted from pre-mapping work.

The classification was done in two steps separated by a field phase, each step using the Random Forest (RF) algorithm (Breiman, 2001), the same composite image and different sets of training polygons composed of habitat pixels (Fig. 3). The first step led to an initial modeling based on training polygons spread over the area covered by the initial map. This first modeling was then used to define a new set of polygons spread over the whole site, which were checked during a two-day field phase in the summer of 2020 to validate/invalidate the model and to acquire supplementary data. The two sets of polygons were finally combined, 75 % of the polygons were used for the training of the final modeling, the remaining 25 % for its assessment.

The composite image corresponded to the fusion of several recent orthophotographs at different seasons and tidal heights to improve model learning (Davranche et al., 2010; Rapinel et al., 2015a, 2015b), with six radiometric indices (Beguet et al., 2018). The orthophotographs were acquired by the SPOT-6 satellite, available on the EQUIPEX-GEOSUD download portal (https://ids.equipex-geosud.fr/). The radiometric indices were: the Normalized Difference Vegetation Index (NDVI) (Rouse and Haas, 1974), the Ratio Vegetation Index (RVI) (Pearson and Miller, 1972), the Soil Adjusted Vegetation Index (SAVI) (Huete, 1988), the Redness Index (RI) (Pouget et al., 1990), the Brightness Index (BI) (Khan et al., 2005) and the Normalized Difference Water Index 2 (NDWI2) (McFeeters, 1996). The sets of training polygons were composed following recommendations made in the literature regarding the number, distribution and corresponding surface area of training data (e.g. Colditz, 2015; Millard and Richardson, 2015). A linear relationship between the area of a habitat and its number of training polygons was established, with a minimum and a maximum number for the fewest and most numerous areal habitats (5 and 30 for the first set, 5 and 10 for the second to be compatible with a two-day field check). The training polygons were defined as 5 m-radius circles corresponding to homogeneous habitat patches, randomly distributed and situated at least 15 m apart from one another. The final modeling was smoothed in order to limit the 'pepper and salt effect' resulting from the pixel-based classifications (Blaschke and Strobl, 2001), by evaluating the dominant habitat within a 3-pixel radius circle and assigning to the central pixel the value of that habitat. The classification was validated using a confusion matrix in which the overall accuracy (number of well-classified pixels across all habitats), producer's accuracy (for a given habitat, the probability that a pixel of this habitat is classified as such) and user's accuracy (for a given habitat, the probability that a pixel classified as this habitat actually corresponds to it) were calculated (see Congalton, 1991 for details).

The process was developed on QGIS (QGIS Development Team,

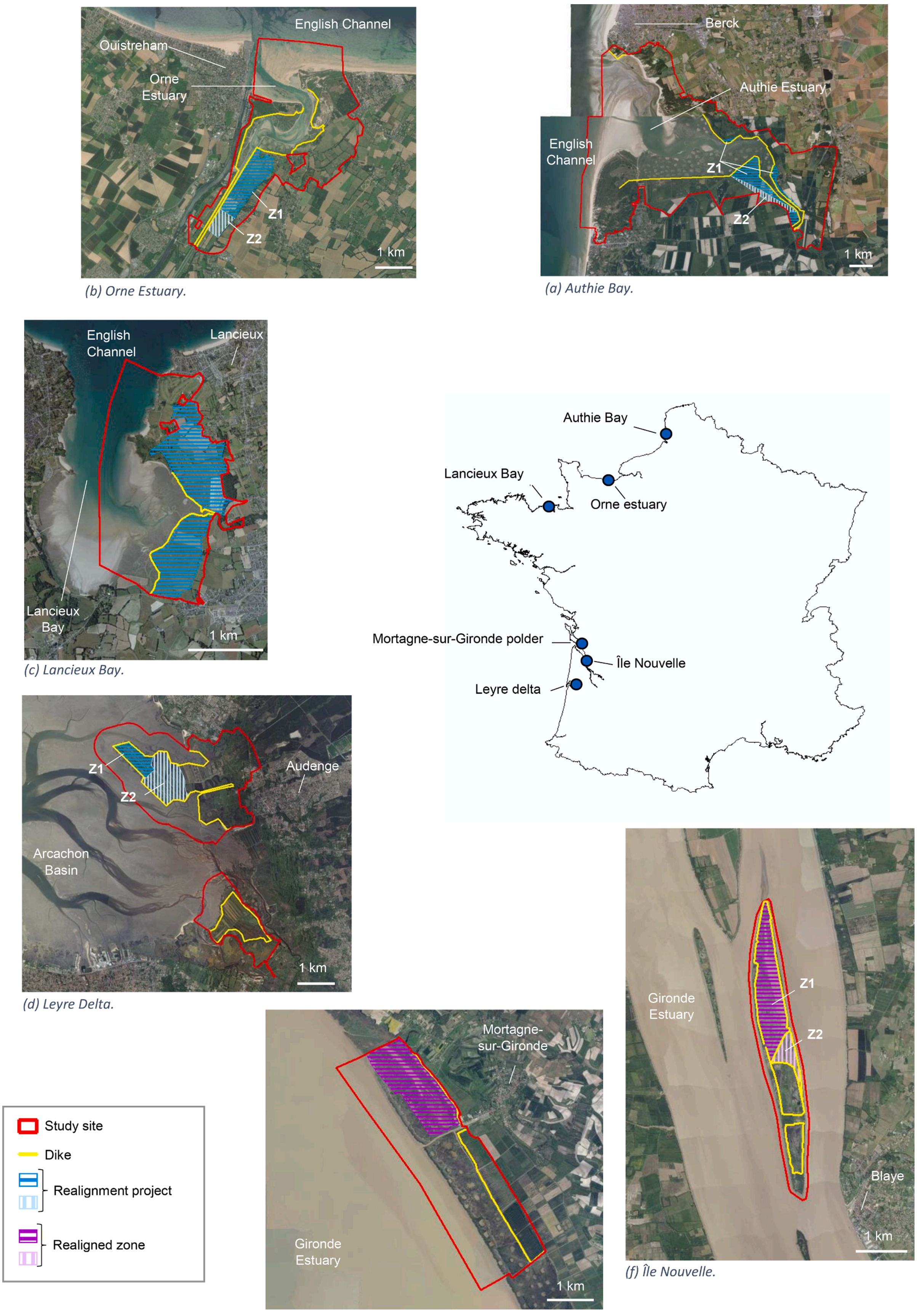

Fig. 1. Site photos and structure.
Reference of the orthophotographs: BD Ortho® IGN.

