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Ecosystem services assessment and compensation costs for installing seaweed farms

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Abstract :

In a global context of promotion and expansion of blue growth initiatives, the development of activities such as aquaculture calls for the assessment of the potential impacts on biodiversity at different levels and associated services. This paper presents an assessment of the potential impact of the installation of seaweed farms on ecosystem services and the induced compensation costs. Biophysical and socioeconomic indicators have been developed for helping decision makers to select the most suitable locations. The approach considers a multi-criteria approach based on Geographical Information Systems (GIS) and Habitat Equivalency Analysis (HEA). The former is used to obtain biophysical ecosystem services and socioeconomic indicators and the latter to evaluate the costs required to compensate the loss of cultural and provisioning ecosystem services. A case-study in the Normand-Breton (Saint Malo) Gulf, France, illustrates this method through the analysis of hypothetical locations of seaweed farms. Results highlight the differences between alternative locations regarding biophysical constraints (in terms of distance and depth), potential risks of conflicts with existing uses, impacts on habitats and the ecosystem services delivered, and compensation costs. This case-study illustrates the flexibility of this approach which can be further adapted to include other indicators in order to deliver integrated information to coastal planners.

Highlights

► Seaweed farms installation requires a multi-criteria approach. ► A GIS-based methodology combined with HEA is proposed. ► We deliver integrated information about ES impacts and compensation costs.

Keywords : Integrated marine policy, Habitat equivalency analysis, Compensation costs, No net loss, Blue growth

1. Introduction

The European Union (EU) Integrated Maritime Policy promotes the sustainable development of new blue growth activities [1], such as marine renewable energy, raw material extraction, leisure activities, and aquaculture including seaweed farming. Currently there are several on-going projects related to seaweed farming, for instance, the EnAlgae project (www.enalgae.eu) seeking to reduce reliance on fossil fuels by developing algal biofuel technologies, and the MARIBE project (www.maribe.eu) aiming to identify and develop business models for blue growth activities, including seaweed farming. Despite reports of several positive effects associated with seaweed farming worldwide [2–4], failures in or lack of knowledge exchange between the aquaculture industry, policymakers, local population, and people who depend on aquaculture, may jeopardize the 'Blue growth', which includes seaweed farming [5]. Additionally, it has also been reported that negative impacts of seaweed on ecosystems have not yet been fully investigated [6]. Altogether, these factors may contribute to the lack of social acceptance of this activity not only in France but also in other countries.

In France, seaweed farming activities started in the 1970-1980s, for instance, with the culture of *Undaria pinnatifida*, an introduced species native to Asia. Currently, there are ongoing projects such as IDEALG (www.idealg.ueb.eu) developing this sector by using local species (e.g. *L. saccharina)*. Since 2008 this activity has gained new interest as a response to the crisis faced by oyster farmers due to the high mortality of oysters. The installation of seaweed farms along the French Atlantic coasts is now perceived as a source of complementary income to these farmers and gives new use to the existing oyster farms. However, not all of the available concessions are suitable for the cultivation of seaweed using subsurface long-lines, which should take place in deep waters rather than on the shore. Additionally, new projects of mussels or seaweed farms in deep waters are facing social resistance from local populations who fear negative impacts on ecosystems, fisheries activities and tourism, related to the degradation of seascape/seawater quality and increasing restrictions on recreational uses. Although the French administration has authorized new concessions, they have not been implemented due to the opposition of residents or associations.

To facilitate the development of these new activities, the European Commission urges countries to implement Marine Spatial Planning (MSP), which includes a consultation phase to identify the use of each marine zone. EU countries are also required to draw up a maritime spatial plan no later than 31 March 2021 [7]. However, considering the opposition faced by seaweed farming projects in France and other countries, it is necessary to go beyond simple spatial planning and to develop new *concepts*, *methods*, and *tools* to facilitate discussion and negotiation between the actors of the system.

The "ecosystem services" *concept* seems interesting to use for facilitating discussion at a territory scale (see for example the Natural Capital Project[1]). Marine ecosystems are complex and changing systems that provide multiple services to humans [8]. However, there is a recognized biodiversity crisis in marine environments, particularly in coastal zones where a diverse set of human activities and drivers are concentrated [9] and interact [10]. Services provided by marine systems have diminished while human exploitation patterns have been increasing [11]. One way of addressing this global problem is through ecosystem-based management (EBM) approaches, which propose managing seas and oceans by maintaining ecosystems structure, redundancies, and resilience to environmental changes [12]. EBM includes local political aspects and management actions at different spatial scales of application [13]. Despite the recognition of the interest in this approach at a global scale through the Millennium Ecosystem Assessment [8,14], successful examples of local EBM

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[1] http://www.naturalcapitalproject.org

approaches are relatively rare [15]. EBM failures have different explanations, for instance, conflicts between users who expect or envision different benefits from ecosystems (e.g. commercial fishing versus conservation interests) or lack of institutions for effective governance [16–18], as well as level of transaction costs to overcome implementing this method [19]. Differences in terminology and knowledge among different groups of interests [20–22] coupled with the complexity and specificities of marine and coastal systems [23] make consultation in EBM a rough task. The use of the ecosystem services framework can help to improve the implementation of EBM approaches by providing a common set of facts and a common currency to better understand trade-offs between alternative development projects [15,24].

In addition to the concept of ecosystem services, it also seems important to adopt multi-criteria methods for describing interactions between human uses and ecological dynamics (and not an aggregated monetary valuation). Indeed, the marine socio-ecosystem is characterized by multiple systems of values with multiple sustainability criteria which makes its governance a global challenge [25,26]. Thus, considering simultaneously the analysis of variables and values characterized by limited comparability is a task that can be assessed only using a multi-criteria analysis [27,28].

Three main dimensions associated with the location of implementation of seaweed farms were identified. First, seaweed farms face operational constraints, such as optimal depth, but also a minimal distance from the coast, which is directly associated to their visual impact. Second, marine ecosystems are subject to multiple uses, and locating farms where uses are already numerous increases the potential level of conflict among users. Third, the implementation of a new farm must be associated with an environmental impact assessment that can raise stakeholders' opposition but also lead to a mitigation procedure (avoiding, reducing, and compensating).

