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Multi-approach mapping to help spatial planning and management of the kelp species *L. digitata* and *L. hyperborea*: Case study of the Molène Archipelago, Brittany

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ABSTRACT

The Molène Archipelago in Brittany (France) hosts one of the largest kelp forests in Europe. Beyond their recognized ecological importance as an essential habitat and food for a variety of marine species, kelp also contributes towards regional economies by means of the alginate industry. Thousands of tons of kelp are collected each year for the needs of the chemical and food industries. Kelp harvesting in Brittany mainly concerns two species, *Laminaria digitata* (59,000 t) and *Laminaria hyperborea* (24,000 t), that, together, represent approximately 95% of the national landings. Estimating the available standing stock and its distribution is a clear need for providing appropriate and sustainable management measures.

Prior to estimating the spatial distribution of biomasses, we produced a detailed seabed topography map with accurate hard substrate delineation thanks to surveys and appropriate processing of airborne optical and acoustic imaging. Habitat suitability models of presence–absence and biomass were then developed for each species by relating in situ observations from underwater video and sampling to the many biotic and abiotic factors that may govern kelp species distribution. Our statistical approach combining generalized additive models (GAM) in a delta approach also provided spatial uncertainty associated with each prediction to help management decisions.

This study confirmed that the adopted strategy, based on an integrated approach, enhanced knowledge on kelp biomass distributions in the Molène Archipelago and provided a promising direct link between research and management. Indeed, the high resolution topography and hard substrate maps produced for the study greatly improved knowledge on the sea bottom of the area. This was also of major importance for an accurate mapping of kelp distribution. The quality of the habitat suitability models was verified with fishing effort data (RECOPESCA program) and confirmed by local managers and kelp harvesters. Based on the biomass maps produced and their associated confidence intervals, we proposed more precise management rules than those already in use for both *L. digitata* and *L. hyperborea*. Our mapping approach is a first step towards sustainable kelp species management in the area. Introducing higher resolution environmental variables and population dynamics would help interannual management.

1. Introduction

Kelp forests are some of the dominant producers and most diverse habitats within near-shore coastal ecosystems (Dayton et al., 1998; Kerumbrun, 1984; Mann, 1973). Beyond their recognized ecological importance as an essential habitat and food source for a variety of marine invertebrates and fish species (Christie et al., 2003; Derrien-Courtel et al., 2013; Fowler-Walker and Connell, 2002), they also contribute to regional economies through the alginate industry. Used to make many products in the pharmaceutical, cosmetic and food-additive industries, their harvest records an ever-increasing demand (Frangoudes et al., 2012).

The Molène Archipelago (Brittany coast, France), located within the Parc Naturel Marin d'Iroise (PNMI) marine protected area, hosts one of the largest kelp forests in Europe. It is mainly structured by four species: *Laminaria digitata*, *Laminaria hyperborea*, *Laminaria ochroleuca* and *Saccorhiza polyschides*. Kelp species differ in their morphology, ecophysiology, and longevity and show distinctive patterns of distribution along

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the different littoral zones (Birkett et al, 1998). *L. digitata* and *L. hyperborea* form the most extensive kelp beds: tens of thousands of tons are collected each year in the Molène archipelago by a professional harvesting fleet (Arzel, 1998).

Management rules to access and exploit kelp have been developed over a long period of time along the coastal area of the French region of Brittany (Anonymous, 2014; Frangoudes, 2011). Although *L. digitata* has been traditionally harvested for almost 170 years, the current rules were developed in the last 40 years when the fleet became mechanized. For *L. hyperborea*, some of the management rules were adapted from kelp harvesting regulations in Norway (Vea and Ask, 2010).

Since 1985, *L. digitata* production has been considered as quite stable in Brittany, even if some annual fluctuations are recorded (Davoult et al., 2011; Laurans et al., 2010). *L. hyperborea* is considered as a new production as its harvest only really started in 1996. Since 2007, the production has increased due to higher demands from industry and new vessels were able to target this species. The main part of the French seaweed harvesting activity takes place within the PNMI, mainly in the Molène Archipelago. Due to the increasing demand from industries and the prominent position of kelp in the coastal ecosystems of Brittany (Leclerc, 2013; Schaal, 2009), the need to increase overall knowledge has become a key issue in order to improve the management of the PNMI area. Identifying the spatial distribution of key species such as kelp at relevant scales is essential for coastal management and conservation of the environment (Holmes et al., 2008; Hooper et al., 2005). Accurately quantifying and mapping each of the main kelp species in the PNMI harvesting area are of upmost importance as exploiting pressure increases.