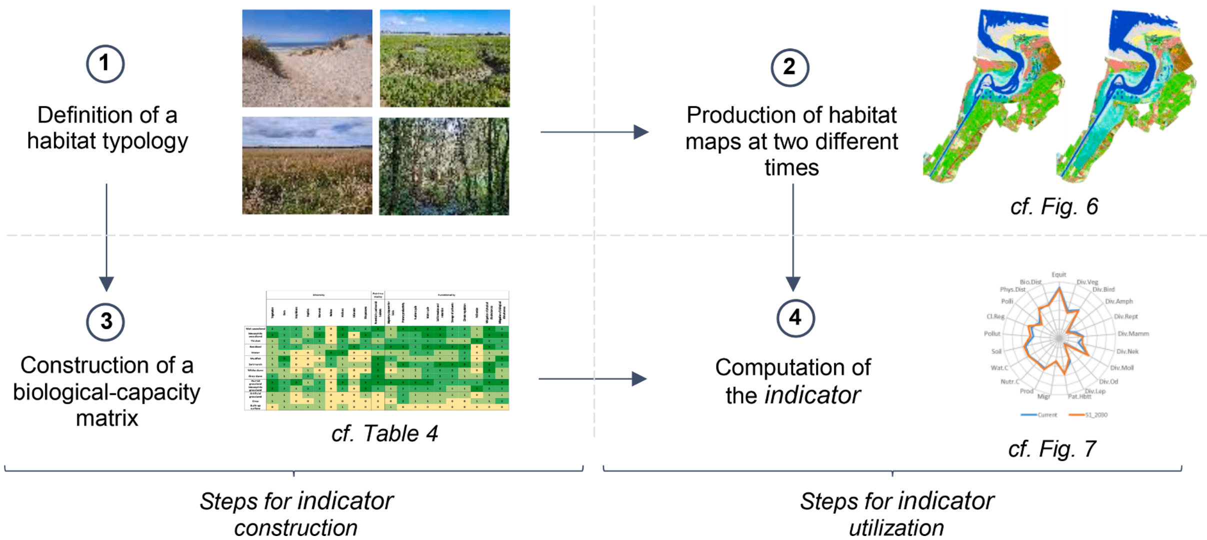

Fig. 2. Steps to build the indicator.

2022) with OrfeoToolBox (Grizonnet et al., 2017) and was implemented for each site individually.

2.2.2.2. Deriving the evolution of habitats by assessing marine-submersion duration. A forecast of the future habitats in the event of submersion was carried out for the four sites concerned by a realignment project (Authie, Orne, Lancieux, Leyre), for two time horizons (2030 and 2050) and for the different scenarios where applicable. It was first obtained by constructing a submersion matrix, from the current habitat map and current submersion durations, and then applying this matrix to a combination of the current habitat map with future submersion durations (Fig. 4).

A submersion matrix was built for each of these four sites, with in rows the habitats of the typology present on site, in columns categories of annual submersion duration and at each intersection a habitat of the typology that may be expected to replace the current habitat, depending on the submersion duration. These matrices are site-specific and based on the habitat map of the site combined with a current submersion map, produced by the BRGM (French Geological Survey). The submersion maps were obtained by combining a current annual tidal curve (at a time step of 5 min) with a digital elevation model (DEM) to attribute to each pixel of the site the percentage of current annual submersion duration, depending only on the elevation (Garcin and Brivois, 2022). The submersion maps were modified to attribute a zero submersion duration to pixels behind dikes. By superpositioning the modified submersion map on the habitat map, the proportion of pixels for each submersion category, per habitat, was determined. For Authie and Leyre, which have water and saltmarsh habitats behind dikes, the proportion of pixels for these habitats was calculated without taking into account the pixels behind dikes, as they are not subject to tides.

The submersion matrix was built on the assumption of three ecological successions, with only the first being readable in both directions, namely (i) non-coastal habitat (woodlands, thickets, grasslands and crops) <–> high marsh <–> middle marsh <–> low marsh <–> pioneer marsh <–> tidal flat <–> water; (ii) grey dunes –> white dunes –> tidal flat –> water; (iii) reedbeds –> pioneer marsh –> tidal flat –> water. A habitat was assumed to tolerate the submersion duration for which its proportion of pixels was the highest and to transform into the successive habitat when the percentage of pixels for the submersion category fell below one-half the percentage of pixels of the successive habitat. The "one-half"-rule was decided arbitrarily, so that a habitat with a high percentage of pixels for a given submersion category would not be transformed into a successive habitat having a similar but higher percentage. Non-coastal habitats and grey dunes were assumed to tolerate submersion durations of less than 1 %. High marsh was assumed to turn into mesophile grassland for a zero submersion duration. Only habitats present on a site were taken into account in the successions.

Finally, the potential future habitats were mapped by combining the current habitat map with a predictive submersion map produced by the BRGM (Garcin and Brivois, 2022) and applying the submersion matrix. The predictive submersion maps were based on the same DEM as the current ones, but also took into account a realignment scenario (i.e. without a submersion duration equal to zero behind dikes) and a + 20 cm or a + 40 cm rise in sea level for 2030 and 2050 respectively. Given that other phenomena such as sedimentation or geomorphological changes are not taken into account in the submersion prediction, future submersion durations can only be equal to or longer than current ones. Consequently, the submersion matrix was applied such that a habitat can transform into a lower habitat in the succession but not into a higher one (e.g. middle marsh can turn into low marsh, tidal flat or water but not into high marsh or mesophile grassland). Habitats behind dikes and not concerned by realignment were considered not to change.

2.2.2.3. Past habitat map for already realigned sites using photo-interpretation. For the Île Nouvelle site, a map of the pre-realignment habitats was made by photointerpreting a 1991 orthophotography made by IGN (French National Institute for Geographic and Forest Information) (IGN, 2022). For the Mortagne site, due to the difficulty of differentiating reedbeds and saltmarshes on an IGN orthophotography from 1996, only the diked zone, corresponding to crops, was photo-interpreted. The habitats of the rest of the site were assumed to be similar to the current ones.

2.2.3. Definition of a biological-capacity matrix

A biological-capacity matrix was created, with each row corresponding to a habitat of the typology and each column to an ecological metric for one of three categories, namely diversity, patrimoniality and functionality. At the intersection of each line and column, a score between 0 and 3 was assigned, corresponding to the importance (zero (0), low (1), medium (2) or high (3)) of the habitat for the parameter.

The diversity metrics were based on a set of taxa representative of the diversity found on the sites (e.g. vegetation types, birds, amphibians, *etc.*). The patrimoniality metric was defined on the habitat level to provide information on the potential of patrimonial species. The scores of the diversity and patrimoniality metrics were based on the compiled literature from the systematic review by Debue et al. (2022) and on the

Table 1
Habitat typologies defined, with a description of each typological unit.