Adopting a multi-criteria analysis based on ecosystem services assessment requires innovative *tools* to provide useful information that can help the emergence of a general agreement. Two different tools were applied: i) the first tool is called InVEST (Integrated Valuation of Ecosystem Services and Trade-offs), which relies on ecological information to map, quantify, and value the distribution of ecosystem services across a landscape (or a seascape) [14,29,30]; and, (ii) the HEA (Habitat Equivalency Analysis), which has been used by the US administration in the case of accidental impacts on marine ecosystems and habitats to determine the size of a compensatory measure based on a biophysical ecosystem services unit criterion [31,32].

The goal of this paper is to provide biophysical and socioeconomic indicators describing the constraints for seaweed farm deployment and the impacts generated on ecosystem services in order to assist decision-makers through an illustrative case study. The selected indicators include biophysical constraints (especially the depth), distance to the coast, impacts on ecosystem services (provisioning and cultural), potential conflicts with other uses, and compensation costs. The objective is not to find the "best possible location" but to illustrate the efficiency of an integrative assessment tool for decision-makers. The approach could also contribute to the design of regional plans for the development of marine aquaculture activities (e.g. the development of the regional development schema of marine aquaculture as part of the fisheries and agriculture modernization law [33]).

2. Data and methods

2.1 Study area

The Normand-Breton Gulf (GNB), located in the western part of the English Channel includes several habitats depending on complex currents and the presence of islands, archipelagos and rocky reefs [34] (Fig. 1). The Normandy and Brittany coasts are heterogeneous areas more developed and densely populated around the main urban centers of Ille-et-Vilaine and Côtes d'Armor, although less than along other French coasts such as the Mediterranean coasts [35]. There are 267 municipalities within a distance of 3km of the coastline of the study area with a population of 600,340 inhabitants in 2011 [36]. However, these values do not consider the high number of tourists that visit the region mainly during the summer (e.g., more than 360,000 tourists visited the city of Saint-Malo in 2014 [37]). The existing marine economic activities include shellfish farming, commercial fishing, agriculture, tourism and leisure activities (e.g. sailing, diving, fishing, others), nuclear power and fuel reprocessing industries, aggregates extraction, and planned offshore renewable energy farms [35].

In this case study, biophysical, ecological, and socioeconomic indicators were calculated for three hypothetical locations, each one dedicated to the installation of seaweed farms of 1km^2 (A, B, and C). The locations were selected to allow a contrasting comparison of the different indicators that are going to be produced in this study. Although these are hypothetical locations, this exercise corresponds to a real need of the study area. A seaweed farming project (300 hectares) in the area of the GNB that has recently been approved by the administration is currently on hold because of the high level of conflict with the local population.

[Fig 1 here]

2.2 Data and pre-processing

A habitat map [37–48] using the European Nature Information System (EUNIS) [49] level 4 classification was used. In level 4 of the EUNIS classification scheme, 'physical' characteristics and biological zones are used as well as references to specific taxa; for instance major epifaunal taxa are used to discriminate rocky habitats although, for soft substrata, the classification is still based on the 'physical' and zonal attributes.

The ocean depth and the 12 nautical mile limits datasets were provided, respectively, by GEBCO [38] and Marine Regions [39].

Census data from the National Institute of Statistics and Economic Studies for year 2011 [36] at the "*commune*" level, the lowest unit of the French territorial administrative division, was used to estimate the number of inhabitants affected by the seaweed farms' potential location. The administrative boundaries are from the French National Geographic Institute [40]. The base land cover map of year 2006, the Corine Land Cover (CLC), is from the European Environmental Agency (EEA) and has a spatial resolution of 100m with a minimum mapping unit of 25ha [41]. The Digital Elevation Model (DEM) used was ASTER [42] with a spatial resolution of 30m.

The geographical datasets of 17 recreational and professional activities were provided by the French Agency of Marine Protected Areas (AAMP) and the French Research Institute for Exploitation of the Sea (Ifremer). The source, type of geometry, and preprocessing activities with Geographical Information Systems (GIS) are described in Table A.1 of Annex 1. All of the geographical datasets are, or were, converted into a common NTF France II (Degrees) projection.

2.3 Methods

The methodological approach for providing indicators for the installation of seaweed farms is depicted in Figure 2 and described below.

[Fig 2 here]

2.3.1 Biophysical constraints: distance from the coast and visual impact

The biophysical criteria include aspects that facilitate the installation of the seaweed farms such the depth, the distance from the coast, and the visual impact of the infrastructures on the population living near the coast. GIS tools and models available in, respectively, ESRI's ArcGIS [43] and InVEST software from Natural Capital Project [44] were used to obtain the biophysical factors.

The optimal depth for seaweed cultivation with subsurface long-lines was defined to be between 6 and 15m. This depth is the same used for a real seaweed farm project, with *Saccharina latissima*, in Plobannalec-Lesconil and Loctudy, in Brittany [45]. Since these infrastructures need to be permanently under water, only the areas outside the foreshore were considered.

Other important aspects considered were the distance of the infrastructure from the coast and the visual impact and restrictions to recreation activities (e.g. sailing, scuba diving, others) caused by the buoys and lines of the infrastructures. Within the 12 nautical mile limit, the closer the infrastructures are to the coast, the less important are the economic costs related to their exploitation, e.g., lower transportation costs. On the other hand, the closer the infrastructures are to the coast, the higher will be the potential visual impact on the population that lives near the coast and the higher will be restrictions for recreational activities in the areas occupied by the infrastructures, thus decreasing the social acceptance to this type of economic activity. An estimate of the potential number of inhabitants affected by each seaweed farm is provided using the InVEST Scenic Quality Model [44]. This model includes the use of a dasymetric technique to represent population density more truthfully by combining census population data with the urban land use and cover classes [46].

2.3.2 The potential use conflicts

The identification of the areas of potential use conflicts with the new infrastructures is an important socioeconomic factor. The potential use conflicts are likely to arise more frequently in the areas where more human activities co-exist. Thus, these areas should be avoided to install the seaweed farms. The human activities, represented by separate geographical layers, were counted using a 1km spatial resolution cell by the InVEST Overlap tool [44] to compute a “potential conflict” score. Legal aspects, such as the access to the maritime space, through the allocation of concessions, or the existing rules for cultivating only species found locally may also limit the installation of the seaweed farms [47,48]. However, these were not considered in this hypothetical exercise.