Previous studies have estimated the *Laminaria* kelp stocks of the Molène Archipelago (Arzel, 1998; Floc'h, 1967; Kerumbrun, 1984; Piriou, 1987), however the different methods used and the imprecise hard substrate delineation led to important differences in stock evaluations and approximate estimations of distribution. Indeed, various methods may be used to characterize the distribution of Brittany's kelp forests (Bajjouk et al., 1996; Ben Moussa, 1987; Kepel, 1995; Kerumbrun, 1984; Piriou, 1987). However techniques traditionally used for underwater vegetation surveying (Guillaumont et al., 1997) have limitations to retrieve required information for kelp species standing stock estimation, in particular when used independently : (i) traditional direct sampling methods such as video or diving are precise but time consuming and costly whatever the working scale of the study area, and (ii) remote sensing tools, such as aerial photography or airborne and satellite imagery allow large area coverage but rapidly reach their limits for sub-tidal surveys because of the absorption of visible radiation by water. In our area, only imaging from the first ten meters depth can be treated, while kelp has been observed down to 30 m (Derrien-Courtel et al., 2013). (iii) Acoustic methods also allow large areas to be covered but may have a limited ability to differentiate macrophyte species, which leads to the difficulty of assessing biomass. We therefore combined these different sources of observations not only for broad scale mapping of algal distribution (Tatarek et al., 2012), but also to estimate biomass production spatially.

Statistical modeling approaches have great potential for predicting distributions over large-scale areas where field data are limited or unavailable (Guisan and Zimmermann, 2000). Several studies have used statistical models to link the effects of several biotic and abiotic factors to kelp species distribution. Bekkby et al. (2009b) modeled the probability of observing four density classes of *L. hyperborea* along the Norwegian coasts according to physical parameters using a generalized additive model (GAM). In Brittany, Méléder (2010) established an occurrence frequency predictive map of kelp forests by applying a parametric linear regression model, but results did not include shallow waters (0–12 m). Coarse resolution maps of physical parameters were used and important parameters such as wave exposure were missing. Bonetti and Populus (2008) continued this work using the same dataset while adding chlorophyll-a concentration as an explanatory variable. More recently, Gorman et al. (2012) used the GAM method to model presence/absence and biomass of kelp forests in the Bay of Morlaix. *L. digitata* and *L. hyperborea* distributions were predicted on the basis of high-resolution maps (25 m pixel size) which provided a level of information compatible with the needs of marine spatial planning.

Since kelp forests require a hard substrate to fix onto, the quality of model prediction relies on an accurate delineation of rocky seafloor. The most accurate bottom substrate maps previously available were at a scale of 1:50000. Rocky areas may be extracted by data analysis from bottom topography (Bekkby et al., 2009a; Erikstad et al., 2013), but the finest bathymetric digital terrain model (DTM) available before our study had a 100 m resolution, which given the high topographical complexity of the archipelago was too coarse (Raffin, 2003). A precise bathymetry is also of particular interest for kelp forest delineation as it is of major importance in the calculation of bottom light availability, the main influential factor for photosynthetic species. For shallow waters, Lidar (Light Detection and Ranging) is quite an original approach to provide accurate DTM (Parrott et al., 2008). This has been successfully applied to coastal areas for ecosystem mapping (Chust et al., 2010; Lefsky et al., 2002), in bathymetric programs (Irish and Lillycrop, 1999; Wozencraft and Lillycrop, 2003) and in other geomorphological applications (Flood and Gutelius, 1997; Stock et al., 2005; Webster et al., 2006). Acoustic technology is also commonly used in many seafloor mapping programs and marine habitat monitoring projects (Cuadrado and Gómez, 2011; Ehrhold et al., 2006; Legrand et al., 2012; Mitchell and Hughes Clarke, 1994).

The present paper shows how different common and recent methods of observation can simultaneously be used to produce precise maps of kelp biomass for sustainable spatially-explicit resource management. The proposed approach consists in firstly establishing surveys and appropriate processing methods in order to provide a detailed underwater topography of the area and to accurately delineate hard substrates (bedrock) potentially colonized by kelp. Secondly, a habitat suitability model is fitted for each species on some carefully selected field stations, measuring kelp presence/absence and biomass. Predictive maps are produced, based on hard substrate areas previously delineated. The third step aims at comparing the predicted standing stock distributions with a fine scale spatial harvesting distribution of effort to propose new tools for management. Owing to the recent equipment of the commercial fleet with a geolocation system (Leblond et al., 2008), spatio-temporal activities of fishing boats could be well known.

This study focuses on three kelp species: (i) *L. digitata*, which has been traditionally harvested for almost 170 years and for which harvesters have observed a strong inter-annual variation in stocks, (ii) *L. hyperborea* which seems to be a promising abundant species for future harvest and (iii) *S. polyschides*, which, although containing no alginate and presenting no industrial interest, is an opportunistic species competing with the other two.

2. Materials and methods

2.1. Study site

The study area is the Molène Archipelago located at the western tip of France, in Brittany, in the Iroise Sea (Fig. 1). The area is an extended plateau, which has a complex topography up to 50 m deep (at the shelf break), with dynamic hydrological conditions and strong currents up to 8 knots and is often exposed to strong Atlantic and Channel winds.

Separated from the Island of Ushant by a channel around 50 m deep, the Molène Archipelago displays nine major islands and secondary islets