Habitat		Description	Example (vegetation; Corine Biotope CB)
Woody habitats	**Wet woodland**	Tree stand strongly marked by the presence of water, which can saturate the soil	Riparian willow formation, alder swamp wood; CB44
	Mesophile woodland	Other tree stands	Oak forest, pine forest; CB41, 42, 43
	Thickets	Transitional environment dominated by a shrub stratum	Blackthorn scrub, bramble scrub; CB31.8
Aquatic habitats	**Reedbeds**	Habitat made up of large helophytes in wetlands	Common reed bed, common clubrush bed, reedmace bed; CB53.1
	Water	Salty or brackish aquatic environment, vegetated or not	Ocean, lagoon; CB11, 12, 13, 2
Saltmarsh habitats	**Tidal flat**	Sandy or muddy environment devoid of vascular plants, subject to the swaying of the tides	Intertidal zone; CB14
	Pioneer marsh	Lower part of the saltmarsh, covered by all tides except the lowest neap tides	Dominated by flat-leaved cordgrass; CB15.2
	Low marsh	Part of the saltmarsh covered by most tides	Dominated by Salicornia spp. and Puccinellia maritima; CB15.11, 15.31
	Middle marsh	Part of the saltmarsh covered only by spring tides	Dominated by Halimione portulacoides; CB15.621
	High marsh	Part of the saltmarsh covered only by the highest spring tides	Composed of Elymus pycnanthus, Plantago maritima, Limonium vulgare, Juncus gerardii, Carex divisa, Sarcocornia fruticosa, Suaeda vera, etc.; CB15.33, 15.35, 15.623, 15.624
Dune habitats	**White dunes**	Mobile sandy environment, bare or occupied by open grass, not submerged or only during high tides	High foreshore, mobile dunes and white dunes; CB16.1, 16.21
	Grey dunes	Fixed sandy medium, occupied by more or less closed perennial lawns	CB16.22
Grassland habitats	**Humid grassland**	Environment with perennial herbaceous vegetation strongly marked by the presence of water which can saturate the soil	CB37.2
	Mesophile grassland	Perennial herbaceous vegetation not marked by the presence of water, often grazed or mowed	Grassland with Poa spp., Festuca spp., Trifolium spp.; CB38
Artificial habitats	**Artificial grassland**	Permanent grassland sown or heavily fertilized	Grassland with Lolium perenne; CB81
	Crops	Cultivated fields	Wheat, maize, sunflower crop; CB82
	Built-up surfaces	Any man-made infrastructure	Dwellings, car parks, roads; CB86

knowledge of nine naturalist experts from the French National Museum of Natural History (ornithologists, entomologists, botanists, *etc*.). Experts were first asked to complete the matrix individually, the results were then pooled and disagreements collectively discussed through a round-table format. For the diversity metrics, the higher the score, the more species a habitat is likely to support. For patrimoniality, the score is maximum for typological entries that include an important proportion of or only patrimonial habitats. The measurement of patrimoniality was first considered at the habitat and species levels, but its assessment by experts when constructing the capacity matrix revealed a correlation between the two, so only the habitat level was retained.

The following functionality metrics were selected based on the Millennium Ecosytem Assessment (Alcamo et al., 2003) and the French evaluation program for ecosystem services (EFESE; Puydarrieux et al., 2017), as well as on work by Costanza et al. (1997) and de Groot et al. (2002):

- Migratory stopover for birds: resting and feeding area for migratory birds;
- Primary productivity: organic matter production;
- Nutrient cycle: organic matter decomposition, nutrient storage and recycling (nitrogen, phosphorus, *etc*.);
- Water cycle: water filtration, retention, storage and regulation;
- Soil formation and retention: organic matter accumulation, sediment retention;
- Storage of pollutants: removal of pollutants through storage, burial and recycling;
- Climate regulation: greenhouse gases, temperature and precipitation regulation;
- Pollination: floral gametes movement by biota;
- Mitigation of physical disturbances: environmental disturbances (waves, wind, flooding, *etc*.), dampening;
- Mitigation of biological disturbances: biological control to prevent the outbreak of pests and diseases.

They were evaluated based on the results from 230 bibliographical references including qualitative and quantitative data (e.g. grams of carbon stored per m^2 and per year for the climate regulation function). The higher the score, the more important the role of a habitat in a function. Because the literature rarely differentiates between different levels of saltmarshes in terms of functionality, they were grouped together for the purpose of this study.

2.2.4. Indicator computation

The indicator was calculated by combining the biological-capacity matrix with the surface area of the different habitats for a given site (Fig. 5). For each parameter of the biological-capacity matrix, an average of the parameter weighted by the area of the habitats was calculated, leading to a 'radar' chart where each axis represents a parameter. An axis was added to evaluate the evenness of habitats, based on the Pielou (1966) index multiplied by a factor of 3, so that it varies within the same range as the other parameters. The indicator was calculated for each site, on the scale of the entire site, for the different time periods (past vs present for Mortagne and Île Nouvelle; present, 2030 and 2050 for Authie, Orne, Lancieux and Leyre) and for the different scenarios (S1 and S2 for Authie; S1, S2 and S3 for Orne). The indicator was also calculated on the scale of the realigned zone (Z1 + Z2) for Authie, Orne and Leyre.

3. Results

3.1. Habitat maps

3.1.1. Cartographic models of current habitats

The results of the modeling phase are shown in Table 2 and presented for two representative sites in Fig. 6(a and d) (other sites in Appendix A).