2.3.3 Impacts on ecosystem services

Although there are more ecosystem services provided by the GNB habitats, the provision and cultural ecosystem services listed in Table 1 were the ones selected as the most relevant and documented for this study.

Biodiversity is here treated as a cultural service and concerns only the GNB notable species. The regulating and maintenance services were also identified for the study area. However, and despite their potential impact on climate change and mitigation against global warming or on macrofaunal and seagrass assemblages [49–53], these were not considered in this study due to the lack of suitable data.

[Table 1 here]

To study the impact on ecosystem services, a matrix that links the 17 EUNIS level 4 habitats to the availability of the ecosystem services listed in Table 1 was created using expert knowledge [27]. This procedure included the analysis of 18 commercial species for food provision services and 14 activities for cultural services. The scores reflected the availability of ecosystem services provided by the habitats for each type of service and could have the values of 0 (absent), 1 (weak), 2 (medium), or 3 (strong). All values were summed and transformed into an interval between 0 and 1, by subtracting the minimum value and dividing by the difference between the maximum and minimum value [54]. This information was used to build maps of ecosystem services availability in the GNB on a grid of 1km spatial resolution. More details about this dataset are available in [27].

2.3.4 Compensation costs regarding impacts on ecosystem services

The compensation cost of the creation of seaweed farms from the ecosystem services approach [55] were assessed using the MEA categories [8]: cultural, provisioning, and regulating services. The Habitat Equivalency Analysis (HEA), which allows to calculate equivalencies between damage and compensation, in biophysical units corresponding to proxies of ecosystem services [32], was also used. The basis of this method was introduced in

1994 by American scientists in order to address the problem of monetary valuation of ecosystem services which were considered by the American Court of justice to be an insufficiently robust method to assess the required compensation after accidental pollution [56–58]. In 1995, the National Oceanic and Atmospheric Administration of the United States released a report on HEA that was subsequently revised [31].

The Visual HEA software [59], version 2.6, was used to apply the HEA method. A more detailed description of this method can be obtained in the works by [32,55,60]. The selection of ecosystem indicators was carried out by experts with extensive scientific knowledge on the GNB and was based on the intensity of presence of selected species for each of the existing habitats. The species that exhibited the greatest intensity of presence were used as proxies for ecosystem services indicators. These ecosystem services indicators comprise the selection of adequate metrics, such as growth rate/cm of oysters as a proxy of provisioning services [55]. The number of hectares is the metric used in the equivalency method for each ecosystem service. The losses due to impacts and the gains due to compensation are presented as Discounted Service Acre-Years (DSAYs). A widely accepted rate of 3% was used to make past and future losses and gains comparable [55,61].

The compensatory ratios used by the US Natural Resources Damage Assessment (NRDA) [55,62] are used in this study. A ratio represents the number of units of compensatory area necessary to compensate one unit of natural area. In this case-study it is assumed that the concession starts in year 2015 and ends in 2030 (Fig. 3). The pre-injury service level is 100% and there is a loss of 100% as a consequence of the seaweed farm installation. When the concession ends, the service level is restored to 100%.

[Fig 3 here]

The compensation action starts in year 2015 and reaches a maximum of 85% because it is assumed that it is not possible to recover as efficiently as Nature does. The recovery time is variable and depends on the selected proxy. Figure 4 shows the recovery time for the maerl beds.

[Fig 4 here]

The area of the damaged zone, in this case the seaweed farm location, is known, i.e. 1km^2. The gains obtained with the compensation measures were then quantified. The size of the compensation project is obtained after calculating the maintenance costs (ha to compensate/impacted area). Finally, the maintenance costs (in \$/impacted ha) are estimated according to specific habitats. The recovery times (years), ratios, and restoration costs of the proxies used as ecosystem services indicators were obtained through bibliographic research.

3. Results

A mask with the suitable biophysical characteristics (i.e., depth, distance to coastline, habitat, within the 12 nautical miles, and visual impact) delimiting the suitable area for the seaweed farm was created. Subsequently, the InVEST Overlap Analysis tool was used to calculate the number of human activities existing in a grid of 1km spatial resolution (Fig. 5). The maximum number of overlapping activities is five and lowest is one.

[Fig 5 here]

Figure 6 depicts using a 1km spatial resolution cell, the ecosystem services availability for each type of ecosystem services. The closer the values are to 0 the lower is the ecosystem services availability by type of service. One would give priority to install seaweed farms in the areas where there is less availability of ecosystem services to cause the minimum possible impact on the existing level of ecosystem services.

[Fig 6 here]

Table 2 shows the types of habitat existing in each seaweed farm location. Farms A and B are located over a single type of habitat, respectively, maerl bed (A5.51) and circalittoral coarse sediment (A5.13). Farm C has 38.4% of its area located over polychaete/bivalve-dominated muddy sand shores (A2.24). The remaining area of this farm is located in infralittoral mixed sediments (A5.43).

The species selected as proxies of ecosystem services were the ones that had the highest abundance according to expert knowledge and fall into the categories of cultural or provisioning ecosystem services.

[Table 2 here]

The adopted recovery times (years), ratios, and restoration costs of the proxies used as ecosystem services indicators are shown in Table 3.

[Table 3 here]

Using Visual_HEA, the following results were obtained for the maerl:

- 13,132 DSAYs are lost in the damaged area.
- 15,243 DSAYs are gained in the compensatory area.
- Using a 3:1 ratio, the HEA shows that 2.585 ha of maerl beds are necessary to compensate for the 1 ha of the damaged area.

The cost of coral reefs restoration programs as an approximation of maintenance costs of maerl beds, which have very similar characteristics [55], was used. According to [63], this cost ranges from \$24,700 to \$123,548 per ha. Converting this range of values to km^2 and multiplying it by the number of ha needed to compensate one damaged ha (2.585) would be an approximation of what should be paid by the seaweed farmer to compensate the creation of farm A (i.e., between \$6,384,950 and \$31,937,158). The same reasoning was applied for the other farm locations. For the farm location C, the costs were calculated using the values provided by [63] mollusk reefs. Results for all the farms, together with the biophysical, ecological, and socioeconomic indicators obtained are shown in Table 4.

[Table 4 here]

Farm A presents the best values for three indicators: the lowest level of provisioning services (42%) and cultural services (20%) in the site and the lowest visual impact (3690 inhab.). However, it is by far the one that presents the highest compensation costs, between $6,384,950 and $31,937,158. It is also the one in which the number of ha to be compensated per damaged ha is the highest (2.585). Farm B is the best for two indicators: potential human use conflicts (one activity) and restoration costs ($365,484). Farm C is the closest to the coast (1 km) and the one which presents the lowest number of ha to be compensated per damaged ha (2.002). However, it is located in an area where a high number of potential conflicts may arise (five activities) (as with farm A). It is also an area where cultural activities are very available (100%).

4. Discussion and conclusions

An EBM approach was proposed to provide quantitative biophysical, ecological and socioeconomic indicators to help marine planners decide on where to create seaweed farms in the GNB. The aim was to provide an approach that supports decision making enabling an informed discussion between administration and local stakeholders during the installation of new aquaculture projects. Being the best in three out of seven indicators, farm A could be seen as the “best” location. However, criteria may have different levels of importance and weighted differently according to the context. This issue should be addressed by stakeholders during the discussion phase by providing feedback on the relative importance of each indicator, allowing them to rank the location of the seaweed farms.

The novelty of this explicit spatial approach to ecosystem services impacts and compensation costs resides in the delivery of this information in an integrated way that can be easily adapted to include more constraints and/or other ecosystem services. To do this a multi-criteria approach combining different tools to inform four identified dimensions was used. Multi-criteria methods provide a systematic methodology to combine different inputs to help rank project alternatives, and there has been an important increase in the literature about these methods [65]. This interest can be explained as it brings transparency to decisions involving a high level of complexity.

Two different tools were used. First, the InVEST tool, developed by the Natural Capital Project, which uses information about the characteristics of the ecosystem to determine the delivery of different ecosystem services [29] was applied. This approach is based on the identification of ecological production functions that specify the feasible output of ecosystem services given the biophysical characteristics of an ecosystem [14]. InVEST has been designed to be integrated into stakeholders' consultation through the co-designing of scenarios to project how the provision of ecosystem services might change in response to different development decisions [24]. As the number of modeling tools is high, InVEST offers the advantage being relatively easy to implement when data are available [66]. Second, the HEA tool to determine the surface and cost of compensatory measures associated with the impact of seaweed farm implementation was applied. This tool relies on the use of bio-ecological proxies to determine equivalency between losses due to impact and gains due to compensation. It has been developed to simplify the calculation of costs that a polluter has to pay in a context of strong opposition of stakeholders against a court decision that was earlier based on contingent valuation [58]. One of the strengths of the method is to focus negotiation on the choice of a single metric that best captures the level of ecosystem services, since results will strongly vary according to this choice [67,68]. Experiences of stakeholders' implication into the metrics selection have been realized using an ecosystem services framework [55].

In the end our analysis summarizes the relevant information needed for decision-making in the perspective of four identified issues. The combination of these tools has the potential to support decision makers to reach consensus among different stakeholders, since all tools rely on the ecosystem services framework that allows the use of a common currency to the different types of benefits users will receive from an ecosystem. Additionally, the tools have been built in a manner to integrate stakeholders' concerns and bring consultation back into decision.

Nevertheless, there are limitations that one must be aware of when using this approach. An important one was the option of using ecosystem indicators through single representative species instead of the whole ecosystem (for the HEA tool). And yet, changes at population level have been shown to have a substantial impact on the ecosystem function as a whole [69,70]. Other neglected aspects were the complexity of the interactions that exist between species and habitats [71] and the exclusion from this study of regulating services that could have positive or negative impacts on several ecosystem services [49–53]. Regarding this last aspect, it is worth mentioning that a recent study considered negligible the impact of seaweed farms on these services [72]. None of these limitations were not possible to address, due to insufficient data or knowledge needed to use these approaches.

Regarding the compensation costs, although these vary in space and over time, the lack of detailed studies about restoration costs for this study area forced us to use information from other studies located in different places. Furthermore, the very high cost borne by developers for compensating impacts on maerl should exclude these locations. This result is in line with the legislation that protects maerl habitats; as the presence of maerl beds would prevent the development of any project.

Regarding the selected dimensions, the question of the production of ecosystem services associated with seaweed farming was probably overlooked. Seaweed communities are the source of valuable ecosystem services such as habitats for specific species, sediment stabilization, and nitrate absorption. More research is needed to determine which of these services persists when seaweed is cultivated. For example, [50] assessed the potential of seaweed farms to fix carbon and thus participate in carbon regulation.

Finally, other physical features, such as tidal coefficients, currents, waves, and winds may be included in the study for future analysis, depending on data availability.

Despite the above mentioned limitations, this approach provides several indicators in an integrated way which are not usually available to stakeholders. The results may open a new space for dialogue on a common conceptual and scientific basis between different stakeholders who have different perspectives and contribute to the management of the various activities of the GNB socio-ecological system. Beyond the completion of this study, which will also include scenario and economic analysis of ecosystem services, the challenge will be to continue working on the usefulness of this assessment and the way it can effectively influence decision-making activities contributing to the maintenance of ecosystem functioning.