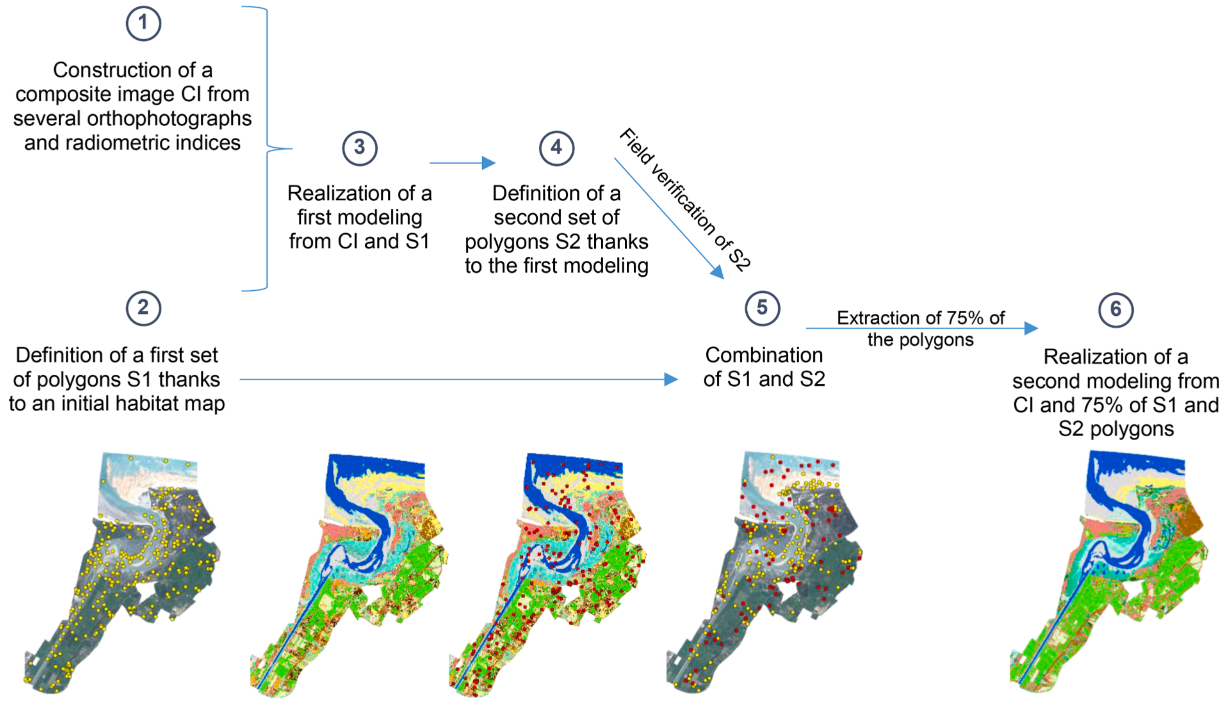

Fig. 3. Steps to produce a map of current habitats by remote sensing.

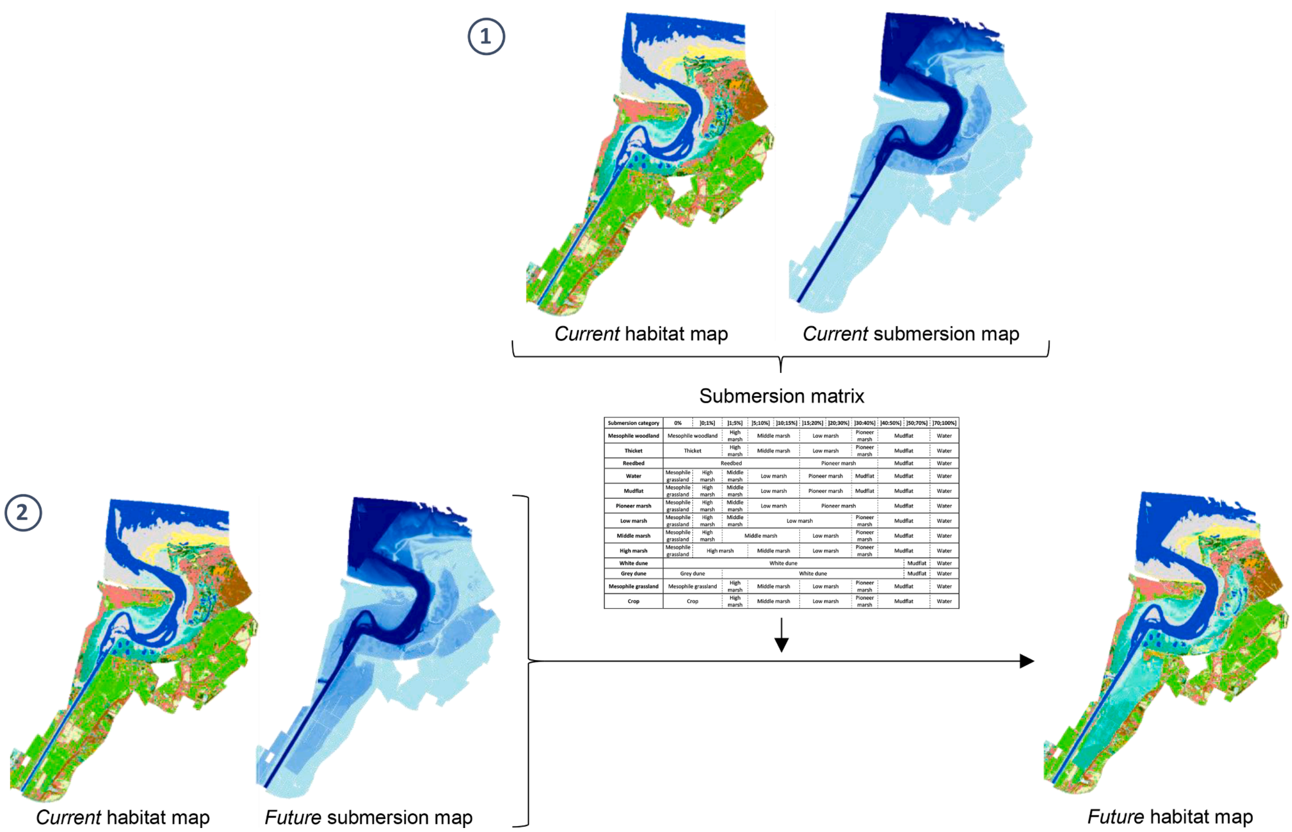

Fig. 4. Steps to produce a potential future habitat map by assessing marine-submersion duration.
(1) Submersion matrix construction from the current habitat and submersion maps. (2) Map of future habitats from the current habitat map, the future submersion map and the submersion matrix.

The cartographic models appear globally consistent with the habitats identified in the field and the structure of the sites. Woodlands, grasslands and crops are well represented on the diked parts of the sites while saltmarshes are located mainly below the dikes, with pioneer, low, middle and high marshes succeeding each other from the low elevation zones to the higher ones.