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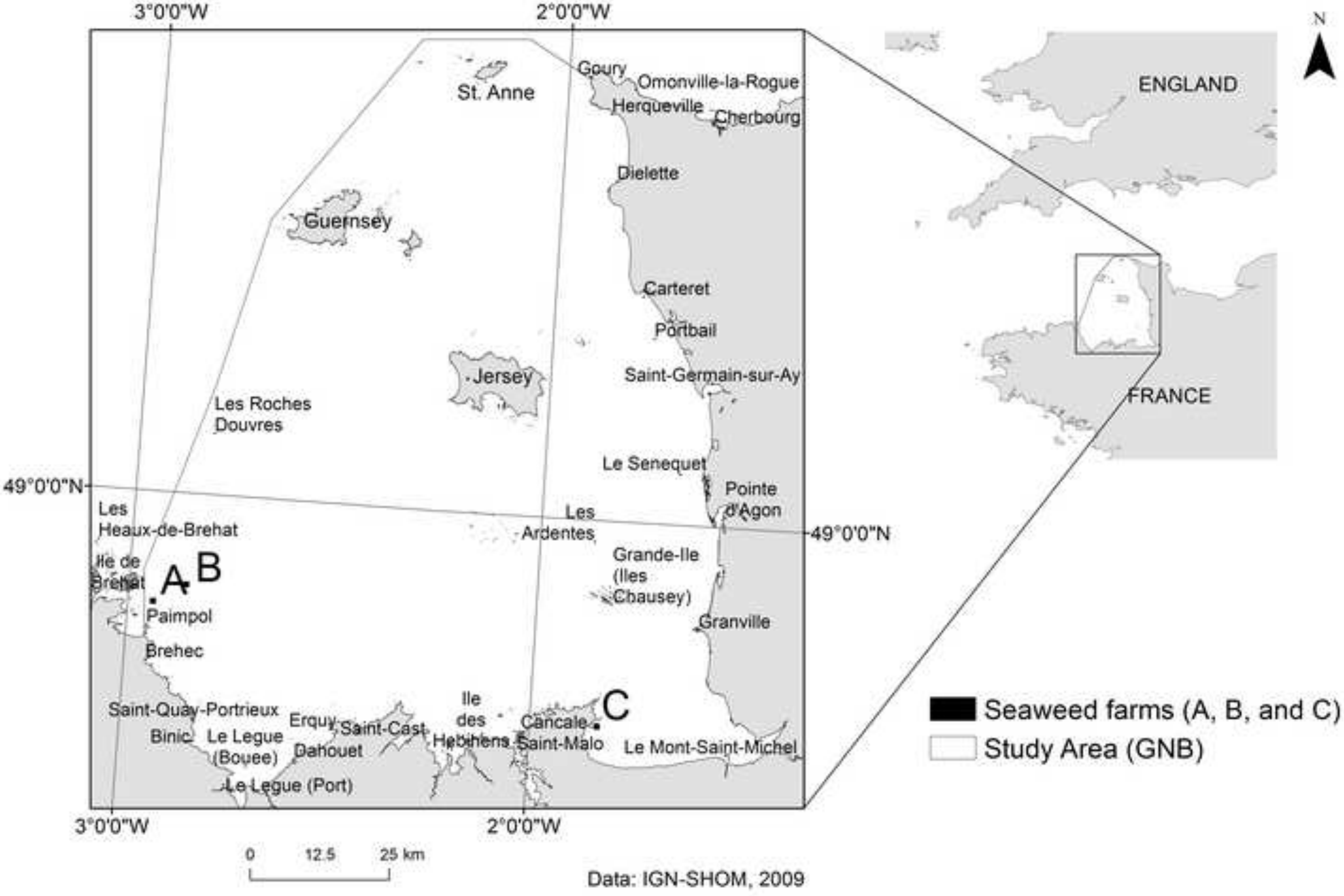
ANNEX 1

[Table A.1 here]

Figure 1

Click here to download high resolution image



Data: IGN-SHOM, 2009

Figure 2

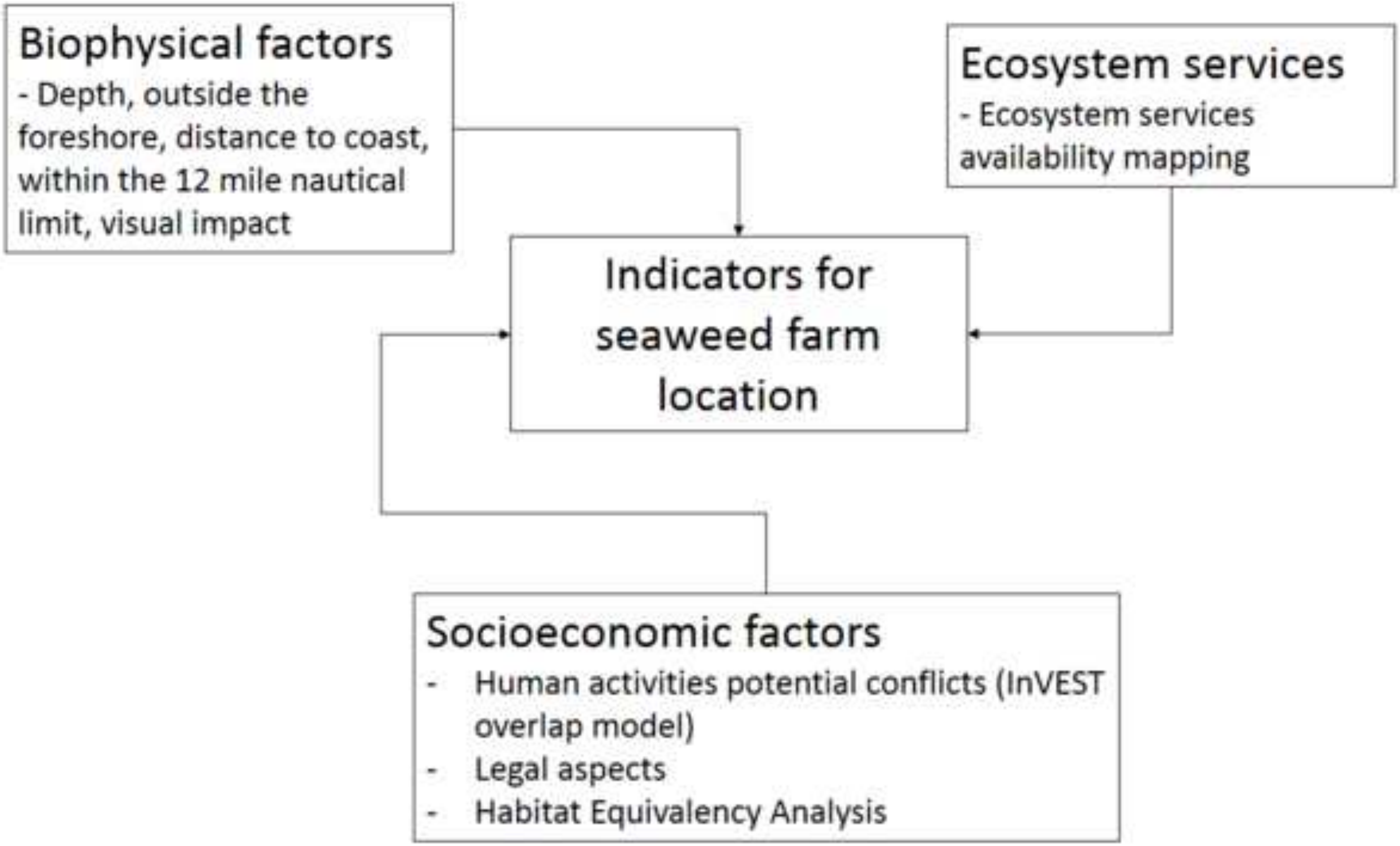

Biophysical factors
- Depth, outside the foreshore, distance to coast, within the 12 mile nautical limit, visual impact
Ecosystem services
- Ecosystem services availability mapping
Indicators for seaweed farm location
Socioeconomic factors
- Human activities potential conflicts (InVEST overlap model)
- Legal aspects
- Habitat Equivalency Analysis

Figure 3

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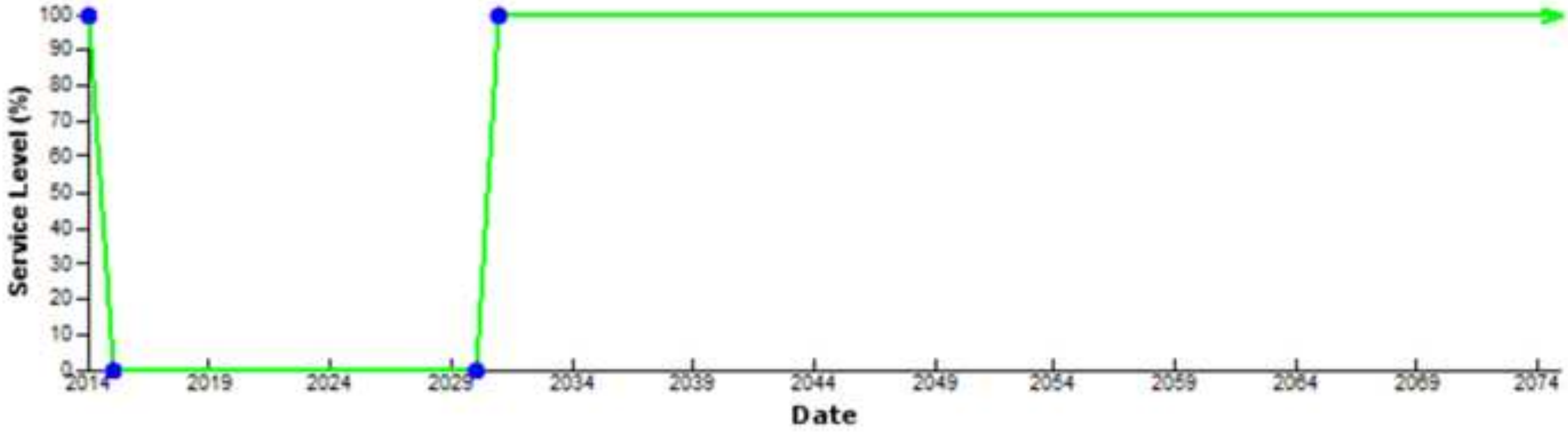

Figure 4

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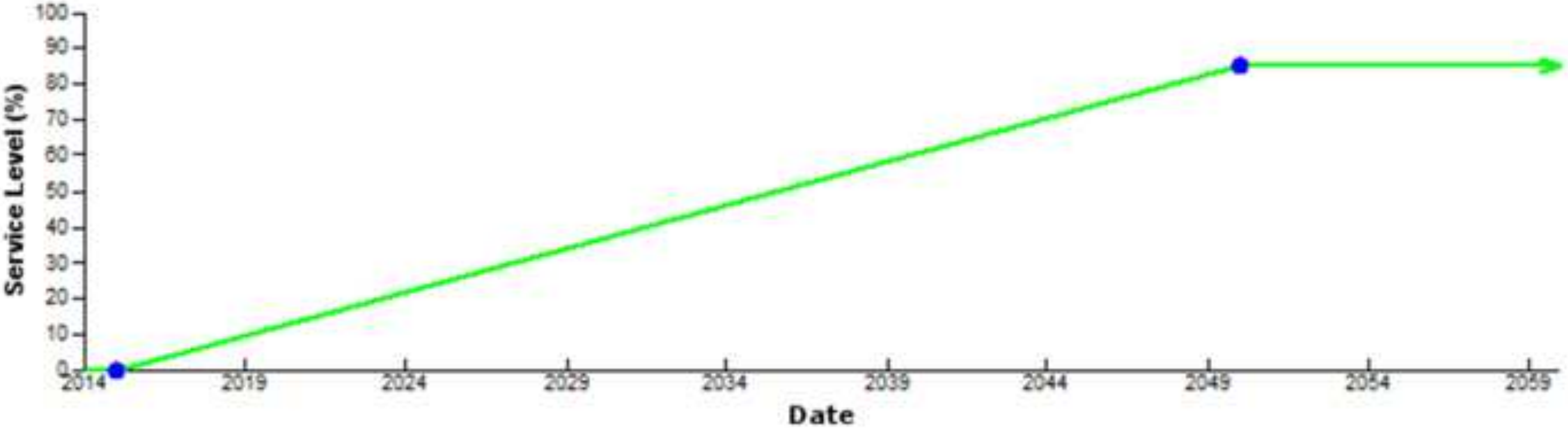
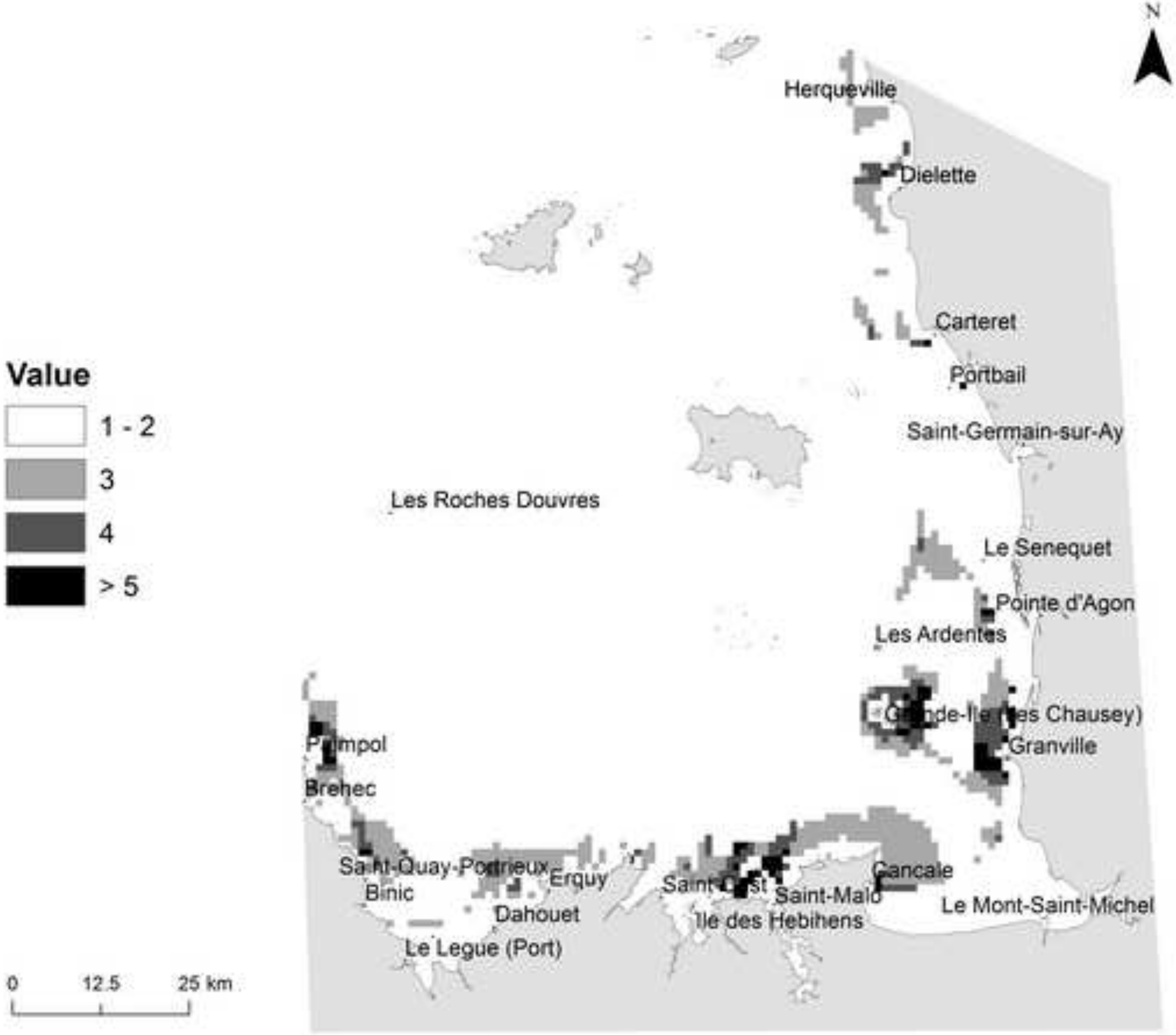