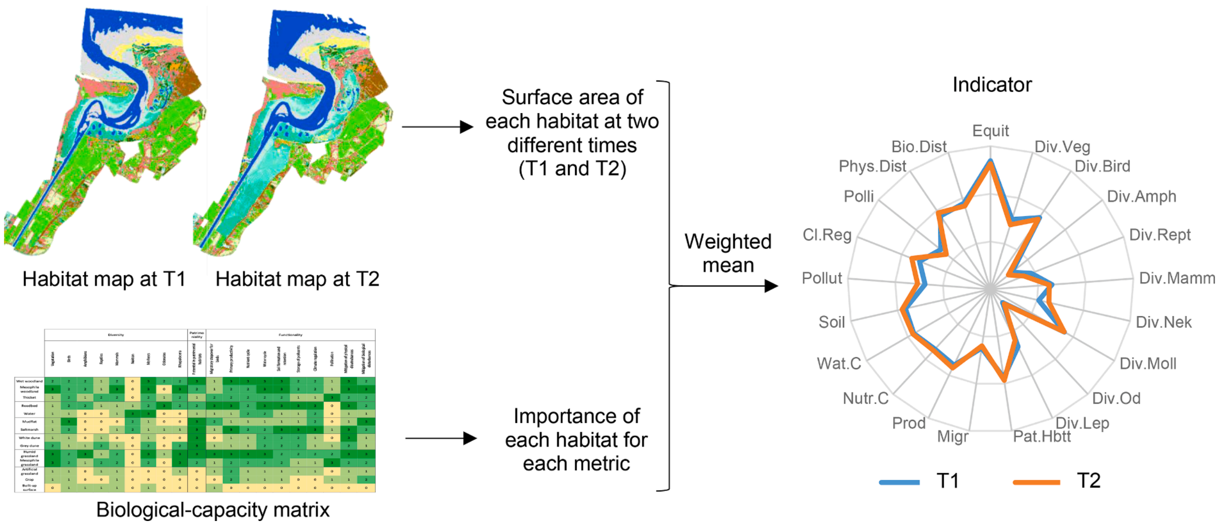

Fig. 5. Steps to compute the indicator.

Table 2
Overall accuracy, producer's accuracy (PA) and user's accuracy (UA) per site and per habitat.

Site	Authie		Orne		Lancieux		Leyre		Mortagne		Île Nouvelle	
Accuracy type	**PA**	**UA**	**PA**	**UA**	**PA**	**UA**	**PA**	**UA**	**PA**	**UA**	**PA**	**UA**
Wet woodland	46 %	69 %			48 %	53 %	51 %	68 %			100 %	63 %
Mesophile woodland	71 %	65 %	91 %	92 %	63 %	51 %	92 %	76 %				
Thickets	25 %	48 %	84 %	62 %	86 %	66 %	84 %	64 %	100 %	100 %	25 %	56 %
Reedbeds	24 %	100 %	79 %	75 %	8 %	43 %	73 %	62 %	96 %	90 %	83 %	90 %
Water	100 %	80 %	100 %	91 %	100 %	100 %	93 %	100 %	98 %	100 %	98 %	91 %
Tidal flat	83 %	93 %	90 %	89 %	100 %	100 %	100 %	80 %	100 %	89 %	98 %	98 %
Pioneer marsh			94 %	82 %			87 %	100 %	62 %	99 %		
Low marsh			76 %	70 %	100 %	100 %	74 %	85 %	88 %	82 %		
Middle marsh	84 %	73 %	59 %	75 %	100 %	94 %	70 %	72 %				
High marsh	84 %	45 %	73 %	84 %	93 %	84 %	38 %	75 %	82 %	100 %		
White dunes	100 %	80 %	87 %	98 %	100 %	81 %	75 %	100 %				
Grey dunes			32 %	39 %	62 %	94 %						
Humid grassland	41 %	70 %										
Mesophile grassland	81 %	57 %	73 %	72 %	80 %	62 %	94 %	80 %	94 %	82 %		
Artificial grassland					82 %	96 %						
Crop	76 %	100 %	58 %	74 %	85 %	100 %			100 %	100 %		
Overall accuracy	**70 %**		**78 %**		**82 %**		**80 %**		**92 %**		**85 %**	

Empty sections in the table correspond to the absence of a habitat on a site.

The overall accuracy for the sites varies between 70 and 92 %. Water, tidal flat and white dunes were the best modeled habitats regardless of the site, with producer's and user's accuracies around 90 % in most of the locations. The different levels of saltmarsh were also rather well mapped, with producer's and user's accuracies being of the same order of magnitude and increasing from high (64 % on average) to low levels (89 %). The modeling of mesophile grasslands, artificial grasslands, crops, woodlands and thickets was less accurate. Reedbeds, grey dunes and humid grasslands were the least well mapped habitats. These results are however variable depending on the site (e.g. reedbeds are very well mapped at Mortagne (96 % producer's and 90 % user's accuracies) but not at Lancieux (8 % and 43 %)). For some low values, it should be kept in mind that some habitats cover very small areas on some sites (e.g. reedbeds cover 28 % of Mortagne but less than 1 % of Lancieux). Three main types of confusion occurred, i.e. (i) between sea-land interface habitats (tidal flats, white dunes, reedbeds and marsh levels), (ii) between inland habitats (between woodlands, thickets and high marsh, or between grasslands, crops and high marsh), (iii) between less well mapped habitats (reedbeds, grey dunes and humid grasslands).

3.2. Assessment of habitat conversion based on submersion simulations

The matrices produced by the superposition of the submersion duration and habitat maps are not shown. These percentage matrices are translated into submersion matrices (Table 3 for the Orne site, Appendix B for the other sites). On the Orne site, these matrices highlight the presence of different levels of saltmarshes for submersion durations between 1 and 40 % of the year. Several levels can tolerate an identical submersion duration because the matrix takes into account the submersion duration as well as the habitat present at the time of the submersion.

The application of the submersion matrices to the superposition of the current habitat maps and the future submersion predictions resulted in predictive maps of future habitats (see Fig. 6b for the Orne site and Appendix A for the other sites). They highlight a colonization of realigned zones by saltmarshes. For the Orne site, mainly middle and high marshes are projected to develop by 2030. By 2050, low and pioneer marsh are projected for the lowest areas.