Figure 5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> 5
Herqueville
Dielette
Carteret
Portbail
Saint-Germain-sur-Ay
Les Roches Douvres
Le Senequet
Pointe d'Agon
Les Ardentes
Grande-Ile (Iles Chausey)
Granville
Paimpol
Brehec
Saint-Quay-Portrieux
Binic
Erquy
Dahouet
Le Legue (Port)
Saint-Cast
Saint-Malo
Ile des Hebihens
Cancale
Le Mont-Saint-Michel
0
12.5
25 km

Figure 6

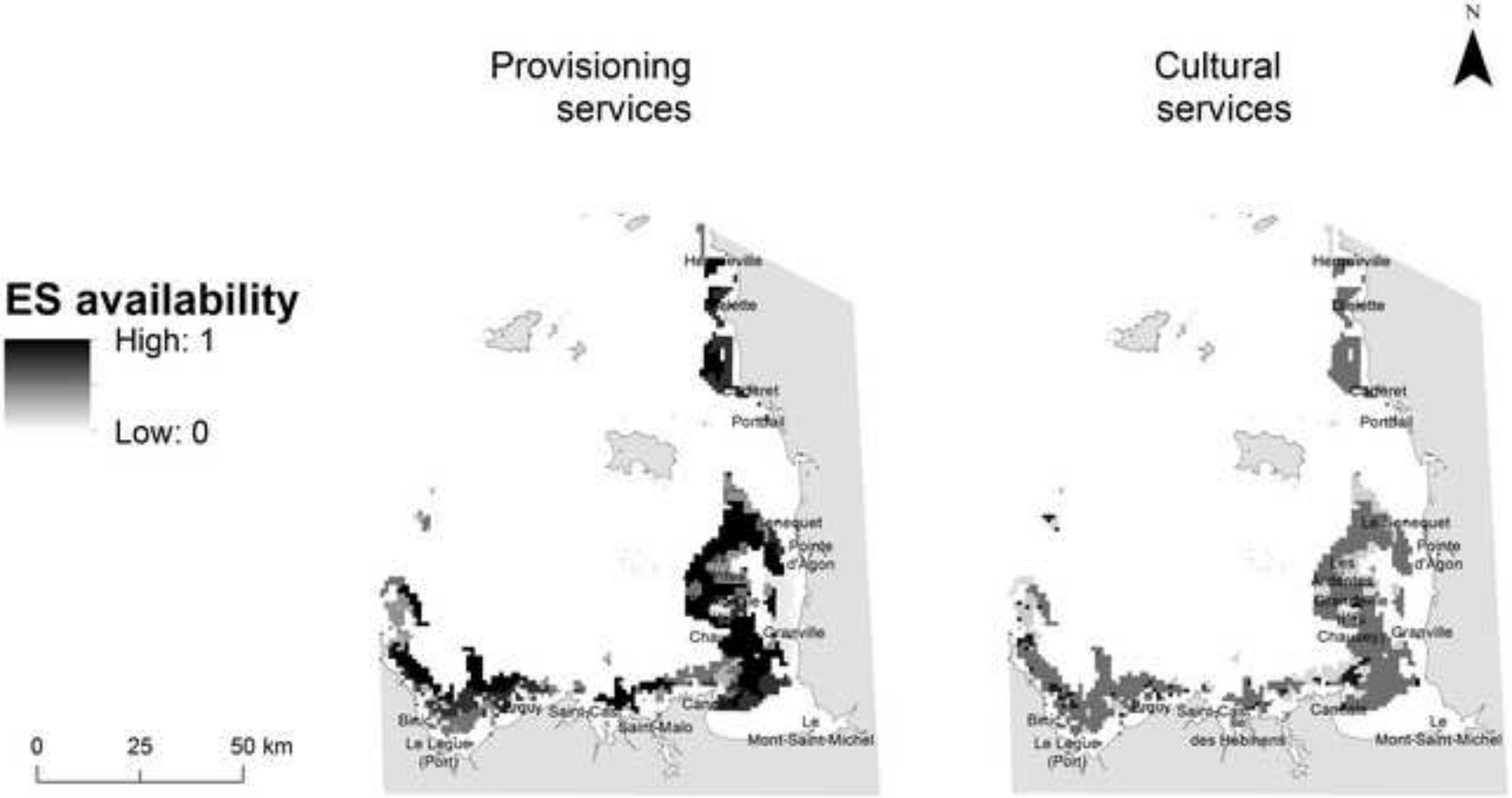
Provisioning services
Cultural services
N
ES availability
High: 1
Low: 0
0
25
50 km
Herqueville
Dielette
Carteret
Portbail
Le Senequet
Pointe d'Agon
Les Ardentes
Grande Ile
Iles Chausey
Granville
Cancale
Saint-Malo
Le Mont-Saint-Michel
Erquy
Saint-Cast
des Hebihens
Binic
Le Legue (Port)

Figure captions list

Fig. 1. The Normand-Breton (Saint Malo) Gulf and the hypothetical location of 3 seaweed farms (A, B, and C)

Fig. 2. Methodological approach

Fig. 3. Service level provided at the injury site

Figure 4. Service level as a result of the compensatory action provided for maerl beds

Fig. 5. Human activities potential conflicts within the suitable area

Fig. 6. Provisioning and cultural ES availability in the GNB

Table 1 Provisioning and cultural ES identified for the GNB habitats and studied here (adapted from [27])

Type	**Ecosystem Service**
Provisioning	Food provision
	Raw material
Cultural	Cultural heritage and identity
	Cognitive benefits
	Recreation
	Notable biodiversity

Table 2

Table 2 Types of habitats and main species for each seaweed farm. Proxies for ecosystem services indicators were selected according to the highest intensity of presence (3)

Seaweed farm	Habitats (% overlap)	Species intensity of presence	Selected proxy	Ecosystem service category
A	A5.51 - Maerl beds (100%)	Scallops (1), Clams (2), Pink clam and sea almond (2), Maerl (3)	Maerl	Cultural
B	A5.13 - Circalittoral coarse sediment (100%)	Scallops *(* (3), Clams (2), Pink clam and sea almond (2), Whelk (3), Soles (2), *Pétoncles vanneau* (2), Bass (2)	Scallops (*Pecten maximus*)	Provisioning
C	A2.24 - Polychaete/bivalve-dominated muddy sand shores (38.4%)	Pacific oysters (3), Mussels (3), Manila clams (2)	Mussels (*Mytilus edulis*)	Provisioning
	A5.43 - Infralittoral mixed sediments (61.6%)	European oyster (3), Scallops (1), Crepidula (1)	European oyster (*Ostrea edulis*)	

Table 3

Table 3 Types of habitats and main species for each seaweed farm. Proxies for ecosystem services indicators were selected according to the highest intensity of presence (3)

Seaweed farm	Habitats (% overlap)	Species intensity of presence	Selected proxy	Ecosystem service category
A	A5.51 - Maerl beds (100%)	Scallops (1), Clams (2), Pink clam and sea almond (2), Maerl (3)	Maerl	Cultural
B	A5.13 - Circalittoral coarse sediment (100%)	Scallops ((3), Clams (2), Pink clam and sea almond (2), Whelk (3), Soles (2), *Pétoncles vanneau* (2), Bass (2)	Scallops (*Pecten maximus*)	Provisioning
C	A2.24 - Polychaete/bivalve-dominated muddy sand shores (38.4%)	Pacific oysters (3), Mussels (3), Manila clams (2)	Mussels (*Mytilus edulis*)	Provisioning
	A5.43 - Infralittoral mixed sediments (61.6%)	European oyster (3), Scallops (1), Crepidula (1)	European oyster (*Ostrea edulis*)	

Table 4

Table 4 Indicators for deploying seaweed farms

Seaweed farm	**A**	**B**	**C**	
Habitats (%)	A5.51 - Maerl beds (100%)	A5.13 - Circalittoral coarse sediment (100%)	A2.24 - Polychaete/bivalve-dominated muddy sand shores (38.4%)	A5.43 - Infralittoral mixed sediments (61.6%)
Proxy	Maerl beds	Scallops	Mussels	European oyster
Provisioning services availability (%)	42	100	50	
Cultural services availability (%)	20	52	100	
Distance to coast (km)	5.2	11.4	1	
Potential human use conflicts	5	1	5	
Visual impact (inhab.)	3690	9100	8250	
Ha compensation per damaged ha	2.585	2.290	2.002	
Restoration cost per farm of 1km² (USD)	\$6,384,950-\$31,937,158	\$365,484	\$1,483,882-\$9,893,684	

Table A.1 Professional and recreational activities geographical datasets

GIS layers	Source	Type	Pre-processing
Professional fishing	Ifremer, SIH, 2012	Polygon	Density of ships per month per statistical sub-rectangle. All engine types. Density > 0.2
Dredge spoil dispposal sites	AAMP	Point	Buffer of 1000m
Harbors	AAMP	Point	Buffer according to number of ships: < 5 = 250m; >=5 and <25 = 500m; >=25 and <100=1000m; >=100=2000m
Off-shore energy	AAMP	Polygon	None
Marinas	AAMP	Point	Buffer of 250m
Anchorages	AAMP	Point	Buffer according to the capacity: <10 = 250m; > =10 and <100 = 500m; >=100 = 2000m
Shellfish farms	AAMP	Polygon	Convex hull for grouping shellfish records
Granulate extraction	AAMP	Polygon	None
Marine traffic	AAMP	Polyline	None
Recreational on-foot fishing	AAMP	Polygon	Selection of the foreshore area
Recreational boat fishing	AAMP	Point	Buffer of 3000m around points and inside the sailing areas
Surfing	AAMP	Polyline	Buffer of 250m
Kitesurfing	AAMP	Point	Buffer of 1km
Sailing	AAMP	Point	Buffer of 1km in the navigation area
Land sailing	AAMP	Point	Buffer of 5km in the foreshore
Scuba diving	AAMP	Point	Buffer of 250m
Sea rowing	AAMP	Polyline	Buffer of 5km