3.3. Mapping of past habitats for already realigned sites

The pre-realignment habitat maps of Mortagne and Île Nouvelle are

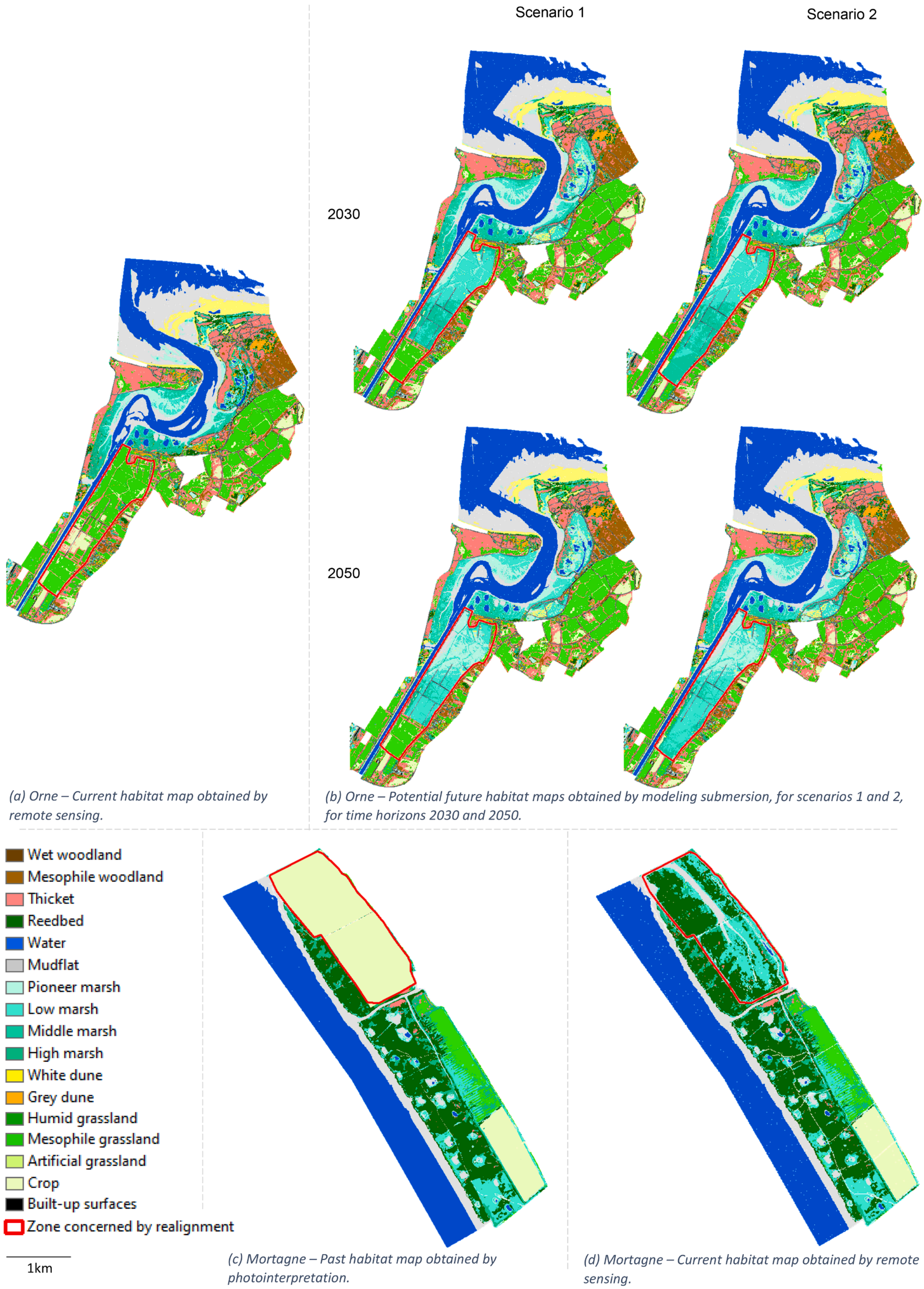

Fig. 6. Habitat maps for the Orne and Mortagne sites, obtained by remote sensing, submersion modeling and photointerpretation.

Table 3
Orne submersion matrix.

Submersion category	0%	]0;1%]	]1;5%]	]5;10%]	]10;15%]	]15;20%]	]20;30%]	]30:40%]	]40:50%]	]50;70%]	]70;100%]
Mesophile woodland	Mesophile woodland		High marsh	Middle marsh		Low marsh		Pioneer marsh	Tidal flat		Water
Thicket	Thicket		High marsh	Middle marsh		Low marsh		Pioneer marsh	Tidal flat		Water
Reedbed	Reedbed					Pioneer marsh			Tidal flat		Water
Water	Mesophile grassland	High marsh	Middle marsh	Low marsh		Pioneer marsh		Tidal flat	Tidal flat		Water
Tidal flat	Mesophile grassland	High marsh	Middle marsh	Low marsh		Pioneer marsh		Tidal flat	Tidal flat		Water
Pioneer marsh	Mesophile grassland	High marsh	Middle marsh	Low marsh		Pioneer marsh			Tidal flat		Water
Low marsh	Mesophile grassland	High marsh	Middle marsh	Low marsh				Pioneer marsh	Tidal flat		Water
Middle marsh	Mesophile grassland	High marsh	Middle marsh			Low marsh		Pioneer marsh	Tidal flat		Water
High marsh	Mesophile grassland	High marsh		Middle marsh		Low marsh		Pioneer marsh	Tidal flat		Water
White dune	White dune									Tidal flat	Water
Grey dune	Grey dune		White dune							Tidal flat	Water
Mesophile grassland	Mesophile grassland		High marsh	Middle marsh		Low marsh		Pioneer marsh	Tidal flat		Water
Crop	Crop		High marsh	Middle marsh		Low marsh		Pioneer marsh	Tidal flat		Water

For example, on this site, a low-marsh habitat should tolerate a submersion duration between 5 and 30% of the year, turn into middle marsh if the submersion duration decreases to between 1 and 5% of the year or into pioneer marsh if it increases to between 30 and 40% of the year.

shown in Fig. 6c and Appendix A. They reveal a high proportion of crop habitat on these sites before their realignment.

3.4. Biological-capacity matrix

The matrix is presented in Table 4.

3.5. Indicator representation

The results of the calculation of the indicator are presented in Fig. 7 for the Orne and Mortagne sites and in Appendix C for the other sites.

The radar charts covering the entire Authie, Orne and Leyre sites do not show significant changes, in that only a small part of each site is impacted by realignment (less than 15 %). On the scale of the realigned zone for these sites and of the Lancieux site as a whole, the charts show greater contrasts and have a similar structure. They show a trend toward

Table 4
Biological-capacity matrix.

	Diversity									Patrimoniality	Functionality									
	Vegetations	Birds	Amphibians	Reptiles	Mammals	Nekton	Molluscs	Odonates	Rhopalocera	Potential of patrimonial habitats	Migratory stopover for birds	Primary productivity	Nutrient cycle	Water cycle	Soil formation and retention	Storage of polluants	Climate regulation	Pollination	Mitigation of physical disutrubances	Mitigation of biological disturbances
Wet woodland	2	2	2	1	2	0	3	2	2	3	1	3	3	3	3	2	2	1	3	2
Mesophile woodland	3	2	2	1	3	0	3	0	3	2	1	2	2	3	3	2	2	1	3	3
Thicket	1	2	1	2	2	0	2	1	2	1	2	2	2	2	2	1	1	3	2	2
Reedbed	1	2	2	1	1	1	2	3	2	2	3	3	2	3	3	3	3	0	3	2
Water	1	1	0	0	1	3	3	0	0	1	1	1	2	2	1	1	2	0	1	1
Tidal flat	1	3	0	0	0	2	1	0	0	3	2	1	1	1	1	1	2	0	1	3
Saltmarsh	1	2	0	0	1	2	1	1	1	3	1	3	2	2	3	3	3	1	3	2
White dune	1	1	0	1	0	0	1	0	0	3	0	1	1	2	2	2	1	0	3	1
Grey dune	2	1	1	2	1	0	2	0	2	3	1	1	1	2	2	2	1	1	2	1
Humid grassland	3	2	3	1	2	0	3	1	3	3	3	3	3	3	2	2	2	2	3	3
Mesophile grassland	3	2	1	2	2	0	2	0	3	2	1	2	2	2	2	1	1	3	2	2
Artificial grassland	1	1	0	1	1	0	0	0	1	0	1	2	1	1	1	1	1	0	1	1
Crop	1	1	0	0	1	0	0	0	0	0	0	2	1	1	1	0	0	1	1	2
Built-up surface	0	1	1	1	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0

Scores range from 0 (no importance) to 3 (high importance).

Fig. 7. Changes in habitat area and indicator implementation at the Orne site (for different time horizons and scenarios, on the site scale and the scale of the realigned zone) and the Mortagne site (for different time horizons, on the site scale).
Equit: Habitat equitability; Div: Diversity; Veg: Vegetation; Amph: Amphibian; Rept: Reptile; Mamm: Mammal; Nek: Nekton; Moll: Mollusc; Od: Odonate; Lep: Lepidoptera; Pat.Hbtt: Potential in patrimonial habitats; Migr: Migratory stopover for birds; Prod: Primary productivity; Nutr.C: Nutrient cycle; Wat.C: Water cycle; Soil: Soil formation and retention; Pollut: Storage of pollutants; Cl.Reg: Climate regulation; Polli: Pollination; Phys.Dist: Mitigation of physical disturbances; Bio.Dist: Mitigation of biological disturbances.

a decrease in diversity for most taxa following realignment, except for birds, nekton and odonates. An increase in the potential of patrimonial habitats can also be expected. Concerning functions, pollination is the most negatively impacted parameter, while primary productivity, soil formation and retention, storage of pollutants, climate regulation and mitigation of physical disturbances show the greatest increases. The more distant the time horizon and/or the larger the area impacted by the realignment scenario, the greater the change in parameters. For the Mortagne and Île Nouvelle sites, almost all parameters increased to varying degrees, except pollination.

4. Discussion

4.1. Habitat maps

4.1.1. Cartographic models of current habitats

The overall accuracies obtained in this study when modeling habitat distribution, ranging from 70 % to 92 %, are in line with previously published studies (e.g. Timm and McGarigal, 2012; van Beijma et al., 2014; Yeo et al., 2020). Water, tidal flats and white dunes are best mapped, while reedbeds, grey dunes and humid grasslands are the most poorly mapped habitats. Various factors may explain the observed confusions between habitats. Thickets, such as grey dunes, are perhaps less well modeled because they are transitional habitats and are more likely to evolve between the different years of the orthophotographs. Even for orthophotographs taken over short intervals, the sites remain changing environments in which less radical and more progressive changes than coastal realignment can take place (variation in water levels, erosion by trampling, management operations, *etc.*) and transform habitats. This may explain the low accuracy in modeling reedbeds, noted in other studies (e.g. Ghioca-Robrecht et al., 2008), whose surface areas change according to fluctuations in water levels and human intervention, notably mowing. Fluctuations in water levels can also explain the difficulty in modeling interface habitats (Belluco et al., 2006; van Beijma et al., 2014). Although water and tidal flats are very different habitats, they are sometimes confused due to the intermittent presence of water during tides and the use of orthophotographs taken at different water heights. Finally, confusions between saltmarsh levels may be related to habitats intermingling and forming micromosaics on some sites such as Leyre. Several habitats may thus be included in the same pixel, forming a "mixed pixel" or "mixel" whose classification may be erroneous (Janssen, 2001). The high marsh appeared to be the most confused saltmarsh level in our study, mainly with thickets and grasslands, perhaps because it is the least subject to the tides and can present woody or grassy vegetation.

It is also important to analyze the results taking into account the influence of the surface area of the habitats, because using a quantity of training polygons proportional to the surface area of the habitats directly affects the overall accuracy of the model. The larger the habitat, the more polygons covering its surface and the more its classification (correct or incorrect) will impact the overall accuracy. For example, water and tidal flats, which are both well modeled, tend to improve the results. However, this effect was mitigated here by limiting the maximum number of polygons used, as well as by the small difference in the number of polygons between the least and most present habitat.

Several avenues of improvement could be explored in the future to increase the overall accuracy of the models. First, the number and size of polygons used for modeling are two parameters that influence the performance of the model and can be manipulated. The number of polygons could have been increased, but the size of the sites and habitats initially limited the number of polygons because the smallest ones could not accommodate more polygons while respecting the minimum distance of 15 m between each. In terms of polygon size, tests were carried out by changing the radius of the polygons from 5 to 15 m, but maintaining the proportion of the site covered by polygons. This resulted in lower accuracies, decreasing 10 to 43 % depending on the site, which could be explained by the autocorrelation of adjacent pixels and by the fact that the heterogeneity of habitats was less well covered (Congalton, 1991; Millard and Richardson, 2015). A second way to improve our models resides in the selection of the orthophotographs used. To that end, Rapinel et al. (2015b) recommended the use of images covering several seasons, including winter, given that the best time for habitat identification differs from one habitat to another depending on the phenology of the vegetation. Similarly, selected images may have been taken under different tidal conditions, in order to better distinguish tidal flats from low levels of saltmarsh (Laengner et al., 2019). This aspect was taken into account as much as possible in this study, to the extent that the images available on the download portal allowed it. Finally, it is known that the number of habitats per site can affect overall accuracy (Millard and Richardson, 2015). This can be observed here for the Mortagne and Île Nouvelle sites, both of which have the best classifications and the fewest habitats present. Merging habitat types, such as different levels of saltmarsh, could therefore improve – albeit in a somewhat artificial way – the overall accuracy of the model, but this may result in operational predictions of limited use to nature managers. In short, an appropriate compromise must always be sought.

4.1.2. Assessment of habitat conversion based on submersion simulations

The maps of future habitats reveal the development of saltmarshes in the realigned zones. However, these results are based only on submersion durations and do not take into account local environmental conditions (e.g. physico-chemical properties of the soil or interspecific competition (Armstrong et al., 1985; Benito et al., 1990; Bertness and Ellison, 1987)) or other modifications due to climate change (e.g. rising elevation of salt wedges, increases in temperature). These submersion simulations are only elevation-dependent, whereas other parameters such as geomorphology (e.g. stream-drainage systems) or local wind regimes may have a strong influence on flooding levels (Bockelmann et al., 2002). They are also implemented with a constant DEM, which does not take into account the morphological changes of a site due to its realignment (e.g. erosion or sediment deposition). However, the values used for the different habitats, such as reedbeds (present for submergence durations of less than 20 % of the time), or the different levels of saltmarshes (high marsh present for submersion times of less than 5 %, middle marsh between 1 and 20 %, low marsh between 5 and 30 % and pioneer marsh between 15 and 50 % depending on sites), are in line with what can be found in the literature (e.g. Deng et al., 2014; Doody, 2008), even if some sources provide wider ranges of values or greater tolerance to submergence durations (Friess et al., 2012; Silvestri et al., 2005). In addition, the submersion matrices are based on the hypothesis of three ecological successions, namely (i) the transformation of a non-coastal habitat into different saltmarsh levels, tidal flats and water, (ii) the transformation of reedbeds into pioneer marsh, tidal flats and water, (iii) and the transformation of grey dunes into white dunes, tidal flats and water. The first two assume that habitats adapt when they reach their salt and submersion tolerance limits, based on saltmarsh-structure and coastal-realignment studies (e.g. Boorman, 2003; Eertman et al., 2002; Karberg et al., 2018; Ranwell, 1972; Sinicrope et al., 1990). The third assumes a burial of grey dunes and a landward transgression of white dunes until a submersion-duration threshold is reached, at which point the habitat becomes tidal flat. However, other habitat transformations could take place, which were not considered here (e.g. thickets turning into forests, colonization of tidal flats by reedbeds).

4.2. Biological-capacity matrix

The biological-capacity matrix used here also has some limitations, e.g. the allocation of scores may be criticized insofar as it is partly based on expertise. However, the setting of scores has been discussed in depth among experienced naturalists and is, in our view, a solid starting point for our models. It is probably as - or even more - reliable than a detailed analysis of the literature that would lack the knowledge available for certain parameters and habitats, or rely on a massive number of publications (Drescher et al., 2013; Krueger et al., 2012). In addition, this gives great flexibility to our approach, which can be transferred to sites in other geographical contexts, provided that experienced naturalists are involved. Another limit is that it does not take into account certain aspects such as the ecological characteristics of an environment (e.g. age of woodlands, connectivity and fragmentation of habitats) or its management (e.g. unmanaged, grazed or mowed grasslands, intensive or extensive crops), all elements which could modify the scores in certain circumstances.

4.3. Indicator interpretation and limits

The graphical representations of the indicator highlight trends that are directly related to habitat changes. Two situations can be distinguished from the results, depending on the dominant habitats before and after restoration, namely (i) the change from grassland habitats to saltmarshes (Authie, Orne, Lancieux, Leyre), (ii) the change from crops to saltmarshes and reedbeds (Mortagne, Île Nouvelle) (see Fig. 6 and Appendix C). In the first case, the decrease in diversity for most taxa can be explained by the fact that saltmarshes are highly constrained environments, with restricted diversity (Boorman, 2003). However, they are important feeding and nursery areas for nekton (Able et al., 2002; Raposa, 2002). The lack of change in avifaunal diversity is related to the fact that both grasslands and saltmarshes are important areas for birds, but it also masks the fact that the change in environment is accompanied by a change in species assemblages (Jacobson, 1986). Concerning odonates, although the saltmarshes are not a very favorable habitat for this taxon, their diversity could increase because mesophile grasslands are even less favorable (Catling et al., 2006; Kalkman et al., 2008). The results are less marked for the Leyre site compared to the other three because even before coastal realignment, a large part of the site is occupied by areas of water, which are favorable for nekton and less so for other taxa. In the second case, the diversity of all taxa remains constant or increases because crops are areas with low specific richness. In both cases, the score associated with the potential of patrimonial habitats increases with coastal realignment, saltmarshes being patrimonial habitats (European Economic Community, 1992). The development of this habitat also explains the decrease in the pollination function, however the decrease is less significant in the second case, given that crops do not play a major role in this function either. The saltmarshes are, on the other hand, recognized for their high primary productivity (Barbier et al., 2011), their role in soil formation and retention (Knutson, 1988), storage of pollutants (Agardy et al., 2005), climate regulation (Duarte et al., 2013) and mitigation of physical disturbances (Spalding et al., 2014), justifying the increase in the scores associated with these parameters.

When interpreting the indicator, it is important to remember that it is an indicator of *potential* ecological quality, which indicates an evolutionary trend but is not based on ecological surveys and does not consider site-specific characteristics (management, habitat fragmentation, *etc*.). The interpretation must therefore be undertaken with caution, i.e. (i) for a given site (the indicator depends on the delimitation of the site and the associated surfaces; significant changes for biodiversity may not be highlighted if only a small part of the site is realigned), (ii) in a given context (the site is part of a larger space, including habitats that can shelter other species and perform other functions), (iii) with given management objectives (certain habitats are more favorable to certain taxa or certain functions than others, it is not possible to maximize all parameters). It is also important to keep in mind that the indicator calculation is based on the assumption of a linear relationship between a metric and the surface area of a habitat. Although this hypothesis can be considered valid for some metrics (e.g. for climate regulation if carbon sequestration, expressed in g/m^2/year, is used as a proxy), such a relationship is debatable for other parameters (e.g. species richness (Connor and McCoy, 2001) or mitigation of physical disturbance (Barbier et al., 2008)).

That being said, this indicator has several advantages. In particular, it can, without in-depth naturalist knowledge and without requiring the use of expensive data, demonstrate that a coastal realignment operation is not all black or all white, but that certain parameters will benefit at the expense of others. It can also serve to generate different management scenarios over different timescales for comparison, in order to favor some parameters such as patrimonial habitats, pollination, climate regulation, *etc*. It can thus be used as a decision-aid tool or, at the least, to raise awareness and communicate the advantages and disadvantages of such an operation in the context of multi-partner meetings (nature managers, residents, politicians) dedicated to the future of sites concerned by sea-level rise.

5. Conclusion

The indicator can be used to study the evolving trends of different diversity and functionality parameters in a context of coastal realignment. Although it is not based on field sampling (its objective being to assess ecological potential), this indicator is a tool intended for managers of natural areas concerned by coastal realignment, enabling them to communicate on its effects on biodiversity and to highlight the resulting gains and losses. Several tools were developed during this study, including the typology, the machine-learning based habitat-mapping protocol, the process of forecasting future habitats in the event of flooding and a matrix evaluating the importance of the various habitats for different ecological parameters and enabling the calculation of an ecological-quality indicator. We are convinced that these tools could be transferred to any other site concerned by managed realignment and/or by sea-level rise, to generate operational forecasts for nature managers worldwide.

CRediT authorship contribution statement

Marianne Debue: Conceptualization, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. **Lucille Billon:** Investigation, Methodology, Software, Writing – review & editing. **Olivier Brivois:** Methodology, Writing – review & editing. **Rémy Poncet:** Investigation, Methodology, Writing – review & editing. **Yorick Reyjol:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2022.109216.

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